Workshop Report: Grand Challenges for Advanced Photovoltaic Technologies and Measurements

May 11–12, 2010
Denver, Colorado

Prepared for the National Institute of Standards and Technology

August 2010

Acknowledgments

This report summarizes the results of the *Workshop on Grand Challenges for Advanced Photovoltaic Technologies and Measurements* held on May11-12, 2010, in Denver, Colorado. The workshop was a collaborative effort of the National Institute of Standards and Technology and the Steering Committee for Advancing Photovoltaic Technologies (members shown below). Thanks are extended to the Steering Committee co-chairs and members for their extensive efforts in guiding this workshop and successfully reaching the outcomes. Thanks also go to Energetics Incorporated for their assistance in facilitating the workshop and preparing this report.

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Source: National Renewable Energy Laboratory (NREL) and Plextronics

SunPower solar electric system.
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Amonix 7700 mega module
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1.0 INTRODUCTION

1.1 Overview of the Topic

Technical barriers continue to limit the performance of crystalline silicon photovoltaic (PV) technology and also impede the development of advanced, next generation technologies such as advanced thin film, crystalline multijunction, organic, and nanostructured PV. These next generation technologies hold promise for potentially disruptive improvements in performance or cost, with the potential to approach or even exceed the performance of silicon at lower manufacturing cost.

The *Grand Challenges for Advances in Photovoltaic Technologies and Measurements* workshop was held on May 11-12, 2010 in Denver, Colorado to identify the critical technology and measurement barriers impeding advances in PV technologies. The workshop was hosted by the National Institute of Standards and Technology (NIST) as part of broad based efforts to identify challenges to commercial development of advanced PV. The workshop was attended by over 70 world-renowned experts from industry, national laboratories, and academia.

This report summarizes the ideas generated at the workshop. Note that the results presented here are a reflection of the opinions and ideas of the participants attending this workshop, not necessarily the entire PV industry, although great effort was made to ensure that participants represented all aspects of the industry. Please note that the opinions presented for each topic area may differ (and at times be contradictory) among the four breakout groups, which included the following PV technologies:

- **Wafer-based crystalline silicon PV.** The most commonly used technology today, crystalline silicon PV uses bulk crystalline silicon materials incorporated into cells with thicknesses of 100 microns or greater, originating from sliced single-crystal or multi-crystalline ingots, and sometimes cut from ribbons of silicon.
- **Thin film hydrogenated amorphous silicon (a-Si:H) and thin film polycrystalline PV.** These technologies use multiple materials in structures of successive thin layers deposited onto an inexpensive supporting substrate such as glass, polymer, or metal.
- **III-V Multijunction PV.** The layered structure of this technology consists of single crystalline semiconductors from groups III and V of the periodic table, such as gallium arsenide (GaAs).
- **Excitonics and quantum-structured PV.** This technology includes solar cells with absorber layers that rely on quantum physics (e.g., confined excitons—bound electron-hole pairs), including organic or polymer-based cells, dye-sensitized cells, or cells using quantum dots/wires, quantum wells, or superlattice technologies.

1.2 Broad Challenges Facing the Industry

1.2.1 Technical Challenges

These challenges cover the range of technology development stages, beginning with basic science and progressing through applied research and development (R&D) and deployment.

- **Materials to device analysis.** A basic understanding of the relationships between fundamental materials properties on the atomic scale and PV device processing and performance is essential to advancing all PV technologies in the future. Such fundamental knowledge is critical for the development of more efficient solar cells and the reduction of manufacturing costs.
- **In-line manufacturing tools.** While methodologies and requirements may differ, all PV technologies can benefit from additional tools for in-line measurements to increase throughput and yield and to reduce cost. Today's manufacturing tools are insufficient for in-line materials and cell characterization, including measurement of mechanical integrity, optical collection, and electronic quality—all essential to product performance.
- **Module characterization**. PV producers currently lack the ability to accurately predict reliability over the lifetime of the PV system, and thus the standards for such predictions among their PV products. Investment confidence and ultimately system efficiencies depend in large part on the reliability (e.g., system lifetime, expected performance over lifetime) of PV products.
- **Standardized module rating system, certifications, and protocols.** The standard methodology and rating system for modules is insufficient for predicting PV system performance. Improvements in this system would facilitate comparison among similar PV products, enabling informed consumer decisions and advancing the evaluation of new technologies based on consistent methods of comparison.
- **Solar resource assessment.** As solar irradiance is the energy supply for all PV technologies, accurate solar resource measurement methods are essential for predicting potential power generation for individual systems over their lifetime. Reliably predicting solar irradiance on an hourly or even more frequent basis is essential for system planning to maximize use of the solar resource and minimize system capital costs.

1.2.2 **Non-**Technical Challenges

While not the focus of the workshop, a number of broad infrastructural, institutional, and other challenges were identified.

- **Low cost and abundant raw materials.** Limited supplies of materials can represent a barrier to PV expansion. For a given PV technology to be a significant contributor to the electricity supply, then the raw materials used by that technology must be Earth-abundant.
- **Environmental impacts of emerging technology.** The environmental impacts of conventional and emerging technologies are not well-understood. Issues include limited knowledge of the toxicity of nanomaterials and other novel materials; potential release

of materials from PV systems into the environment during and after use; safe operation of PV manufacturing plants; and cost-effective recycling of cells.

- **Interconnect rules and fees.** Excessive standby and interconnection charges will prohibit integration of PV systems with grid electricity. State and local agencies will need to determine equitable interconnection charges, standby charges, and net-metering requirements and fees for solar electricity generated in distributed applications and then sold to the grid.
- **Deep market penetration.** Substantial penetration of PV into electricity markets could require significant transmission expansion and grid operations advancement.
- **Regulation and permitting.** Many of the permitting requirements in the United States are cumbersome or create disincentives, making deployment more complex and costly.
- **Consumer awareness.** Consumers must become better educated about purchasing solar energy products and using solar energy for their electricity needs; they must also have access to further information enabling them to evaluate the performance and payback period of PV systems over time.

1.3 Role of Measurement Science in PV Technology

Advanced measurement capabilities are crucial throughout the innovation process in photovoltaics. As technologies mature, fundamental improvements must be driven increasingly by an in-depth understanding of the relationships between material properties down to the atomic scale and device performance. As a result, the importance of this theme arises in technologies varying from the current generation of wafer-based crystalline silicon (Si) PV to future generations of quantum and nanostructured PV.

Many of the measurements required to establish these relationships are time consuming and may be destructive to the materials and devices. There is a significant demand that cuts across all technologies for high speed, non-invasive measurements that can be implemented on the production line for monitoring the PV product at the different stages and for potential feedback and control. Once module fabrication is complete, three interrelated measurement methodologies are required for accurate prediction of PV system performance over its lifetime. These methodologies include a standardized module rating system to enable comparison of products; an accurate solar resource measurement for prediction of PV expected output depending on module rating, location, and other factors; and reliability analysis for predictions of performance versus time in the field.

2.0 Wafer-Based Crystalline Silicon PV

2.1 Overview of the Topic

Discussions of wafer-based silicon PV focused on solar cells originating from sliced single and multi-crystalline ingots. Solar cells made from wafers cut from ribbons of silicon were also discussed.

Wafer-based crystalline silicon PV technology has the longest track record of all PV technologies, is the most commercially advanced, and has captured a majority of the global PV market. Current multi-crystalline module efficiencies are in the range of 13–20%; mono-crystalline efficiencies range from 16-20%. Wafer-based PV has approximately 85% of the global market.

Many advances have been made during decades of commercial use, but challenges still exist to further expansion of this technology into the market. These include increasing efficiency, reducing kerf loss without compromising quality, and reducing costs. The vision, technical challenges, non-technical challenges, and measurement issues identified are discussed in the following sections.

Wafer silicon solar panels (Source: SunPower)

2.2 Future Drivers and Characteristics

2.2.1 Vision

Over the next 20 years, it is anticipated that wafer-based crystalline silicon PV will continue to constitute a large portion of PV installed in the United States. While this PV technology is relatively mature, necessary improvements are expected to be made in cell and module performance as well as manufacturing. Examples of needed improvements include better low-light collection, enhanced thermal control, increased yield, and monolithic design with one thermal step. Future developments may lead to an increased shift to single crystal-based cells or development of multi-crystal technology that performs similarly to single crystal-based cells. Figure 2.1 summarizes the future vision for this area.

Figure 2.1: Vision for the Future of Wafer-based Crystalline Silicon PV

- **Greater PV electricity generation**. Approximately 20% of U.S. electricity is generated from PV in 2030, the majority of which is from wafer-based crystalline silicon PV
- **Architecturally integrated**. In 2030, PV will be a standard feature of new buildings. Wafer-based crystalline silicon technologies will have products that easily integrate into buildings
- **Related technology breakthrough**. Advances in other technologies, such as electric

2.2.2 Drivers

Several overarching drivers of crystalline silicon technology also affect the entire PV industry, including lower module costs, greater power conversion efficiency, and lifetime reliability. One other general driver—improvements in manufacturing processes—has many components, both technical and non-technical. The high capital expense to set up manufacturing facilities and to fund large PV installations constrains the ability of small innovators to participate in the PV industry.

Another driver is the ability to collect the full solar spectrum, including down conversion of high energy photons, up conversion of low energy photons, and improved capture at the module level. This would drive greater adoption of wafer-based crystalline silicon PV, as would be the case for all technologies.

Wafer silicon solar panels (Source: iStockphoto)

2.3 Broad Barriers

2.3.1 Technical Barriers

Several technical barriers were identified that impede advances in wafer-based crystalline silicon PV technologies. The major themes are discussed below. Appendix B contains a complete list of technical barriers that were identified.

Efficiency limitations

The highest priority technical barrier identified was the efficiency limitation of single junction silicon cells. These efficiency limitations may increase interest in other approaches, such as multijunction cells, with higher theoretical efficiencies.

Thinner wafers

Thinner wafers are desirable for many reasons including reduction of silicon use (e.g., lower cost, reduces weight). However, there are many technical challenges to handling and processing thin wafers (approximately <100 microns) from ingots. Creating thinner wafers leads to more breakage (which results in waste) as thinner wafers are more brittle and current slicing technology is not adept at reducing breakage. In addition, for thinner wafers surface recombination needs to be reduced and module interconnections improved. The move to reduce wafer thickness may divide the industry, with different handling techniques for thin 40 micron wafers versus the more standard 180 micron wafers. Both manufacturing processes should address the added substrate support needed during processing and temperature cycling.

Efficient silicon usage

Reducing the amount of silicon consumed in producing a set amount of module power is a challenge, but would provide lower installed cost per watt. For example, if 6 to 8 grams per Watt peak (g/Wp) are currently used, then a goal could be to attain 2 g/Wp. Reducing silicon usage may be achieved by reducing kerf loss, increasing recycling of waste material, producing thinner wafers, and reducing breakage. All of these approaches have unique challenges.

Product form

Module packaging, which has not changed in more than three decades, is overdue for a makeover. To continue to capture market share, both technical and non-technical changes to module and systems should be incorporated. Some of these changes include reducing system weight (kg/m^2) for rooftop applications and incorporating smart module features (e.g., in-situ cooling, maximum power tracking, self cleaning coatings, automatic turnoff capability during fires, and embedded electronics).

2.3.2 Non-technical Barriers

Non-technical barriers addressed potential regulatory hurdles for PV in the United States. With manufacturing capabilities and end use markets increasing in other countries, the United States would benefit from a strong domestic demand and capability. Streamlining existing regulations for PV could facilitate industry growth in the United States. Examples of regulatory hurdles include permitting of systems, standardizing balance of system (BOS) components, and simplifying interconnection rules.

2.4 Measurement Challenges

A number of areas were identified where measurement challenges could create impediments to wafer-based silicon technology progress. These are summarized below and listed in Appendix B.

Wafer crack detection

Detection of cracks during manufacture is essential to ensure high yield and maintain quality products. While methods currently exist to detect wafer cracks, various improvements were identified. Developments needed include a non-contact wafer crack detection tool with the capability to scan wafers at high speed (e.g., <1 second/wafer). The tool should measure total thickness variations, measure the spatial location of cracks, and rapidly scan the whole wafer for cracks.

Materials/process characterization

Characterization of materials and process parameters during manufacture is extremely important for detecting defects early in the process and ensuring the products will be within specifications. One important challenge is the ability to measure quality factors (e.g., surface recombination velocity, dielectric charge state/strength, and hydrogen passivation stability in time) for silicon wafers that lead to high open circuit voltage (V_{OC}) and fill factor in multicrystalline silicon. Another key supporting capability is in-situ monitoring during processing including direct measurement of ingot quality, wafer thickness, junction depth (from sheet resistance measurements), anti-reflective coating, and voltage of junction before contact application. Inline, non-destructive measurements are preferred.

Energy rating

Energy ratings affect various aspects of the PV market such as the commercialization of module products and financing of PV systems. Development of a systems energy rating methodology was identified as a top priority. A standard methodology for energy-rating of modules is also necessary. Institution of mandatory performance and reliability standards in the United States for PV modules and inverters are important aspects. A levelized cost of electricity (LCOE) metric for systems, where all costs are considered (land, financing, operation, insurance, etc.), would create more comprehensive energy ratings.

The demand for PV is such that all kinds and quality of silicon are needed during production. However, a wide spectrum of efficiencies can be obtained using wafers from the same ingot. With proper test equipment, individual wafers can be rated and used according to the efficiency demands of particular applications.

Reliability

Reliability of materials, modules, and systems is very important to gain consumer confidence, meet lifetime guarantees, and predict performance over time. To advance wafer-based silicon PV technologies, measurement and understanding of polymer degradation was identified as a key challenge, including the adhesion of encapsulants (e.g., density of chemical bonds, stress inside encapsulant). Another key challenge was the measurement of the quality of solder bonds using a non-destructive method that can scan either a string or a module. Correlation of accelerated stress tests (for modules) with field performance would aid in the understanding of faults and improvement of product reliability.

2.5 Grand Challenges for Technology and Measurement

Based on the technology challenges and the measurement issues identified previously, a more comprehensive set of Technology and Measurement Grand Challenges was developed. In some cases these combine various aspects of several challenges, and also provide additional detail on performance targets, applications, impacts, and pathways for development. The Grand Challenges are listed below and illustrated in detail in Figures 2.2 through 2.7.

Figure 2.2	Overcoming crystalline wafer efficiency limitations through materials monitoring and control, including materials and device compatibility measurements
Figure 2.3	High throughput measurement of wafer mechanical integrity
Figure 2.4	Process monitoring and control from materials to wafer to cell
Figure 2.5	Improved interconnection schemes for thin (50 micron) silicon cells
Figure 2.6	Accurate prediction of system energy output
Figure 2.7	Measuring and predicting the degradation of materials

Figure 2.2: Overcoming crystalline wafer efficiency limitations through materials monitoring and control, including materials and device compatibility measurements

Performance Targets/Goals:
Achieve the highest efficiency Si-based devices, reducing $/watt and $/kWh

Technology and Measurement Science Challenges/Barriers

» Understanding the variability of coatings (anti reflective, other)
» Limited materials availability and compatibility of materials issues
» Direct control of final product quality
» Understanding impact of environmental interferences on materials

Applications

» Advanced device characterization techniques
» Heterostructure interface characterization
» Highest quality, highest yield Si for PV applications

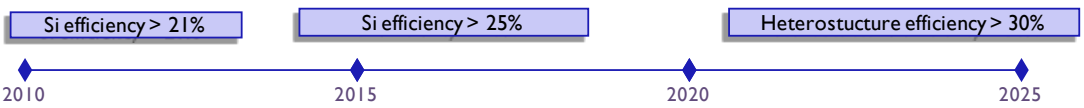
Impacts

» Produces more power per unit area, reducing cost related to area (including system costs) and increasing viability of new applications
» Lowers cost of the product
» Creates high power density modules
» Opens up additional applications for products

Pathway

1. Identify process parameters that need to be controlled directly (e.g., ingot growth, slicing, device fabrication, etc.)
2. Establish non-contact control of interface shape and movement, and use it for feedback control
3. Characterize grain boundaries, orientation, and uniformity segregation of ingots and wafers
4. Determine effect of process and atmosphere on quality of silicon as it relates to cell efficiency
5. Develop highest quality Si (e.g., n-type Czochralski substrates), with low oxygen, non-interactive grain boundaries, and reduced impurities—leading to new device structures
6. Develop new processing steps to capture all free carriers, using entire spectrum, even in low light conditions
7. Consider advanced heterostructure and multi-junction coatings

Milestones



Stakeholders and Roles	
Industry	Materials and device producers
Research laboratories, universities	Basic research
National laboratories	Measurement technology development

Figure 2.3: High throughput measurement of wafer mechanical integrity

Performance Targets/Goals:

- Develop an automated system to scan, measure, and bin wafers
- Develop a system to measure the crack distribution at wafer perimeter

Technology and Measurement Science Challenges/Barriers

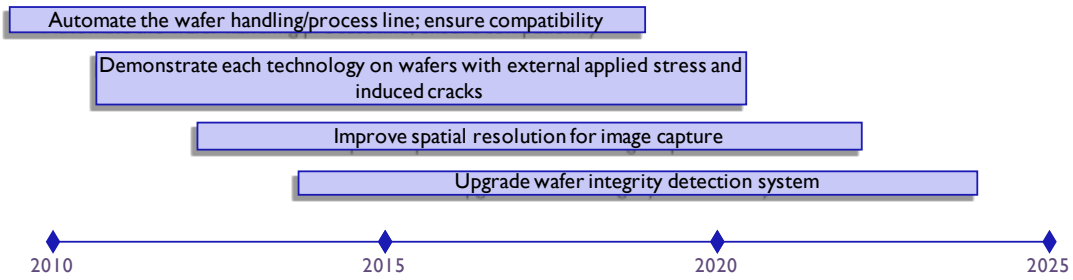
» Automated low-stress handling of wafers
» Scanning technology to scan wafers for cracks
» Understanding stresses and cracks in order to predict fractures

Applications	Impacts
» Guidance on mechanical integrity of thin wafers	» Reduces breakage » Provides greater control of wafers

Pathway

1. Develop measurement tools (ultrasonic, optical, and electrical) for scanning and evaluation at ingot and wafer/cell level
2. Establish analytical methods for interpreting data (optic processing and fusion)
3. Establish validation tools for high throughput measurements
4. Create standards for measuring wafer mechanical integrity

Milestones



Stakeholders and Roles	
Industry	Develops, implements innovations
National laboratories	Develops techniques, standards
University	Trains students in techniques

Figure 2.4: Process monitoring and control from materials to wafer to cell

Performance Targets/Goals:

- Understand process steps for crystal growth, wafering, junction formation, and passivation
- Intelligent controls based on inline monitoring in conjunction with physical models and measurements

Technology and Measurement Science Challenges/Barriers

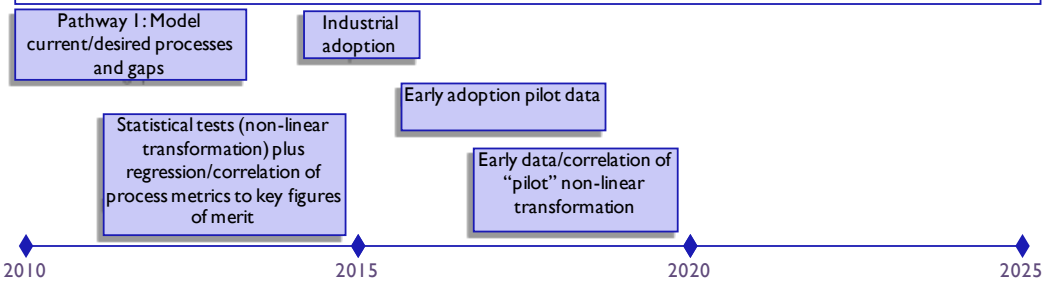
» Improving substrate non-uniformity (e.g., surface recombination velocity, or SRV)
» Monitoring and controlling impurity/defect interactions which create process interruptions
» Lack of proxies for "real" measurements (e.g., limited diffusion profiles)
» Achieving process measurement/control (i.e., oxide thickness) in thin Si

Applications	Impacts
» All manufacturing aspects, including junctions, passivation, wafering, and crystallization	» Faster return on capital expenditures » Improves competitiveness of U.S. manufacturers via integration of process measurements, models, and control

Pathway

1. Define current state and desired state for process monitoring and control of all phases of manufacture; set performance targets for new systems
2. Identify gaps and limitations in current control schemes; define new measurement and tool capabilities
3. Integrate understanding of process-to-material from wafer thru cell, using linked measurements, models, and controls for all processing steps
4. Establish industry buy-in; conduct large statistical tests to establish targets for specific correlation coefficients

Milestones



Stakeholders and Roles	
Cell manufacturers	Test and validation
Supplier to cell manufacturers (e.g., wafer suppliers)	Input to models, validation
Process equipment makers	Test and validation
Metrology/inspection equipment makers	Test and validation
Standards organizations	Semiconductor standards
Universities / Federal laboratories / Research consortia	Models, tests

Figure 2.5: Improved interconnection schemes for thin (50 micron) silicon cells

Performance Targets/Goals:
New approaches for interconnection that reduce stress and minimize breakage of thin x-Si cells

Technology and Measurement Science Challenges/Barriers

» Level of stresses induced on thin cells by current interconnection methods
» Lack of non-destructive methods for measuring bond quality, electrical and mechanical
» Inability to measure stress in cells after bonding to circuit

Applications

» Tabbing or interconnection methods for thin film crystalline cells

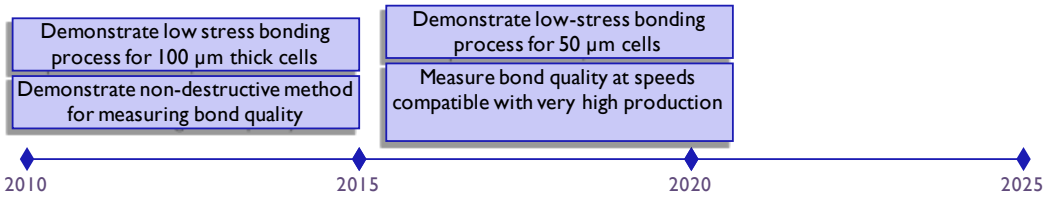
Impacts

» Enables module fabrication from thin x-Si cells
» Lowers the complete system cost

Pathway

1. Develop and validate new chemistries for liquid precursors used in non-contact metal printing that could be adapted as interconnection or bonding schemes
2. Use flexible circuit approach for module level interconnection
3. Develop low thermo-mechanical stress cell bonding to circuit
4. Develop a mechanical support for 50 µm cells that can be interconnected

Milestones



Stakeholders and Roles	
Module manufacturers	Demonstration and production
National laboratories	R&D on new methods
Universities	R&D on new methods

Figure 2.6: Accurate prediction of system energy output

Performance Targets/Goals:
Achieve prediction of system energy production to within +/-3% covering a wide range of field performance

Technology and Measurement Science Challenges/Barriers

» Improving tool accuracy and establishing a standard that adds value

» Resources and time needed for development, population, and validation of an effective energy output rating system covering diverse field parameters (climate, spectral effects, mounting strategies, etc.)

Applications

» All PV systems (residential, commercial, and ground)

Impacts

» Reduces cost of capital

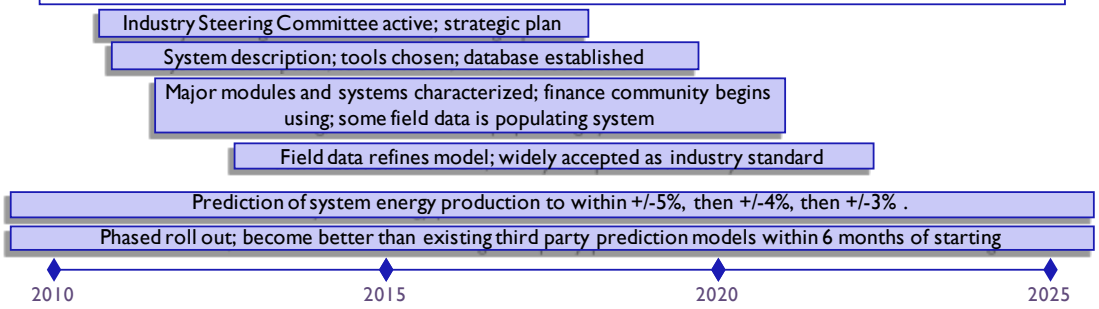
» Large impact on complete costs (>25%) by creating a more favorable certificate of compliance for PV systems

» Increases confidence in technology via predictions and validation from a neutral party

Pathway

1. Understand Module Energy Rating System (coefficients for accurate field performance in full range of climates), including spectral effects and degradation—all factors which influence energy production over the life of modules
2. Establish population and validate module database
3. Create a PV system prediction tool that includes performance of all components
4. Validate systems performance—audited field performance; correlate to prediction tools
5. Improve and establish uniform data for meteorological predictions (30-year resource prediction)

Milestones



Stakeholders and Roles	
PV module manufacturers	Modules and understanding
PV system providers	Bankable systems with low cost of capital; field data and models
Academia	Learn parameters which influence performance; modeling
National laboratories	Modeling

Figure 2.7: Measuring and predicting the degradation of materials

Performance Targets/Goals:

- Establish deeper understanding of degradation mechanisms
- Formulate/qualify new materials that will survive ~ 50 years in the field

Technology and Measurement Science Challenges/Barriers

» Poor understanding of polymer degradation mechanisms, such as discoloration, loss of solar insolation, and degradation at materials interfaces, and its impact on stability and other performance characteristics

» Effectively measuring chemical and structural characteristics at the atomic level

Applications

» Development of new materials

» Statistical justification for extending module warranty, which supports finance for all large systems

Impacts

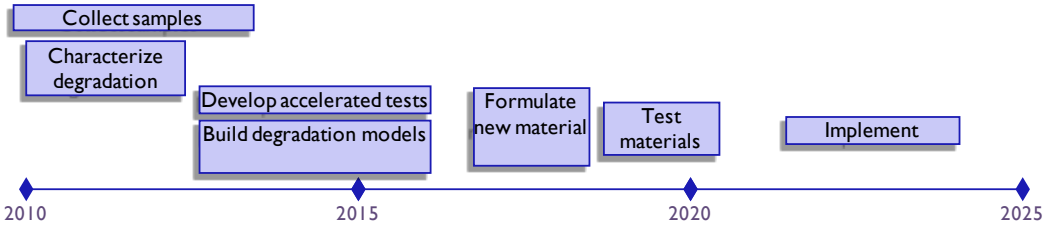
» Faster deployment of new material

» Decreases complete systems costs for PV systems

Pathway

1. Characterize changes in polymer structure after long field exposure times—compared to new materials (for multiple encapsulants)
2. Devise accelerated tests that duplicate the structural changes in the polymer seen in Pathway 1
3. Identify additional properties to be evaluated; include spectral transmission over time, change in adhesive properties to all other components in module (i.e., glass, AR coating, and metal), changes in water vapor permeability, and changes in modulus of elasticity

Milestones



Stakeholders and Roles

Material suppliers	Provide sampled older materials, develop new materials
Module manufacturers	Provide fielded modules with pedigree
National laboratories	Develop accelerated tests; help develop the measurement techniques to characterize the polymer degradation

3.0 Amorphous Silicon and Polycrystalline Thin Film PV

3.1 Overview of the Topic

The discussion of amorphous silicon (a-Si) and polycrystalline thin-film PV included multiple technologies with the common structure of successive thin layers of materials deposited onto an inexpensive supporting substrate such as glass, polymer, or metal. This includes the commercial thin film technologies cadmium telluride (CdTe) and multijunction thin film silicon, and the emerging technology copper indium gallium diselenide (CIGS). Other topics included alternative absorber materials (e.g., $Cu_2ZnSn(SxSe_{1-x})_4$), novel architectures for capturing the solar spectrum and collecting carriers, and evolving technologies. The discussion was limited to the module level, excluding system components such as module mounting hardware, inverters, and grid interconnects.

Thin film solar cells are constructed of several thin layers including an absorber material with high absorption coefficient. This allows the actual device to be on the order of several microns thick, which permits use of inexpensive substrates and decreases processing costs. Thin film technologies have made significant market penetration in utility scale PV (CdTe on glass) as well as in building integrated PV (e.g., amorphous silicon on steel foil). Thin film PV could potentially be disruptive to crystalline silicon PV because of its lower manufacturing cost and product flexibility.

Glass CdTe module (Source: First Solar)

Multijunction thin film silicon and CdTe, which exhibit power conversion efficiencies (PCE) approaching 12.5% (stabilized) and 16.7%, respectively, in small area laboratory cells are the most mature technologies in thin film. CIGS is less mature but has shown a PCE of over 20% in laboratory cells. Module level efficiencies, however, show a much larger gap between champion or theoretical efficiency than first generation Si technologies. Considerable promise exists for further improvements in current thin film technologies, and transformational advances are anticipated in identification of new materials and manufacturing processes.

3.2 Future Drivers and Characteristics

3.2.1 Vision

By 2030, it is envisioned that the thin film PV industry will have advanced to a state of low manufacturing costs ($50 per square meter), high performance (greater than 20% module level efficiency), and long-term reliability (30-year product warranties) (see Figure 3.1). In addition, the thin film market will account for a significant portion of PV production world wide by 2030, have broad acceptance by the general public, and have advanced by continued U.S. technological leadership. It is envisioned that thin film and PV products will be grid-integrated, representing a significant share of the utility electricity production. By necessity, solar fuel systems will be available to overcome the problem of storage. Over the next 20 years, the PV community will have a far greater understanding of the performance characteristics of devices and their relationships to the fundamental microstructural, electronic, and optical properties of thin film materials. The community will also advance measurement techniques that are useful for process monitoring, and are robust, valuable, and reliable over the long term under a range of conditions.

Figure 3.1 2030 Vision for the Future of Thin Film PV

- **Low cost** ($50/m^2 modules). Flexible film power modules as a commodity at costs below conventional electricity generation
- **High efficiency.** Module-level efficiency of 20% or greater
- **Reliable**. Moisture resistant materials and typical 30-year warranty on products
- **Integrated.** Thin film components integrated into full solar fuel system, including electrolysis and catalysis, with more than 50% of the power grid accommodating PV (including storage capabilities); enhancements in functionality integrated with the system, including light-emitting diodes (LEDs), thin film batteries, DC/DC voltage conversion circuitry, and other smart gadgets. Significant share (50%) of buildings have building integrated PV
- **Accepted.** Easy to use, deploy, and apply in different applications, is aesthetically attractive and lightweight, and is a universally recognized as the "greenest" of the technologies with the shortest energy payback time
- **Market share.** Holds the majority share of the approximately 200 gigawatt (GW) annual world PV production in 2030; about half of all buildings (new and retrofits) covered by thin film BIPV, and nearly 100% of new buildings covered by thin film BIPV
- **Scientific understanding.** Advanced understanding of the physical and chemical properties, including microstructure and interfaces of thin films, their impact on the optical/electrical cell behavior, and knowledge base to control their properties; consistent techniques and measurements over the components' lifetime, and consistent and reliable power ratings under different conditions; available standards for replacing modules in systems
- **Production Capacity.** Automated factories account for the capacity of thin films, and political leadership provides bold support that maintains U.S. industrial leadership
- **Sustainable**. Recycling and refurbishing is seamless in 2030
- **Consistent and reliable power rating schemes are available**

3.2.2 Drivers

Advancements in thin film PV technology development and application are driven primarily by technological, economic, environmental, and societal factors (see Figure 3.2). These include improving the attractiveness of the technology to investors, utilities, builders, and homeowners. The key technical driver required to meet the anticipated growth of PV markets is improved manufacturing leading to enhanced cell performance and system reliability. Basic understanding of the science and technology will be needed across all types of thin film technologies, many of which are applicable to PV in general.

Levelized cost of electricity (LCOE) was identified as one of the key drivers for the growth of demand in the PV sector. LCOE, in turn, is driven by the ability of banks to offer attractive financing terms, which is critically dependent on the long-term (~30 year) reliability of the thin film systems. Furthermore, manufacturing throughput and yield, as well as materials costs, contribute to LCOE.

Figure 3.2 Drivers for Advancements in Thin Film PV

- **Scientific knowledge**. Scientific community keeping pace with industry and demand growth through development of knowledge base that sustains continuous improvements
- **Reliability**. Lifetime of building and utility scale systems
- **Acceptance.** Acceptance of PV materials internationally; aesthetics and simplicity of systems; installation standards for homeowners and builders; homeowner acceptance through control of energy usage to exploit the diurnal nature of solar
- **Demand.** User demand by end use (utility scale, building-integrated, household), especially in countries with rapid electricity growth such as China and India
- **Financing.** Financing terms, particularly for distributed systems
- **Demand.** User demand by end use (building-integrated, utility scale, household), especially in countries with rapid electricity growth such as China and India
- **Economic impact.** Job creation and the corresponding link to supportive policies, especially in the United States (as has been done in the European Union)
- **Industry structure.** Vertical integration of PV manufacturing and energy production companies; increased corporate resources and production capacity improvements
- **Environmental factors.** Increased emphasis on greenhouse gas accounting and life cycle analysis for decision-making in energy supply policy

3.3 Broad Barriers

3.3.1 Technical Barriers

Broad technical challenges to the advances in thin film technologies are primarily focused in four areas: improvement of materials through fundamental understanding, module efficiency, manufacturing processes and cost, and system reliability. The most important points are summarized below; a complete prioritized list is provided in Appendix B.

Fundamental understanding of materials

Foundational to each of the key technical challenges in thin film PV is the existence of a knowledge base for each of the layer materials and their interfaces. Important hurdles exist in the fundamental scientific understanding of materials, such as dopant control, point and extended defects, and microstructure, as well as the stability and transport across interfaces. These issues cut across all technologies, and better understanding of the associated materials science should guide process and device improvements and inspire novel uses of materials, leading to transformational changes in thin film technologies.

Module efficiency

The highest priority technical goal is to produce a stable, manufacturable thin film module that achieves 20% efficiency. Current efficiencies are as follows: a-Si (4-7%); CdTe (8-11%); CIGS (7-11%); tandem silicon hydride (Si:H) (6-10%); and triple junction Si:H (8%). Key barriers to achieving this goal include the inability to characterize and understand the role of point defects and charge transport across interfaces, and the lack of measurement tools for rapid screening of new PV materials.

Uni-Solar thin film laminate (Source: NREL)

Manufacturing processes

Unlike Si processing, the manufacturing process for think film PV are not supported by a mature related industry. A priority technical barrier in manufacturing is the uncertainty in how to rapidly scale-up to low-cost, high-throughput, high-yield, and high-performance manufacturing. This includes managing non-uniformities and determining the materials and process parameters that predict materials and device performance. Improved manufacturing processes will be enabled by the development of advanced, low-cost measurement tools that could ultimately promote high volume U.S. manufacturing facilities and expand markets. Online tools that probe the key process and device parameters are needed and should be high speed, non-destructive, and noninvasive.

Reliability

Increasing reliability to enable 30-year and longer warranties for thin film products represents a priority challenge. Technical barriers stem from the lack of scientific understanding of degradation mechanisms. Reliability testing requires large, uniform sample sets, and accelerated lifetime protocols according to technology, and validated protocols are not yet available.

Addressing this technical barrier and increasing reliability is a key component to improving acceptance by the capital markets thus driving down financing costs.

3.3.2 Non-technical Barriers

It was noted that the availability of raw materials is an important non-technical barrier, as described below. A prioritized list of barriers is provided in Appendix B.

Low-cost, abundant raw materials

Supply constraints from thin materials such as indium and tellurium represent a potentially limiting barrier to scale-up to the terawatt (TW) level. The Earth's mineral resources accessible today are not sufficient to meet the TW market demand envisioned for some of the thin film technology options. Unfortunately, the more abundant materials such as thin film Si tend to be lower in efficiency. Although the barrier is the non-technical issue of limited materials supplies, overcoming this barrier may be accomplished by a technical approach. For example, the development of thinner absorber layers may increase the worldwide scale-up potential of the technology.

3.4 Measurement Challenges

A number of areas were identified where measurement challenges could create impediments to technological progress in the advancement of thin film photovoltaics. These are summarized below and listed in full in Appendix B.

Thin film silicon cluster tool (Source: NREL)

3-Dimensional, high resolution characterizations

A high priority challenge involves visualizing defects, impurities, chemical intermixing or segregation, density variations and voids, nanodomains, and grain boundaries to better understand carrier transport and recombination. There is insufficient 3-dimensional (3-D)-correlated mapping of structure, chemical composition, potential, optical electric-field (E-field), and recombination in devices, at the multi-scale down to less than 50 nanometer (nm) resolution.

Characterization of interfaces

Understanding interfaces through advanced measurement was identified as among the top measurement challenges. This includes nanoscale atomic and charge transport across interfaces, for example between cadmium sulfide (CdS) and CIGS, and between CdS and transparent conducting oxides (TCO), among others. A critical need is developing better characterization tools for understanding the electrical transport within nanodomains, through grain boundaries, and across interfaces particularly in chalcopyrites and kesterites. Measuring the excess free energy at the interfaces also represents an important barrier that, if overcome, would help generate an understanding of fundamental material issues.

Real-time, inline measurement

The lack of measurements made in real time and inline was considered one of the most important barriers inhibiting advancements in thin film PV manufacturing. Inline measurements of interest include physical characteristics of thickness, composition, and impurity concentrations, and the mapping of electronic properties (e.g., lifetime, cell performance parameters), and, ultimately, microscopic property mapping of selected areas with sub-micron resolution in real time. Real time indicates that acquisition and processing times of minutes or less to enable closed-loop feedback systems.

The solution to the lack of real-time and inline measurements will likely involve developing equipment that is readily available "off-the-shelf" with the ability to map stoichiometry better than 0.1% and impurities better than 10 parts per million (ppm) in high spatial resolution. Overcoming this challenge would dramatically improve process control, yield, performance, and potentially reliability. It would also reduce variability in manufacturing output, improve quality control, and help to narrow the performance distribution of modules.

Standards, certifications, and protocols

One of the important challenges is creating universally accepted standards, protocols, and certifications on the time frame that meets the needs of industry. This is pertinent to a wide range of issues, including standards for output and reliability, measurement protocols including performance under accelerated life testing, and product certifications by independent parties. The technical challenges also include improvement in understanding of the accelerated life testing (ALT) mechanisms. Better correlations between process models and field measurements would improve the value of the standards, protocols, and certifications.

3.5 Grand Challenges for Technology and Measurement

Based on the technology challenges and the measurement issues identified previously, a more comprehensive set of Technology and Measurement Grand Challenges was developed. In some cases these combine various aspects of several challenges, and also provide additional detail on performance targets, applications, impacts, and pathways for development. The Grand Challenges are listed below and illustrated in detail in Figures 3.3 through 3.7.

Figure 3.3 3-D tomography of chemical composition, structure, and optical electric-field

Figure 3.4 Materials screening to enable stable, manufacture-able low-cost thin film modules

Figure 3.5 Low cost, high throughput/yield/performance thin film PV manufacturing

Figure 3.6 Real-time and in-line measurements enabling closed loop control for thin films

Figure 3.7 Accelerated lifetime and reliability testing for thin films

Figure 3.3: 3-D tomography of chemical composition, structure, and optical electric-field

Performance Targets/Goals:

- Improve multi-scale information from µm down to <50 nm
- Connect the information to the understanding and modeling of electronic properties and device performance parameters

Technology and Measurement Science Challenges/Barriers

» Incorporating bias and illumination, critical to recombination and potential measurements

» Exposing surfaces by ablating or cratering alters the surface, creates defects, and changes potential distribution, distorting the 3-D map

» Preparing nanoscale samples representative of the feature to be studied

» Developing synchrotron or pion (a meson having a mass approximately 270 times that of an electron)facilities for the pathway outlined below; large magnets and specialized detection methods will be required

Applications

» CIGS, CdTe, nano-crystallines, a-Si and other low-cost, normally poly or amorphous, PV materials

Impacts

» Acknowledges these low cost materials will likely always have important structural, stoichiometric and other defects; enables visualization of grains boundaries, defects, chemical segregation, impurities, density variations, and voids to fully understand carrier transport and recombination

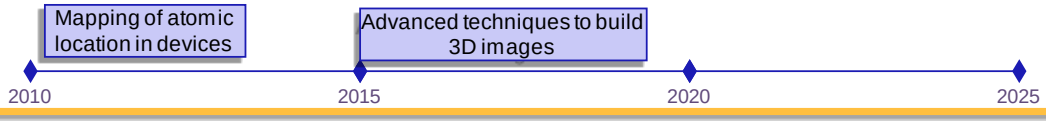
» Enables design and test of optical light-trapping structures for measurements of intensity and polarization.

» Confirms transparent conductive oxide degradation is dominated by penetration of atmospherics through fissures

Pathway

1. Use spatial and time-correlated detection of atoms blown off a field-emission tip to map atomic locations in a nano-portion of a device
2. Embed fluorescent, radioactive or magnetic markers in devices to build 3-D images of key PV information (such as recombination, optically-produced E-field, E-field) under bias and illumination
3. Use ablation under scanning electron microscope and/or transmission electron microscope to enable probing by movable atomic force microscope tips or optical fibers that probe the exposed surface
4. Use tomography with probes that interact with device materials over short-length scales although its penetration length is long enough to permit detection (e.g., soft X-rays, muons)

Milestones



Stakeholders and Roles	
National laboratories	Measurements and characterization
Thin film PV companies	Test and validation
Thin film PV groups	Test and validation

Figure 3.4: Materials screening to enable stable, manufacture-able low-cost thin film modules

Performance Targets/Goals:

- Achieve 25% cell level for existing thin film materials with ~1.5 eV band gap
- Achieve 20% efficiency in high band gap (e.g., 1.7–1.8 eV) thin film
- Demonstrate 25% cell level efficiency with earth-abundant elements (with a multijunction configuration)

Technology and Measurement Science Challenges/Barriers

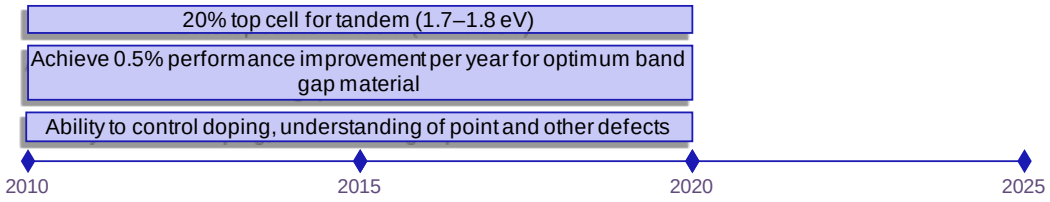
» Visualizing and understanding point defects
» Understanding charge transport at interfaces
» Developing measurement tools for rapid screening of new PV materials (e.g., absorbers, buffer layers, TCO)

Applications	Impacts
» High-efficiency, low-cost thin film technology	» Leads to stable high efficiency, a major driver for cost » Increases efficiency which will open up markets for thin film PV (e.g., rooftop) » Relaxes limits on materials availability

Pathway

1. Develop an absorber material (single junction) that operates efficiently at the optimum band gap (1.5 eV)
2. Understand chemistry and physics of defects (point and extended) in thin film materials to allow defect modeling and control and processing
3. Develop viable multi-junction thin film module
4. Improve band gap engineering to optimize thin film PV device

Milestones



Stakeholders and Roles	
Universities	Foundational R&D, manpower/education
National laboratories	Foundational R&D; standardization of measurement; technology development
Industry	Technology development; manufacturing; deployment

Figure 3.5: Low-cost, high throughput/yield/performance thin film PV manufacturing

Performance Targets/Goals:

- Meet or exceed grid parity without incentives
- Reduce cost/Wp at high kWh/kW
- Increase market share of thin film PV to 50%
- Encourage thin film PV emergence as the leader in aesthetic BIPV

Technology and Measurement Science Challenges/Barriers

» Improving high efficiency, high yield/inline metrology and closed loop control, with a high degree of automation

» Determining process and material parameters to predict materials and device performance

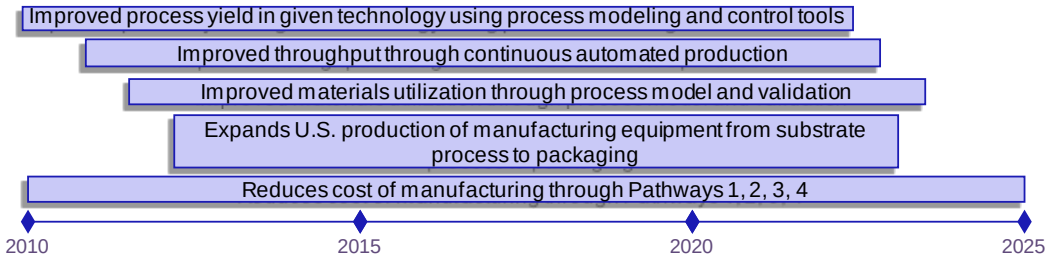
» Technology that is high speed, non-destructive, and non-invasive

Applications	Impacts
» Large volume manufacturing » Understanding of basic materials, devices, and manufacturing processes	» Recaptures U.S. competitiveness in PV manufacturing » provides job creation and retention in areas of traditional strength, and additional jobs along value chain » Allows for high volume U.S. manufacturing facilities » Expand markets for U.S. products

Pathway

1. Improve process modeling and validation from substrate to packaged product
2. Develop in-situ, real-time process monitoring and control predictive of device performance
3. Establish continuous automated manufacturing process from substrate to product, improving the rate of deposition
4. Create vertical integration of entire supply chain

Milestones



Stakeholders and Roles	
Government	Programs to accelerate pathways to improved performance in manufacturing and measurement based fundamentals
University	Core research and educational programs for training in relevant R&D
Industry	Close collaboration with university and national laboratories, as well as supply chain companies

Figure 3.6: Real-time and in-line measurements enabling closed loop control for thin films

Performance Targets/Goals:

- Establish ability to map stoichiometry better than 0.1% and impurities better than 10 ppm with depth resolution
- Use equipment available off-the-shelf with production cycle times
- Use holistic models that can bridge from observables to performance
- Ensure availability of appropriate imaging equipment

Technology and Measurement Science Challenges/Barriers

» Lack of non-destructive high chemical resolution (comp/impurities) lack of imaging capabilities

» Manufacturing implementation (simple, low-cost) of laboratory techniques (e.g., EL, PL, Hall, others)

» Algorithms that relate observables to process or performance parameters

» Equipment for sub-micron high speed property mapping

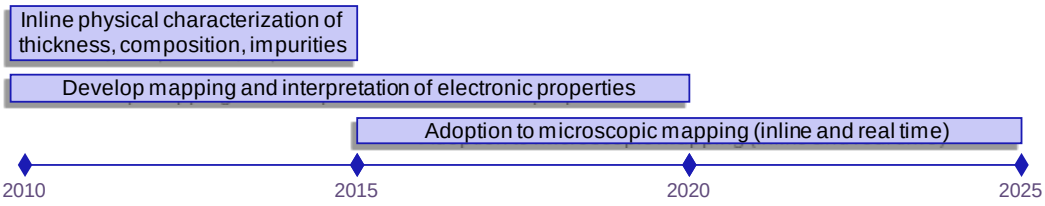
» Inadequate imaging capabilities

Applications	Impacts
» Highly effective closed loop control systems for thin films	» Improves process control, yield, and performance » Establishes early identification of process excursion that could affect performance or reliability » Develops rapid gap closure between champion modules and norm, and between laboratory and manufacturing » Reduces variability in manufacturing output

Pathway

1. Establish inline physical characterization of thickness, compositions, and impurities
2. Establish inline mapping of electronic properties (lifetime and performance parameters)
3. Interpret results in terms of process and device performance-related parameters
4. Adopt microscopic property mapping to selected areas with sub-micron resolution (inline and real time)

Milestones



Stakeholders and Roles	
Module manufacturer	Adopts new technologies
Instrument manufacturer	Realizes solar in an economic fashion
Process equipment manufacturers	Adopts new technologies
Laboratory (national and academia)	Develops maturing and measurement technologies

Figure 3.7: Accelerated lifetime and reliability testing for thin films

Performance Targets/Goals:

- Establish universally accepted standard accelerated life testing (ALT) protocol
- Determine accepted acceleration factors to allow projected product lifetime using standard tests
- Design-for-reliability: apply tests to achieve 30+ years lifetime (materials/device structure)

Technology and Measurement Science Challenges/Barriers

» Complex, multi-measurement study required for root cause analysis
» Limited understanding of true degradation mechanisms
» Improving degradation mechanism assessment from module testing
» Improving reliability with large, consistent sample sets

Applications

» Accelerated life testing
» Design for reliability

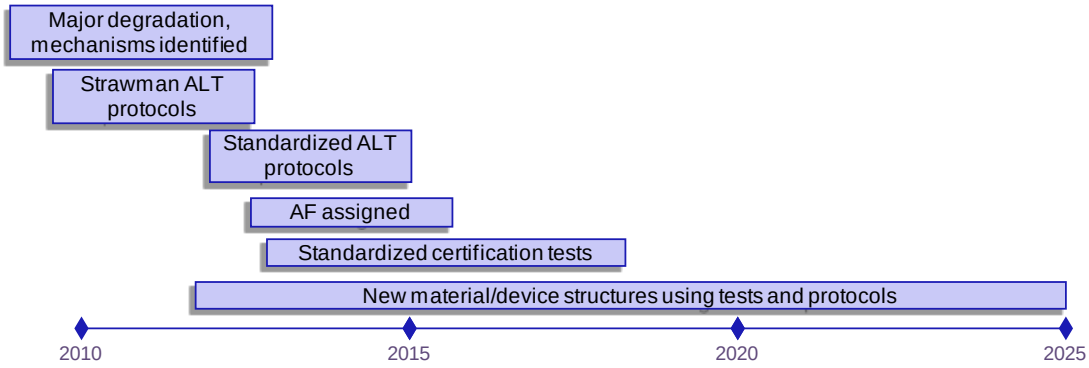
Impacts

» Powerful vehicle to reduce risk, leads to increased acceptance and reduced working cost of capital (reduced LCOE)
» Improves understanding of true expected product lifetime

Pathway

1. Identify major (performance-specific) degradation mechanisms due to outdoor exposure, by technology
2. Develop well-correlated ALT protocols by technology
3. Design for reliability
4. Create standards for certification tests

Milestones



Stakeholders and Roles

Laboratory	Degradation mechanisms
Standards organizations	Certification and test

4.0 III-V Multijunction PV

4.1 Overview of the Topic

Discussions focused on III-V multijunction PV cells, which consist of layered single crystalline semiconductors from groups III and V of the periodic table. These layered semiconductors, due to their varied band gap energies, absorb different portions of the solar spectrum, and in conjunction with the high crystalline quality, result in the highest cell efficiencies of any type of PV cells. Current laboratory cell efficiencies, under concentration, are greater than 40%. These PV cells are typically produced using metal organic chemical vapor deposition (MOCVD) fabrication methods.

While III-V PV cell efficiency is the highest compared to other PV technology types, III-V cells are also among the most expensive to produce. The III-V PV cells were first implemented in space applications where the advantage of high cell efficiency (and resulting small size and light weight) outweighed the higher costs; however, III-V cells are finding increasing terrestrial uses in CPV systems. These systems utilize optics to concentrate sunlight on the III-V cell—often to intensities greater than 500 suns.

Topics included advances to reduce consumer costs (i.e., by increasing performance or reducing materials and manufacturing costs) and strengthen investor and consumer confidence through reliability improvements. Technical and measurement challenges for III-V multijunction technologies were focused on concentrating photovoltaic (CPV) modules and module components. The importance of balance of system components such as inverters, hydraulic trackers, mounting hardware, and general grid connectivity issues was emphasized. However, these components were considered outside the scope of the discussions to allow for sufficient focus on relevant issues at the module level.

Amonix 7700 mega module (Source: Amonix)

4.2 Future Drivers and Characteristics

4.2.1 Vision

Over the next 20 years, III-V PV technology is envisioned to achieve low cost, high performance, and long lifetime products to enable its use as a major domestic and global energy source. Modeling tools to predict performance as a function of conditions (e.g., geography, spectral content, temperature, and age), conduct lifetime testing simulations, and enable a better understanding of device degradation mechanisms will be major contributors to achieving this vision. Figure 4.1 summarizes the future vision for this area.

Additional areas identified as being integral components of the vision include: manufacturing advances that allow for inline testing capabilities and the ability to measure and control defects in real-time; improved data sources and documentation (e.g., spectral history and input cost parameters); well developed III-V PV standards; consumer buy-in; and policy measures that put a price on carbon.

Figure 4.1 Highlights of the Vision for the Future of III-V Multijunction PV

- Dramatically reduced optics costs and 10% increased efficiency (i.e., from 80% to 90%) of optics
- 50–100 year lifetimes for CPV fields (especially utility scale)

4.2.2 Drivers

The three overarching drivers expected to spur the rapid advancement of III-V PV technologies are cost, performance/efficiency, and reliability. Consumer buy-in and acceptance of this advanced solar technology is currently limited due to high costs and uncertainties surrounding technology reliability and lifetime. Affordable financing for CPV projects is also limited for these same reasons. Breakthroughs in III-V PV will be geared towards achieving reliability of all components at the system level and reducing the cost of energy through efficiency/performance improvements and reductions in materials and manufacturing costs. Such improvements will be the overarching drivers for advances in III-V PV technology over the next 20 years.

4.3 Broad Barriers

4.3.1 Technical Barriers

A number of technical barriers were identified that currently limit development and adoption of critical technologies, tools and systems integral to commercial scale deployment of III-V PV technologies. The most important of these are summarized below; a complete prioritized list is found in Appendix B.

Materials, substrates, and growth

The lack of low-cost substrates that enable growth of >40%-efficient cells or a process that allows practical reuse of substrates was identified as the major materials barrier to achieving cost targets. Another opportunity for cost reduction would be low-cost, low-hazard precursors for MOCVD growth. Performance and reliability may be improved through techniques that allow optimized cell designs to be implemented with near-perfect quality, real-time in-situ growth monitoring that improves cell yield and performance, low-cost, stable optical materials that are immune to ultraviolet (UV) and other aging, and the implementation of designs that combine low cost with high performance and reliability.

Cells and interconnects

New fabrication techniques, materials, and novel cell structures provide multiple pathways to achieving higher efficiency cells. With further R&D, III-V multijunction cells are expected to continue to increase in efficiency as researchers increase the number of junctions and/or optimize cells for use under high concentration. To achieve efficiencies greater than 50%, 4-junction cells need to be developed. The lack of standardized cell specifications, resulting in too many options for size, shape and concentration level of PV cells, is a barrier to III-V PV technology deployment. An agreed-upon set of optimal standards for cells would be helpful to achieve the scalability and cost targets for III-V PV technology.

Manufacturing and production

A major barrier associated with manufacturing is the lack of affordable inline characterization and production equipment specific to III-V multijunction technology (including cells, packaging, and modules). Testing equipment that can detect, and potentially correct, defects in real time would greatly mitigate reliability concerns, increase throughput and reduce costs. Industry, however, has faced challenges in designing equipment that has these capabilities and is also affordable, automated, and reliable.

Optics

Various technical challenges are associated with optical efficiency improvements in CPV optics. Cell coatings are needed that incorporate higher anti-reflective protection, offer greater protection from elements, and improve the transmission of a matched spectrum to the cell. In general, the community needs to move beyond the use of "classical" optical designs (e.g., Fresnel lenses, mirrors, and prisms) to the use of more novel designs. These novel designs can be used to minimize the effects of non-uniform illumination and localized heating and/or achieve targets such as +/- 1° acceptance angle at 1,000 suns.

Degradation pathways

As discussed above, reliability is an extremely important driver of III-V PV technology innovation and must be addressed to gain consumer and investor confidence. The lack of understanding of degradation mechanisms and failure modes of CPV components was identified as a major factor limiting advances in the reliability of III-V PV systems. Such understanding is necessary to accelerate these mechanisms for lifetime testing and standards development and for making quantitative service life predictions based on geographic location. Determining degradation pathways and failure modes is also necessary for the long-term and accurate simulation of UV exposure effects on CPV components (including adhesives and lenses), which are also needed for proving system reliability.

Modeling

Advanced modeling capabilities and an accurate CPV information database of solar resources are essential for determining optimum cell and module designs for high performance and reliability. The community lacks a consensus about the best way to model power output corrections to standard conditions or energy output projections for specific sites. Poor existing data of direct normal irradiation (DNI) also hinders the ability to accurately model incoming solar radiation. Spectral data is further limited by the need to have increased data collection frequency (e.g., one-second intervals) and a broader wavelength range (e.g., 300-2000 nm) of collected data.

4.3.2 Non-technical Barriers

The non-technical barriers identified focused primarily on production cost and environmental impact uncertainties and public policy issues.

Cost and environmental uncertainties

The lack of knowledge of the impacts of III-V PV cell technology on the environment and public health further complicates efforts to evaluate the relative value of technical advances, as understanding environmental impacts is necessary for determining the lifecycle costs of the technology, including costs associated with waste disposal and recycling of cells after its useful life. In addition, concerns about the relative toxicity of new materials needs to be addressed in order to gain greater public acceptance.

Incentives for adoption

The mass deployment of III-V multijunction technology and PV in general, depends on its competitiveness with other power generation technologies. In addition to technology advances towards increasing efficiency and lowering production costs, policy incentives and funding could help to drive widespread III-V PV technology adoption. In particular, an LCOE that reflects a price on carbon emissions will increase the cost of traditionally cheap fossil fuel sources relative to PV and help redirect public dollars towards low carbon renewable energy.

Lack of consumer understanding and buy-in is a significant barrier to investment in PV technology. This is not only due to the existing uncertainties about the technology's performance, reliability, and lifetime, but also due to consumer misperceptions of the technology based on incomplete or inaccurate information. Consumer education on III-V PV technology could be accomplished through a variety of avenues such as a reach-out award program conducted by each U.S. Department of Energy (DOE) department (e.g., similar to the NASA program) and could be a component of III-V PV technology request for proposals (RFP).

4.4 Measurement Challenges

In this workshop session, participants were asked to suggest opportunities for developing measurement capabilities to accelerate the development of III-V PV technology over the next 20 years. Themes that emerged from the discussion are discussed below, while the complete raw output from this session is presented in Appendix B.

Advanced in-situ/inline measurements

The development of quick and accurate inline/in-situ cell and module testing techniques (and their associated metrics) is vital to developing the cost-effective manufacturing methods that could lower the production costs of III-V PV. The types of measurements falling under this category are diverse, but all fall under the general theme of making measurements rapidly and automatically during the manufacturing process. Several high priority cell measurement needs were identified, including the development of a high-speed, industrial inline flash tester for CPV receiver assembly at concentration; rapid J ratio measurements; the evaluation of electroluminescence (EL) as a cell screening method (for example a vision system for the automatic detection and classification of various types of defects in cells using advanced EL measurements); vision technology for inspection; and measurements to indicate cell performance under high concentration using 1X concentration measurements.

During the material growth process, several other in-situ measurements were identified including next-generation, real-time diagnostic tools to measure stress, doping, and optical properties of novel alloy materials at high temperatures; contactless measurement methods; and nanoscale chemical and atomic characterization measurements such as the determination of the concentration of specific dopants at growth temperature.

Cell characterization and testing methods

There is significant potential to advance the state of cell characterization and testing methods. Such advancement will contribute to a better understanding of cell and system properties, enable efficiency improvements (due to the ability to assess incremental changes), and contribute to the development of standards. Participant-identified characterization methods included quantum efficiency (QE) measurements of each subcell at operating light levels (greater than 500 suns); combination optical and electrical measurements on embedded nanostructures such as quantum dots or wells; chemical compositional characterization of nanostructures; and techniques for the direct measurement of the space-charge region temperature of the cell at operating conditions (> 500 suns). Some of these cell characterization methods may be performed in-situ during the manufacturing process and thus also help reduce manufacturing costs, increase throughput and improve reliability.

Develop predictive tools for system components

Poor investor and consumer confidence in III-V PV system reliability was cited as a major factor keeping costs high and ultimately limiting technology adoption. To address this concern, the development of predictive tools for all system components (i.e., cell, packaging, and lens) is needed in order to better understand specific degradation and failure mechanisms and achieve more predictable and reliable systems. These tools will likely need to include multi-variable accelerated stressing equipment (i.e., temperature cycling, humidity, concentrated sunlight, and temperature). Novel measurement techniques of bond quality and degradation chemistry will also need to be explored, as will new methods for precisely measuring high-intensity UV radiation according to wavelength, which is necessary for accurate accelerated UV reliability testing.

Improved solar spectrum simulation capabilities

Current state-of-the-art solar simulators were identified as a major hindrance to the advancement of III-V solar PV. This topic is especially important for III-V PV due to the great reliance of III-V PV on the properties of the incoming solar radiation with respect to the concentrating optics, cell configuration, and other system properties. Light sources are needed to simulate the sun on a large area with adequate angular, spectral, and uniform characteristics in order to measure and track optical efficiency at the module level. These sun simulators would need to include agreed-upon calibration standards and measurement procedures in order to be broadly utilized by manufacturers for CPV module quality control in indoor test settings.

Improved solar resource data collection capabilities

A major deficiency was recognized in solar resource data availability and accuracy, which requires innovative measurement techniques. Measurement tools that can produce accurate solar resource data are important as they support the development of standards and modeling efforts.

4.5 Grand Challenges for Technology and Measurement

Based on the technology challenges and the measurement issues identified previously, a more comprehensive set of Technology and Measurement Grand Challenges was developed. In some cases these combine various aspects of several challenges, and also provide additional detail on performance targets, applications, impacts, and pathways for development. The Grand Challenges are listed below and illustrated in detail in Figures 4.2 through 4.7.

Figure 4.2 Materials growth monitoring and control for higher efficiency multijunction cells

Figure 4.3 Affordable, automated, in-line production and characterization equipment for III-V multijunction devices and modules

Figure 4.4 Accurate, traceable, and detailed measurement techniques for characterizing CPV modules

Figure 4.5 Measurements to support standards for spectral response

Figure 4.6 Accurate solar resource assessment and solar spectrum simulation

Figure 4.7 Accelerated lifetime and reliability testing for concentrating PV

Figure 4.2: Materials growth monitoring and control for higher efficiency multi-junction cells

Performance Targets/Goals:

- Model epitaxial growth process and inter-diffusion and its impact on performance
- Monitor growth of materials (improved processes and in-situ monitoring)
- Provide input data for modelers

Technology and Measurement Science Challenges/Barriers

» Lack of understanding of modeling requirements
» Advanced epitaxial growth processes with real-time control tools for first-pass success
» limits on incremental improvements due to measurement uncertainty

Applications

» Cell and concentrator industries

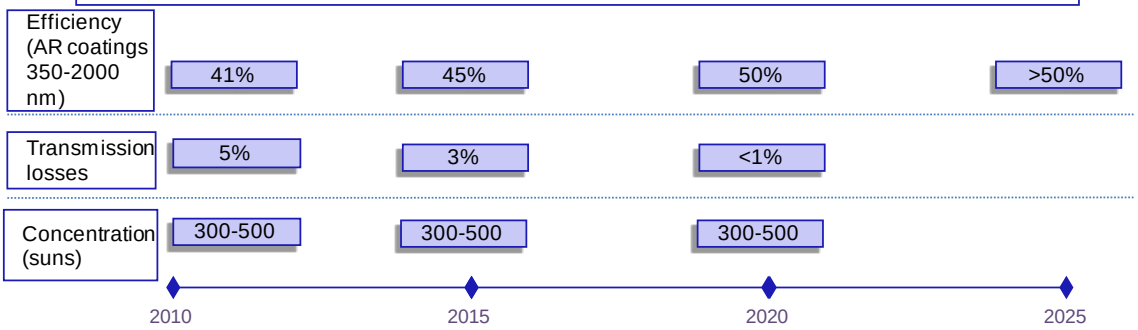
Impacts

» Lowers cost of energy
» Improves processing and enables higher efficiency cells

Pathway

1. Develop better modeling tools for simulating growth, nanostructures, device performance, and predictive understanding of interface electronic properties
2. Improve broadband anti-reflective (AR) coatings
3. Develop rational design of metamorphic and nanostructured devices
4. Minimize optical and electrical losses at interfaces
5. Develop characterization and measurement tools to assess incremental changes

Milestones



Stakeholders and Roles	
Universities	Long term research
National laboratories	Mid-term modeling research
Industry	Model test and validation
Government agencies	R&D programs

Figure 4.3: Affordable, automated, in-line production and characterization equipment for III-V multi-junction devices and modules

Performance Targets/Goals:

- Achieve test costs of < 5% of cell costs
- Develop10-minute characterization time per 4-inch wafer to achieve 35 MW/year per inline characterization tool

Technology and Measurement Science Challenges/Barriers

» Developing a high concentration simulator with quickly adjustable spectrum
» Lack of basic understanding of cell defects

Applications

» High-volume cell manufacturing and testing

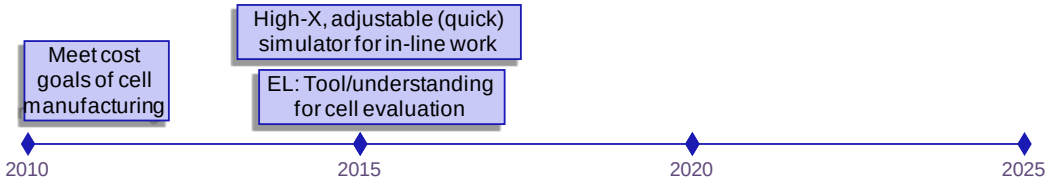
Impacts

» Improves quality and reliability
» Reduces cost of cells
» Enables high throughput production

Pathway

1. Evaluate EL as a screening technology for cells; include vision technology for inspection
2. Consider alternative cell evaluation methods (1x I-V tests, generic spectrum high-X, tests, other cell evaluation methods)
3. Develop high concentration solar simulation compatible with inline testing
4. Develop methods to measure current density ratio of cells

Milestones



Stakeholders and Roles	
National laboratories	Spectral requirements for high-X solar concentration

Figure 4.4: Accurate, traceable, detailed measurement techniques for characterizing CPV modules

Performance Targets/Goals:

- Measure CPV module efficiency to an accuracy to 1%
- Achieve module testing costs <1% of total module cost in production

Technology and Measurement Science Challenges/Barriers

» Measuring cell temperatures under concentration
» Measuring outdoor solar spectrum accurately
» Measuring simulator spectrum and angular dispersion from sun and simulator
» Measuring cell temperature and illumination non-uniformity

Applications

» Module rating
» Reliability testing
» Production line testing
» Diagnostics for engineering development

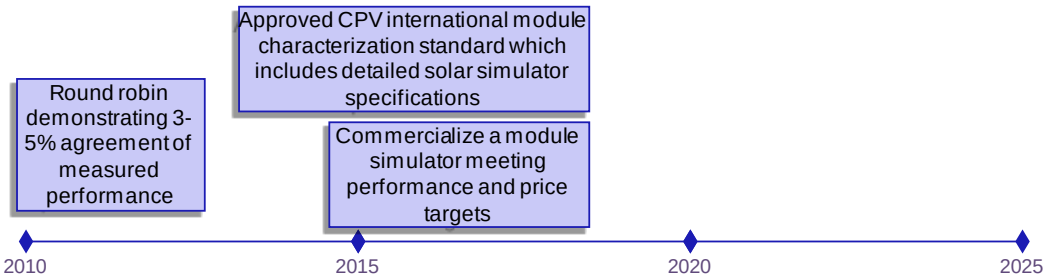
Impacts

» Improves long-term predictions of performance and reliability
» Improves investor confidence in CPV technology

Pathway

1. Develop simulator hardware for production line characterization with adequate angular, spectral, and uniformity characteristics
2. Identify measurement procedures for accurate, traceable, repeatable module characterization both indoors and outdoors
3. Create procedures for differentiating losses associated with optics, cell temperature, non-uniform illumination, spectral variations, and component alignment

Milestones



Stakeholders and Roles	
CPV module manufacturers	Test and validation
Standards organizations	Primary standards
Universities and national laboratories	Measurement data, support for standards and test
Measurement equipment manufacturers	Measurement equipment
Certified test laboratories	Support for standards and test

Figure 4.5: Measurements to support standards for spectral response

Performance Targets/Goals:

- Achieve spectral response measurements in <10 minutes
- Evaluate spectral response uncertainties <1% in the 250–2500 nm range at one sun or higher concentration; take measurements as a function of temperature

Technology and Measurement Science Challenges/Barriers

» Thermal issues (controlling cell temperature under concentration)
» Establishing the uniformity of the beam
» Achieving λ intervals ≤5 nm
» Making measurements faster
» Coupling between junctions for multi-junction QE measurements

Applications

» Manufacturers (cell)
» Solar cell research
» Qualifications for calibration laboratories

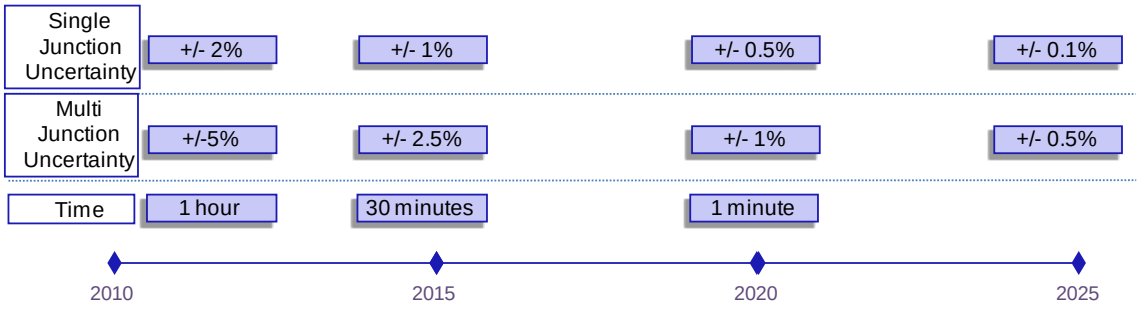
Impacts

» Lowers cost related to more accurate assessment
» Accelerates solar cell development and performance assessment

Pathway

1. Develop one detector for spectral measurements from 250–2500 nm
2. Develop the primary calibration procedure to <1% uncertainty for concentrator cells
3. Extend Physikalisch-Technische Bundesanstalt procedures to 500 suns and higher temperatures
4. Develop single junction and extend to multijunctions

Milestones



Stakeholders and Roles	
Standards organizations	Primary standards and calibration
National laboratories	Provide context and scope of service, participant in development; support for standards
Industry	Supply cells

Figure 4.6: Accurate solar resource assessment and solar spectrum simulation

Performance Targets/Goals:

- Improve high performance direct and global spectrum instrumentation and data
  - –Angle 0.5° to 180°—250 nm to 2500 nm—one second intervals and averaging
  - –Multiyear, multiple locations—satellite and weather data
  - –Humidity, aerosol optical depth, wind speed, temperature
- Develop low-cost instrument for monitoring/cross-calibration of existing and potential sites

Technology and Measurement Science Challenges/Barriers

» Instrumentation with sufficient accuracy and performance
» Coordination of data from diverse sources (satellite, local weather)
» Lack of sufficient detectors
» Limited solar characteristics and module performance computer models

Applications

» Optimized cell and module design
» Active input for power grid management
» Improved data for business model predictions (long term)

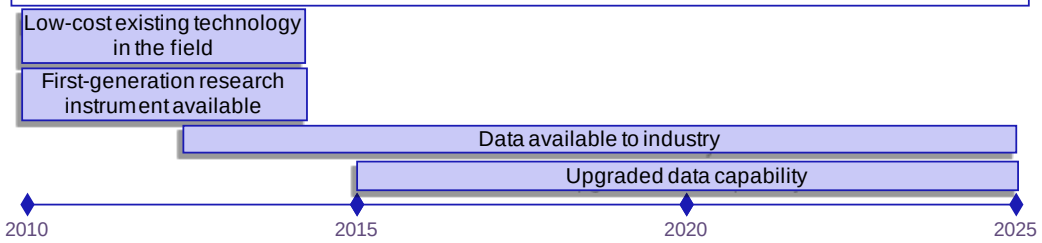
Impacts

» Creates suite of instruments to collect data necessary for rating modules
» Optimizes products for geographic location
» Increase PV market share based on higher marketability and predictability
» Lowers financial risk based on predictable performance

Pathway

1. Improve sensor and instrument development/selection; include additional data sources such as weather. Create two versions: 1) high performance and cost; and 2) low cost and performance
2. Ensure calibration procedures are assessed and improved
3. Conduct physical hardware maintenance (long-term, calibration, exchange, and upgrades)
4. Improve database management, expansion, distribution, validation (on-going,30 years)

Milestones



Stakeholders and Roles	
Cell and module manufacturers	Design trade-offs
Utility companies/grid regulators	Integration of data
Banks/investors	Finance and risk management
Laboratories/universities/independent companies	Acquire, analyze and distribute data Guide instrument development
Industry	Produce instruments to acquire data
Government/academia	Maintain database

Figure 4.7: Accelerated lifetime and reliability testing for concentrating PV

Performance Targets/Goals:

- Develop equipment and test protocol to predict CPV module lifetime
- Create a model for all degradation/failure mechanisms

Technology and Measurement Science Challenges/Barriers

» Establishing/maintaining a field failure data collection program over many (10–30 years) years (collaboration of CPV companies)

» Lack of a more precise/accurate performance measurement (to be able to detect small changes after tests or on-sun hours)

» Lack of an automated vision-system analysis of defects

Applications

» Necessary inputs to financial engineers for LCOE calculations

» Understanding of degradation to improve design and longer lifetime of modules

Impacts

» Increases finance ability of CPV systems

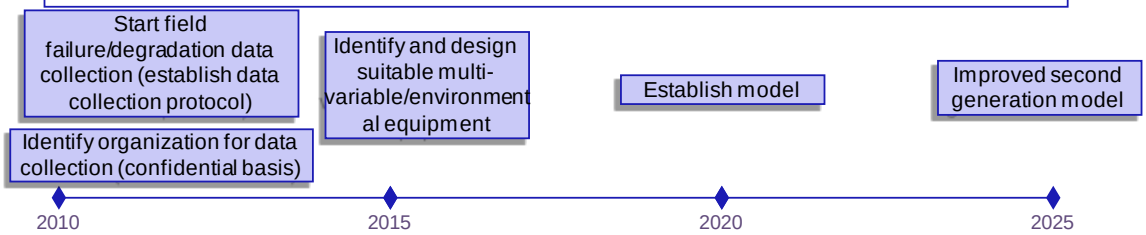
» Provides feedback on design: improvements driven by understanding of degradation mechanisms

» Enables reliability standard

Pathway

1. Catalog field failures, degradation at different location (after deployment)—Pareto chart
2. Develop multi-variable accelerated stressing equipment (temperature cycling, humidity, concentrated sunlight, temperature soak, and current)
3. Understand degradation and failure mechanisms and establish model
4. Disseminate lifetime prediction tools through reliability standards and testing laboratory's infrastructure

Milestones



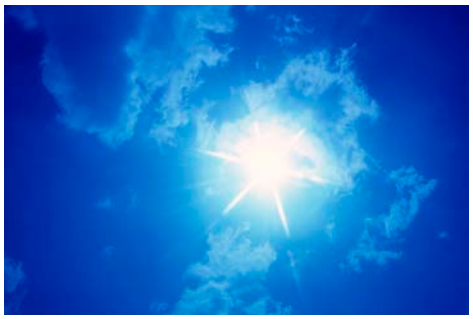
Stakeholders and Roles	
Data hub	Data collection and dissemination
Test laboratories (private and government)	Failure and performance data
CPV companies	Test and validation
Cell suppliers	Test and validation
Component suppliers	Test and validation
Financial institutions and engineers	Data requirements
Customers	End use performance testing

5.0 Excitonic and Quantum-Structured PV

5.1 Overview of the Topic

For the purposes of this report, excitonic and quantum structured (EQS) cells are solar cells with absorber layers that rely on quantum physics (i.e., confined excitons). The focus is primarily on organic-based and quantum dot/wire technologies. While dye-sensitized solar cells (DSSCs) are also being developed, this area is not represented explicitly in this report since the EQS PV group was mostly composed of OPV experts (DSSC experts were invited but were unable to attend). While the issues may be related to OPV in this report, many are also relevant for DSSC technology. EQS solar cells in the form of DSSCs can exhibit laboratory PCEs of up to 8.1%.

EQS cell technologies are classified as third generation, with some commercial scale efforts beginning to emerge after significant R&D efforts. Organic PV technology has achieved recent success in research-scale and small-area devices, leading to limited production capacity. Module efficiencies of organic PV technologies are approximately 5%, with research scale efficiency as high as 8.1%. Quantum-structured PV remains primarily in the research phase.



(Source: Microsoft Online)

While significant development work is currently ongoing, numerous challenges exist, both fundamental and technological, to achieving broader commercialization. These include a fundamental understanding of many of the complex chemical, physical, and electrical processes, as well as materials and device stability. The lack of existing manufacturing base/infrastructure and data on long-term reliability adds to the challenges.

5.2 Future Drivers and Characteristics

5.2.1 Vision

Over the next 20 years, it is anticipated that technology advances could significantly enhance capabilities for innovative PV cells based on organic, dye-sensitized organics, or nanoscale structures, as shown in Figure 5.1. The value, stability, and acceptance of excitonic and quantum-structured PV versus other types of PV will be well-established and publicized. This will allow

much broader application of PV, and could eventually enable all flat surfaces to be multifunctional covered by inexpensive PV technologies.

Organic PV (OPV) will be low cost but more efficient in the future, and much longer-lived cells will be available. With technology advances, it will be possible to routinely measure and control defect structure, and as a result, material stability during processing time will be understood and controlled. The science of manufacturing OPV at large scale will be well established, enabling cost-effective production at high throughputs.

Figure 5.1: Vision for the Future for Excitonic and Quantum-structured Cells

- Manufacturing throughput and volume for organic cells:
  - $(\text{meters})^2$ per minute
  - 1 TW or more at low cost
- Operating parameters for organic multi-junction cells:
  - 12-15% efficient modules
  - >20 year life time
  - <$0.50-$0.60/WP
  - >10 gigawatts at peak sunlight production

5.2.2 Drivers

Technology advances for excitonic and quantum-structured cells will be driven by the same factors that impact most solar technologies. These include requirements for greater efficiency, reduced cost, and longer lifetime. However, these PV concepts are in the R&D and early production stages, and considerable advances will need to be made via basic and applied research to attain greater efficiencies and lifetimes.

5.2.3 Radical Advances for the Future

A number of transformative technologies and processes were identified as important to the advancement of excitonic and quantum-structured cells, illustrated in Table 5.1. While some are cross-cutting in nature or apply to general performance characteristics, others are more relevant to the early-stage development of OPV and advances that still need to be made.

Achieving greater performance and application will require modular, flexible systems that are produced via lower cost processing technologies and materials. Simple systems such as those that could be painted, are semi-transparent, or applicable on colored surfaces would require radical advances but could lead to greater acceptance and use. Coupling of PV with energy storage is also critical for the future of PV and solar in general. All PV applications will ultimately be limited unless viable storage routes are found.

Table 5.1 Radical Technological Advances for Excitonic and Quantum-structured Cells

Target Performance and Applications	
	• Light, mobile, flexible, roll-it-out power • OPVs with robust interfaces • High efficiency and stable devices with low cost processing (e.g., no indium-tin oxide, simple sheet lamination, and printing) • Ability for customers to easily build their own solar cell by painting surfaces • Coupling of PV with energy storage • Semi-transparent OPV that is accepted by customers • Ubiquitous technology for colored multifunctional surfaces • Multi-layer harvesting of photon energies to provide high efficiency (e.g., low cost/high speed coating technology)
Design	
	• Materials by design for PV • Advanced cost models to help guide design (e.g., substrate and electrodes) • Molecular to device level integration—to enable design and creation of products with a specified efficiency • Clearly understood mechanisms to guide design rules for materials and morphology • High efficiency through understanding and control of excitons
Manufacturing	
	• Simpler synthesis to reduce costs • Molecular assembly processes to enable production of "smart" materials • Control of nanoscale alignment/structure/interfaces on solution cast or otherwise inexpensive scale fabrication techniques • Theory-guided synthesis and processes for complicated system of structures • Precise control of structure (size, shape, doping of inorganic nano/micro structure over large area using lost cost processes) • Single-layer encapsulant • Improved contact configurations or removing the evaporative metal contact • Equipment developed to print OPV on any surface (e.g., printing)

Advances such as materials by design concepts, molecular to device integration, or much improved cost models could greatly enhance upfront materials and device design. In manufacturing, theory-guided synthesis and processes for complicated structures, including models and combinational mechanics, could enable radical improvements. This includes analysis using methods from quantum mechanics through continuum mechanics (e.g., finite elements, chaos theory, and multi-coupled models) and would enable development of module designs via such analysis routes. Analysis would need to be tied to experiment and include all levels for modeling (e.g., structure, electronic, and optical).

5.3 Broad Barriers

5.3.1 Technical Barriers

A number of technical barriers were identified that currently limit progress in excitonics and quantum-structured cells. The most important of these are summarized below; a complete prioritized list is found in Appendix B.

Fundamentals

The highest priority barrier identified is the limited understanding of organic-organic and organic-inorganic interfaces and their optimization for efficiency and lifetime, particularly in these interface-dominated devices. Poor understanding of the structural and electronic fundamentals of OPV in general is a critical barrier. These fundamentals include, for example, interface/surface recombination occurring in nano, quantum-structured, and organic materials; origin and physics of low V_{OC}; and mechanisms of charge separation.

Materials

Material stability during processing is a critical barrier, considering that massive improvements in stability and life are needed to increase acceptance of these advanced PV concepts. The use of specialized equipment to enhance stability can increase costs and alternative routes are needed. Another key barrier is inadequate materials development, specifically for multijunction devices. A related priority barrier is the need to understand how to overcome impurities, purify materials cheaply, or use impurities to some advantage. This stems from a basic lack of understanding of impurities.

Models and theory

The currently limited capability of using computational mechanics and computational chemistry, from fundamental physics and chemistry to multi-coupled systems, is an important barrier, as these theories could be used to aid in more effective design and development of devices. The ability to model multi-level, multi-coupled systems based on first principles is also a challenge. Modeling of degradation mechanisms could be used to decouple differences in substrate-electrode interfaces, semiconductors, and the packaging barrier, enabling more effective design and understanding of stability and performance.

Production

A major challenge is to understand the basic science of manufacturing at scale for gigawatts/terawatts of production, especially at high yield and low cost. This will be necessary for achieving the desired larger scale production using OPV as well as other technologies in the future. Defining architectures for modules that retain the efficiency of small area devices is another key challenge for production and scale up of new concepts. Other important issues for production include the high cost of raw materials including the substrate, barrier films, and active materials. Today, multi-layer thin film coating technologies are not mature and more development will be needed before it is suitable for high-volume production.

5.3.2 Non-technical Barriers

Most of the identified non-technical barriers concerned environmental impacts and cost.

Environmental impacts

The current understanding of the impact of OPV or other quantum-structured cells on ecosystems and human health is currently limited. Issues include the limited knowledge of the toxicity of nanomaterials, which leads to a perception by some that all nanoscale materials may be toxic. Limited understanding of the environmental impacts propagates these views. There is also the opposing view, i.e., that these new materials could potentially be safer than the more stable silicon used in most of today's PV cells. Disposal of the cell after its useful life and the potential for recycling also constitute a challenge. The lack of reliable life cycle analysis (LCA) and reliable data exacerbates the ability to respond to environmental concerns.

Cost issues

The lack of a clear cost analysis and pathway to achieving a desired cost per Watt remains a barrier. More data will be needed to understand variable costs for both materials and processing, now and in the future. Raw material costs are not negligible and currently constitute a significant challenge. Batch processing of materials is expensive today, as the chemical industry is reluctant to make large batches. Production of materials at large volumes would mitigate this challenge. The reliability of these new systems also impacts return on investment (ROI) as development is still a risky proposition.

5.4 Measurement Challenges

A number of areas were identified where measurement challenges could create impediments to technology progress in excitonics and quantum-structured cells. These are summarized below and listed in full in Appendix B.

Characterization of electronic properties of materials

The correlation of electrical and photoelectrical properties with composition, morphology, processing conditions, and other key parameters from nanometer-length scales up to macroscopic scales was identified at the workshop as a priority. Broad imaging tools for characterization that provide an understanding and even a visualization of charge generation, separation, and transport at sub-10 nm resolution in modules represent key instrument development challenges. Direct characterization of V_{OC} loss which can lead to an understanding of its origin is critically important. Determination of the minimum difference in lowest unoccupied molecular orbital (LUMO) between the donor and the acceptor needed for charge separation as well as analysis of interface/surface recombination and charge separation mechanisms are important measurement challenges.

Interfacial characterization

Broad characterization of interfaces from many aspects was identified as one of the top measurement challenges for this area. One of the most critical needs is developing in-situ characterization of the work function at the molecule/metal and molecule/molecule interface, including dipole and polarization analysis. Another major challenge is characterization of the 3-D nanoscale distribution of domains including size, shape, and connectivity, with the capability for nanoscale interface imaging. Also important is the need to characterize molecular arrangement at internal and external interfaces, including orientation and conformation. The ability to quantitatively assess surface/interface structure in two-dimension (2-D) or 3-D, and relate to recombination parameters is another key area where current capabilities are lacking.

Device manufacture

Defect characterization was identified as the most pressing challenge today for this area. The ability to measure and control defect structures is significantly lacking and impacts many aspects of device performance. An important supporting capability is 3-D nanoscale materials and device characterization (in one tool and coupled with 2-D characterization). The desired tool would also be suitable for inline metrology in support of scale-up. This tool would provide both molecular and physical properties, and could also be used for devices to help pinpoint defects. The ability to probe within the devices and identify future failure mechanisms during manufacturing is important and currently lacking.

Another challenge related to devices is characterization of packaging barrier properties, including water vapor transmission rate (WTVR), oxygen transmission rate (OTR) and correlation of these parameters with device lifetime. Oxygen and water can impact stability of the device material and consequently degrade performance and lifetime. For electronic properties, a probe for charge carrier dynamics inside a working device was identified as an important tool, as was an online tool for characterizing the 3-D field distribution, density of states (DOS), and charge carrier distribution in a working device.

Accelerated life testing

A high priority is to achieve a greatly improved understanding of ALT degradation mechanisms and their relevance to performance. This would require much better benchmarking of field

versus laboratory measurements, and assessing real impacts after the device is deployed. Accelerated reliability testing is another priority and closely related. The reliability of the test itself may currently be insufficient. Reliability of modules directly impacts ROI and consequently capital investment.

5.5 Grand Challenges for Technology and Measurement

Based on the technology challenges and the measurement issues identified previously, a more comprehensive set of Technology and Measurement Grand Challenges was developed. In some cases these combine various aspects of several challenges, and also provide additional detail on performance targets, applications, impacts, and pathways for development. The Grand Challenges are listed below and illustrated in detail in Figures 5.2 through 5.6.

Figure 5.2 Three-dimensional nanoscale characteristics

Figure 5.3 3-D tomography of electronic structures at variable length scales

Figure 5.4 Application of fundamental knowledge to increase efficiency in excitonic and quantum-structured cells

Figure 5.5 Inline tests for cell/packaging defects and failure mechanisms for excitonics and quantum-structured cells

Figure 5.6 Accelerated lifetime and reliability testing for quantum-scale technology

Figure 5.2: Three-dimensional nanoscale characteristics

Performance Targets/Goals:
Improve spatial resolution <1nm; thickness up to 1 µm; composition in solutions ~2%; <100 meV energy resolutions; predictive capacity for device performance within 25%

Technology and Measurement Science Challenges/Barriers

» Improving contrast between original phases, small length scale
» Fragility of molecules
» Developing a consolidation framework
» Developing multiple techniques

Applications

» Improvement of excitonic PV cells, including organic/organic and hybrids
» Extension to other complex functional media (batteries, capacitors)

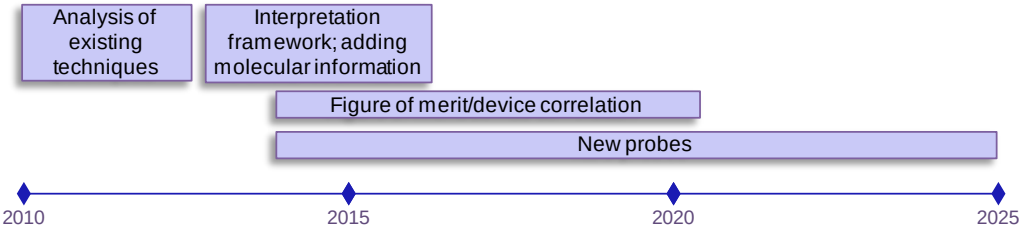
Impacts

» Advances and accelerates technology development through knowledge-based design of materials and processes

Pathway

1. Analyze potential and shortcomings of existing techniques, including nanoscale microscopies, (e.g., transmission electron microscopy, scanning transmission X-ray microscopy, atom probe, and spectroscopy and scattering techniques); evaluate appropriateness for organic systems
2. Interpret framework for structure, addition of sensitivity to molecular orientation, conformation, and defects; add in-situ capabilities
3. Develop figure of merit from structure and establish relationship to devices
4. Develop new probes that would add sensitivity to electronic properties, (e.g., density of states, spin, and work function (Ø))

Milestones



Stakeholders and Roles

Industry	Excitonic PV companies: optimized materials combinations for measurement development
Research laboratories, universities	Optimize materials combinations for measurement development
Government laboratories	Develop tests; facilitate link between fundamental science and industrial application; take data from measurements and develop analysis tools

Figure 5.3: 3-D tomography of electronic structures at variable length scales

Performance Targets/Goals:
Nanometer to macro-scale understanding of device physics, leading to models for rational design of materials and devices

Technology and Measurement Science Challenges/Barriers

» Improving sensitivity for photoelectrons, high resolution scanning probes for conductivity, and field distribution measurements; four–five different parameters must be assessed simultaneously

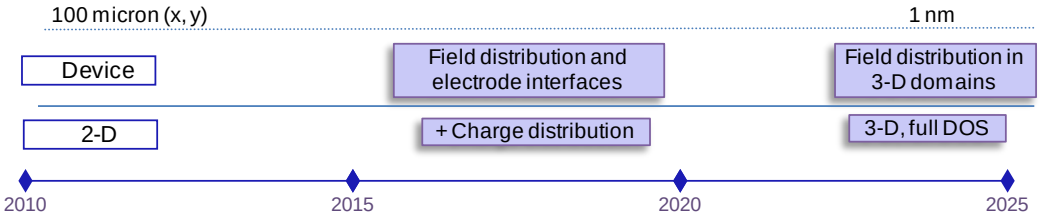
» Improving the ability to conduct photoemission spectroscopy of liquids (immersed films)

Applications	Impacts
» Semiconductor devices with nanometer scale dimensions	» Improves understanding of devices and enables better design of materials, interface, and device structure

Pathway

1. Use small spot ultraviolet photoelectron spectroscopy/inverse photoelectron spectroscopy (UPS/IPES) (angle resolved, temperature controlled), plus X-ray photoelectron spectroscopy/ valence band (XPS/VB) spectroscopes (time resolved, high resolution)
2. Use UPS/IPES for liquid phase
3. Develop a means to measure field distribution in a working device [Fourier transform infrared (FT-IR)]—chemically sensitive electro-absorption
4. Use scanning probe microscopies to map radical cation and anion statistics (x, y, and z parameters); scanned probe deep level transient spectroscopy; free carrier density from scanned microwave conductivity; capacitance

Milestones



Stakeholders and Roles	
Industry	Collaboration during pre-competitive stage
Research laboratories, universities	Test and validation of tools developed by laboratories
Government laboratories	Establish measurements needs; develop measurement tools

Figure 5.4: Application of fundamental knowledge to increase efficiency in excitonic and quantum-structured cells

Performance Targets/Goals:
Predictive models leading to device design and supporting all aspects, from measurement to models to theory to prototype

Technology and Measurement Science Challenges/Barriers

» Limited tools for measuring meso-scale properties that are relevant to device function, particularly at the nanoscale
» Lack of dedicated computational power
» Lack of multiple-scale models

Applications

» All excitonic PV approaches—organic PV, inorganic—organic PV, dye sensitized-solar cells

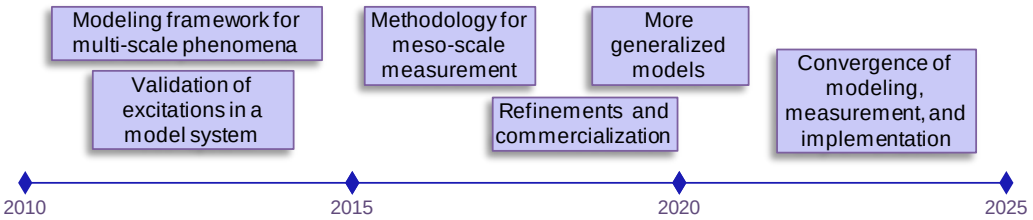
Impacts

» Creates first principles lifetime prediction
» Improves power conversion efficiency
» Improves reliability, stability, and ROI

Pathway

1. Increase fundamental understanding of excitations in disordered and nanostructured media (excitons, charge carriers, and phonons)
2. Conduct quantum chemical modeling and design of molecular and nanostructured materials
3. Develop measurements that probe properties that emerge at each length scale (e.g., band structure, density of states, chemical potential)
4. Conduct multi-scale modeling that addresses the emergence of complexity from nanoscale to microscale to macroscale and to system performance (accounting for the stochastic and heterogeneous nature of these systems)

Milestones



Stakeholders and Roles

Industry	Product development and commercialization
Research laboratories, universities	Research and development
Government laboratories	Research and development

Figure 5.5: Inline tests for cell/packaging defects and failure mechanisms for excitonics and quantum-structured cells

Performance Targets/Goals:
Identify device and packaging failure mechanisms and correlate to organic PV lifetime

Technology and Measurement Science Challenges/Barriers

» Inability to sufficiently measure at the speed and resolution needed for high volume manufacturing
» Lack of capability to measure device properties inline during manufacturing

Applications

» Improvement of printed electronics such as OLEDs, OPV, organic thin film transistors (OTFT), solid state lighting, displays, radio frequency identifications, and others

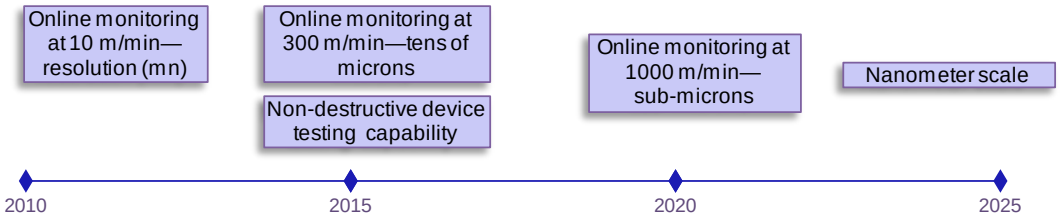
Impacts

» Maximizes cost and yield to enable maturation of the technology, making it available and affordable to society

Pathway

1. Develop inline equipment to image and characterize defects such as pinholes, dewets, and scratches, tailored towards OPV manufacturing
2. Improve research geared towards detecting defects in the nanometer to microns scale at fast (300m/min) coating speeds
3. Develop research for non-destructive, on-roll device/module tests
4. Establish research to identify and model failure mechanisms and to direct the design of new inspection tools

Milestones



Stakeholders and Roles	
Industry	Metrology equipment developers and OEMs develop tools to enable device manufacture; industry consortia to organize roadmaps and standards efforts
Research laboratories, universities	Basic device research
Government laboratories	Basic device research
Federal, state, and local governments	Partnerships

Figure 5.6: Accelerated lifetime and reliability testing for quantum-scale technology

Performance Targets/Goals:
Identify key probes (e.g., photo-luminescence) and determine the level of uncertainty to be considered in the measurement over time (e.g. ,+/-5%, +/-1%, etc.); assure strong correlation between accelerated indoor and outdoor tests; establish acceleration factors with 10% or better

Technology and Measurement Science Challenges/Barriers

» Lack of robust instrumentation for key properties that need to be monitored in situ during ALT; a key for root-cause analysis impact of water and ambient conditions
» Lack of instrumentation to provide reliable chamber diagnostics (light level, uniformity, composition of atmosphere, temperature uniformity, out gassing)
» Limited testing chambers and tests that are relevant to modules (e.g., delamination)

Applications

» Improvement of product R&D
» Increasing module reliability
» Improving system financing

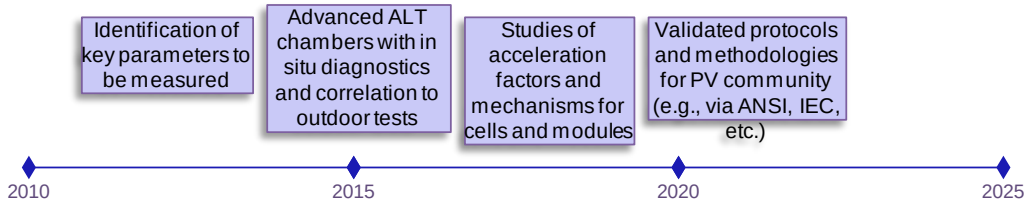
Impacts

» Establishes confidence in PV in energy market
» Provides new guidelines to make more stable products
» Improves engineering solutions for products and industries
» Reduces cost via more certain reliability

Pathway

1. Perform outdoor tests to assess parameter space, key properties, and degradation factors/mechanisms relevant to advanced PV cells/modules
2. Build environmental test chambers to mimic outdoor testing under accelerated time scales; ensure it mimics outdoor conditions and in-situ monitoring
3. Study degradation mechanisms in new indoor accelerated life testing chambers, confirm it relates to outdoor mechanisms, and establish the acceleration factors
4. Develop standard protocols and methods for the broader (next-generation) PV community

Milestones



Stakeholders and Roles

Industry	Equipment—instrument makers; validation—PV companies; mechanisms; protocols—IEC, ASTM, PV companies
Research laboratories, universities	Mechanisms
Government laboratories	Mechanisms; protocols

6.0 Cross-cutting Issues

Several challenges that were considered applicable to multiple PV technology areas were identified. The five most significant cross-cutting themes include:

- 3-D analysis of material properties from nanoscale to macroscale and their correlation with device performance
- Inline manufacturing probes for higher yield and reduced cost.
- Testing methods for characterizing modules, including associated power output
- Solar resources, (e.g., data collection and complete libraries)
- Reliability studies and accelerated life-time testing

In addition to the quantum-structured PV applications covered under the excitonics area, the wider applications of nanoscience and technology represent a cross-cutting issue under exploration in all PV areas. These developments are occurring in PV areas for which the nanoscale phenomena are secondary to device physics (e.g., light capture via plasmons and nanotube electrical contacts).

As a result, advances in nanotechnology have many applications in the PV industry that could increase performance, among other benefits. Two primary cross-cutting approaches are (1) semiconductor quantum structures, such as quantum dots and wells, which may be embedded/incorporated into traditional semiconductor materials (in particular, thin Si and III-V semiconductors) to tailor and enhance their performance; and (2) nano-engineered structures, such as carbon nanotubes and nanowires which may also be integrated into contacts and other non-semiconductor components of traditional semiconductor devices. The use of nano-engineered structures allows for tuning and expanding the spectral response, enhancing the local fields, exciting multiple excitons from a single photon, or up-converting infrared photons, thus providing possible routes individually or in combination toward substantial (revolutionary) gains in PCE.

Appendix A. Acronyms & Abbreviations

ANSI	American National Standards Institute
ALT	accelerated life testing
AOD	aerosol optical depth
a-Si	amorphous silicon
AR	anti-reflective
ASTM	American Society for Testing and Materials
ATP	Advanced Technology Program, now the NIST Technology Innovation Program
BIPV	building integrated photovoltaics
BOS	balance of system
CdS	cadmium sulfide
CdTe	cadmium telluride
CIGS	copper indium gallium diselenide
CPV	concentrating photovoltaic(s)
CSR	concentrated solar radiation
CuxZnSn	compound containing copper, zinc and tin
CW	continuous wave
DC	direct current
DNI	direct normal irradiation
DLTS	deep level transient spectroscopy
DOE	U.S. Department of Energy
DOS	density of states
E-field	electric field
EL	electroluminescence
EQS	excitonic and quantum structured

eV	electron volt
FT-IR	Fourier transform infrared spectroscopy
g/Wp	grams per Watt peak
GW	gigawatts
HOMO	highest occupied molecular orbital
IEC	International Electrotechnical Commission
LCOE	levelized cost of electricity
LED	light-emitting diode
LIV	light I-V (light current-voltage)
LUMO	lowest unoccupied molecular orbital
m	meters
M^2	square meters
MBE	molecular beam epitaxy
mc-Si	multicrystalline silicon
meV	milli-electron volt
MOCVD	metal organic chemical vapor deposition, also known as organometallic vapor phase epitaxy (OMVPE)
NDE	non-destructive evaluation
nm	nanometer
NIST	National Institute of Standards and Technology
OLED	organic light-emitting diodes
OPV	organic photovoltaic
OTFT	organic thin film transistors
OTR	oxygen transmission rate
PCE	power conversion efficiency
PL	photoluminescence
ppm	parts per million
PMAX	peak power, also Pmax
PV	photovoltaics
QE	quantum efficiency
R&D	research and development
RFID	radio-frequency identification
RFP	request for proposal
ROI	return on investment

Se	selenium
Si	silicon
Si:H	silicon hydride
SRV	surface recombination velocity
STXM	scanning transmission X-ray microscope
TCO	transparent conducting oxides
2-D	two-dimensional
3-D	three-dimensional
TEM	transmission electron microscope
TW	terawatt
UPS	ultraviolet photoelectron spectroscopy
UV	ultraviolet
Voc	voltage at open circuit
Wp	Watt peak
WP	Watt power
WVTR	water vapor transmission rate
XPS	X-ray photoelectron spectroscopy

Appendix B. TECHNOLOGY AND MEASUREMENT CHALLENGES

The following tables contain the full set of technology and measurement challenges identified by participants during the workshop. Individual tables are provided for each of the four breakout groups.

Each table separates the challenges into prioritized categories of high, medium, or low priority. These priorities were determined by a voting process where participants were each given 5 votes.

The prioritized technology and measurement challenges form the basis for the priority topics identified in this report.

Table B.1: Technology Challenges for Wafer-based Crystalline Silicon PV	
High	• Overcome power conversion efficiency limitation (10 votes)) – Heterostructures are a route to doubling efficiency • Handle and process thin Si (9 votes) • Increase Si utilization (g/Wp) (8 votes) – Utilization currently is at 6 or 8 g/Wp with a desired goal of 2 g/Wp • Develop a plan for an improved interconnection scheme (8 votes) – Soldering interconnects creates stresses – High cost and limited availability of silver is a problem, not enough to get to 10 TW • Reduce cost of capital for systems (7 votes) – system rating, and reliability serve to increase confidence in energy production • Consider new product forms -- unchanged in more than 35 years (6 votes) • Understand wafer breakage (5 votes) – Breakage worsens as wafer gets thinner • Measure for cracks/stress (5 votes)
Medium	• Understand the large uncertainty in measured output of PV module (5%) and PV plant (7%) (4 votes) • Develop modules with long lifetime (~50 years) and with minimal degradation while gaining the confidence of customers on these developments (4 votes) • Understand polymer degradation (4 votes) – Understanding of fundamental degradation issues is needed – Support for materials that do not perform is required – Aging properties of modules should be captured • Understand screen printing limitations (3 votes) – Limitations include entrenched technology, high volumes of messy consumables; high contact with PV cell • Develop design for high volume production (3 votes) – Moving from MW to GW facility designs is required • Improve energy payback time, which needs to be ≤1.5 years to have net energy with >50% annual growth rate (3 votes) • Increase throughput of wafer/cell inspection (3 votes) • Encourage investment by U.S. vendors in metrology tools (non-destructive evaluation) by increasing production (2 votes) – U.S. value chain distribution for metrology vendors in PV is insufficient
Low	• Clarify process → structures → properties → device performance relationships for key device performance forms (bulk and surface) (1 vote) • Understand system weight (kg/m^2) for rooftop applications (1 vote) • Identify unnecessary glass/frame designs (1 vote) • Improve client experience (1 vote) – Improvements are possible in both installation and management • Enhance production of Si feedstock (1 vote) – Targets include increasing capacity, lowering cost, and increasing recycling – Utilization also should be maximized (thinner wafers with less breakage) • Develop thinner wafers with low surface recombination in cells (1 vote) – Handling thin wafers is critical – Reduction in surface recombination is also critical **The following challenges did not receive votes, and some are closely related to the above**

Table B.1: Technology Challenges for Wafer-based Crystalline Silicon PV

challenges

- Develop continuous inline process for growing ribbon
  - Activity requires R&D funding
  - Thermodynamic stabilization of edges in ribbon growth is a challenge
- Move away from bulk crystalline growth
  - Liquid-phase methods are of interest
- Develop smart module
  - Development should include maximum heat power tracker, self cleaning coatings, automatic turnoff during fires, and embedded electronics
- Develop non-contact processing
- Improve module interconnections for 50 µm wafers
- Improve diagnostics and understanding of ingot production
- Develop different way of making substrates
- Increase crystallization velocities
  - Oxygen use is a possibility
- Develop new metal process—eliminate silver screen print paste
- Predict module performance and reliability in various environments—currently unknown
- Enhance transparency in installed base performance
- Track lifetime measurements in thin Si (50 µm)
- Automate handling of wafers/cells
- Improve ability to quantify and measure reliability
  - Improvement requires model to check kW
- Create accurate measures of quality indicators for silicon wafers
- Integrate with other technologies to deliver value to client
  - Technologies of interest include batteries for storage, and light-emitting diodes (LEDs) for illumination
- Reduce other module costs
- Obtain increased capacity of low-iron glass production
- Eliminate transition metal impurities in Si feedstock, especially iron
  - Consistent chemical composition is needed in feedstocks
- Remove cracks in cells and in modules
  - Some cracks in wafers are not a problem if module design is correct
- Address belief that thin film is next generation can hinder crystalline Si acceptance
- Reduce distinction in the future between module and BOS boundary
- Develop new module architecture (and packaging) for Si (flexible, no glass)
- Modify wafer size (to minimize tedious stringing)
- Develop new module packaging
  - Desirable characteristics include improved durability, lighter weight, and reduced thickness
- Bifurcate the industry: (1) 40µm wafers with different handling; (2) 80-100 µm wafers
  - Substrate support is needed during processing
  - Wafers must withstand temperature cycling
- Develop less expensive, simpler device structures with higher efficiencies
- Transition from silver usage
- Develop novel processing technologies
- Eliminate screen printing

Table B.2: Measurement Issues for Wafer-based Crystalline Silicon PV

Table B.2: Measurement Issues for Wafer-based Crystalline Silicon PV	
Wafer Crack and Uniformity Detection	
High	• Develop non-contact wafer crack detection (11 votes) – Measurement characteristic of interest includes high speed (< 1 second/wafer) – Total thickness variation would also be a desirable outcome of measurement
Medium	• Develop rapid measures of wafer quality and uniformity, lifetime, stress, and breakage (4 votes) • Develop scanning work function measurements to measure cracks (2 votes)
Low	• Measure stresses in thin wafers with infrared polariscopy (1 vote) • Evaluate crack size distribution and resulting wafer strength – Ability to measure spatial location and size of cracks is lacking – Ability to distinguish between crack sources, e.g., edge, contacts is lacking – Ability to rapidly scan whole wafer for cracks is lacking
Stress Induced Crack Propagation	
Low	• Measure process induced stresses/defects (1 vote) – Mechanical: Includes mechanical and thermo-mechanical stresses • Ensure contactless handling (1 vote) – Move wafer without imparting stresses to reduce breakage • Develop inline measurements – Quality characteristics are obtained in line at wafer location – Wafers expected to break in processing, and handling should be identified in advance – Propagation of cracks is unrelated to stress
Materials/Process Characterization	
High	• Measure quality factors for Si wafers that lead to high V_{oc} and fill factor in mc-Si (9 votes) – Quality factors include SRV and dielectric charge state/strength – Instability of hydrogen passivation with time is of importance • Develop in situ monitoring during processing (6 votes) – Properties of interest include sheet thickness, junction depth from sheet resistance measurements, anti-reflective coating thickness and properties, voltage of junction before contacts are formed
Low	• Monitor process parameters in situ (2 votes) – Of specific interest is a direct measurement of ingot quality • Map solid-liquid interface during or after growth of ingot (2 votes) • Develop method for measuring interconnect resistances (2 votes) • Characterize multi-layer films on textured surfaces (2 vote) – Characteristics of interest include thickness, refractive index, and extinction coefficient • Measure activity of impurities at operating temperature rather than composition at room temperature (1 vote) • Develop oxide thickness measurement for small (10 micron x 10 micron) areas (1 vote) • Create carrier mobility patterns within textured feature • Develop X-ray tomography/laminography for ingots – Approaches include infrared and ultrasound for detection of cracks and near surface defects • Promote adhesion of encapsulants – Key properties include density of chemical bonds and stress inside encapsulants
Other Measurement Approaches and Attributes	

Table B.2: Measurement Issues for Wafer-based Crystalline Silicon PV	
Low	• Develop new measurement capabilities: (1 vote) – Method must be established, equipment commercialized, uniform acceptance achieved (key for NIST) • Study non-contact solar cell measurements methods (1 vote) • Evaluate photoluminescence as a measurement tool (1 vote) • Evaluate destructive vs. non-destructive probes • Review inline vs. in-lab testing • Identify requirements (e.g., Ph.D. to analyze, technician, and machine) • Requires low cap expenditure and quick inline high throughput • Connect to output, i.e., discriminating pricing vs. tighter/shift yield center – There must be reasons to measure; measurement results must be connected to output • Develop analytical/informatics tools – Data must be usable • Develop the ability to directly measure key performance driver at individual process step
Energy Rating	
High	• Create a systems energy rating (9 votes) • Develop an energy-rating methodology for modules (7 votes)
Medium	• Develop "LCOE meter" for systems (3 votes) – Desired attributes include measurement of peak power and component faults and optimization of output. – ≤2% error is desired
Low	• Institute mandatory performance and reliability standards in the United States for PV modules and inverters (1 vote) • Forecast if and how global warming will affect PV energy output
Reliability	
High	• Evaluate polymer degradation (12 votes) – Both measurements and understanding are required. – Adhesion of encapsulants is key — density of chemical bonds, stress inside encapsulant • Evaluate quality of solder bonds (7 votes) – Evaluation must be nondestructive and doable on string or module size
Medium	• Apply accelerated stress tests (for modules) in correlation with field performance (3 votes)
Low	• Develop module-string field test dark I-V for installation checkout (large arrays) (2 votes) • Obtain full module external quantum efficiency/internal quantum efficiency tool to identify the origin of the small but significant yearly degradation, e.g., discoloration (2 votes) • Identify an inexpensive source of UV in order to characterize degradation in PV module components (1 vote) – Desirable attributes include high intensity and selectable wavelength ranges • Stabilize boron-oxygen dimer regenerated state at long time scales (1 vote) • Determine the factors and levels of stress related to geographical location (e.g., Florida vs. California vs. Colorado) to model degradation • Identify low cost methods to determine degradation in individual fielded modules

Table B.3: Technology Challenges for Amorphous Silicon and Polycrystalline Thin Film PV	
Materials	
High	• Answer open fundamental questions about the material (doping, defects, microstructure) (8 votes) • Understand interfaces (7 votes) – An understanding of the basic science of interfaces in the complex chalcogenides is critical – Transport, trapping, and recombination measurements on the nanoscale at buried interfaces is needed – Grain boundaries must be understood – Electronic structures of inorganic/inorganic interfaces must be understood
Medium	• Understand and use new materials (5 votes) – Tremendous material opportunities in: absorbers (abundant elements, novel oxides/nitrides) and TCOs (textured, titanium dioxide) must be realized – New materials: high gap chalcopyrite compatibles, higher band gap oxides, novel nanocrystalline materials are needed – Efficient wide-gap cells for multijunctions are needed. • Develop low-cost, abundant raw materials (5 votes) – Devices and packages should have low raw materials cost per unit area at TW scale – High efficiency and low LCOE under potential supply constraints must be established for thin devices – New search for limited materials such as indium and tellurium is important • Overcome the Staebler-Wronski effect in a-Si: H (2 votes)
Low	• Find a CdS alterative: cadmium-free and more thermally stable couple with CIGS-related materials for tandem • Find low temperature (below 200-300°C) deposition processes for both CdTe and CIGS materials
Manufacturing Processes	
High	• Produce a stable, 20% thin film module (10 votes) – Process control diagnostic tools and quality control tools are important – Defect chemistry vs. processing must be balanced – Thin film deposition uniformity is required over large areas – Multi-method, multi-scale location-correlated spatial mapping diagnostics are critically important – Key device metric knowledge (measurements) should include: recombination rates, electric field, photoconductivity • Develop manufacturing processes for low-cost, high throughput/yield/performance (8 votes) – Manufacturing-friendly processing must be elevated to the level of performance achieved in laboratories – Small area efficiency must be achieved in large area manufacturing with uniformity – Large-area planar devices vs. small, discrete cells should be balanced in view of (i) the challenge to characterize “large” products for DOE, (ii) the management of non-uniformities (efficiency/reliability), and (iii) the development of processes focused on uniform growth – Process modeling for scale-up is critical
Medium	• Develop high deposition rate, high throughput processes (5 votes) • Reduce cost of contacts, packaging (1 vote) • Apply roll-to-roll manufacturing to flexible thin film PV with intelligent CIGS processing using a wide variety of metrology tools (1 vote)

Table B.3: Technology Challenges for Amorphous Silicon and Polycrystalline Thin Film PV	
Low	• Develop standards and best-practices for custom processes and equipment – Convergence of CIGS absorber manufacturing processes is sought – Standardized equipment for CIGS is of interest – Custom processes and equipment for custom products are desired – Accurate forecasts are required for raw materials costs as well as the costs for various PV production levels and technologies
Cells and Interconnects	
High	• Develop photon collection and management (6 votes) – Light trapping and overall photon harvesting is critical – Non-imaging concentration may be improved – Anti-reflection not based on interference is sought for wide-angle collection – Photon management of up-conversion, down-conversion, down-shifting can have a great impact
Medium	• Use nano-structured materials in new device structures (3 votes) • Produce high-quality thin-film semiconductors on low-cost substrates or nano-structured collection geometry (1 vote)
Low	• Intensify process and product integration
Cross Cutting	
High	• Improve reliability (7 votes) – Improvements in accelerated testing are critical – Design concepts for reliability are needed – Reliability issues with new materials for terawatt deployment are of great interest
Medium	• Develop durable, flexible packaging for flexible thin film modules, > 25 years for BIPV, CIGS and CdTe (4 votes) • Develop optical modeling beyond geometric limit (3 votes) – Low throughput is an issue • Thin-film device physics should be studied for new knowledge and its dissemination (3 votes) • A relationship between efficiency and LCOE is needed (1 vote)

Table B.4: Measurement Issues for Amorphous Silicon and Polycrystalline Thin Film PV	
Fundamental Materials/Device Issues [New Materials, Device Design, Module Efficiency (20%), Understanding/ Controlling Reliability]	
High	• Evaluate 3-D-correlated mapping of chemical composition, structure, optical e-field, potential, and recombination in devices, multi-scale down to <50 nm resolution (15 votes) – 3-D (or 4-D including time) mapping is of great interest, providing: chemical and structural information, optical E-field, electric potential, and recombination in devices—using methods that are non-destructive and can be applied in a single cell – New methods of profiling interior of device structures (density, potential, field) are sought – Suite of optical/electrical imaging tools are needed to identify losses and mechanisms at grain size resolution and below – Mapping of impurity and/or compositional variations on scales of <50 nm is of great interest

TABLE B.4: MEASUREMENT ISSUES FOR AMORPHOUS SILICON AND POLYCRYSTALLINE THIN FILM PV	
	• Measure, understand, and characterize interfaces (8 votes) – Nano/atomic-scale atom and charge transport must be measured at interfaces in CdS/CIGS, TCOs – Tools for understanding electrical transport between grain boundaries, across interfaces, and within nanodomains in chalcopyrites and kesterites are needed – Excess free energy at interfaces must be measured to understand fundamental materials issues – Tools for characterizing buried interfaces must be improved • Link computational models to measurements—in order to understand relevance (8 votes) – Relationships between structure and electronic defects/device properties should be understood in both research cells and modules
Medium	• Study sub-micron image of surface crystallinity and composition during growth of a thin film (2 votes)
Low	• Evaluate sources of Shockley-Read-Hall recombination: performance limits, degradation, and interface/bulk traps (1 vote) • Measure voids and fissures in thin films—location and extent—which are important for transport and reliability (1 vote) • Develop chemical mapping (1 vote) – Depth profiling of composition, and doping and impurity concentrations is desired – New inexpensive tools for chemical analysis are required • Facilitate fundamental understanding of comprehensive testing (compositional, microstructure, electrical, optical) on individual set of samples • Develop optical mapping • Develop electrical mapping – Junction field distribution (z-direction) should be measured for understanding charge distribution at interfaces, transport, and charge collection • Ensure measurement requirements are addressed without duplication
MANUFACTURING [ADOPTION/SCALE-UP, YIELD/COST]	
High	• Create inline measurements (9 votes) – The loop should be closed relating measurement to process in materials and devices – This will involve data processing -> control algorithm -> actuator – High throughput mapping measurement of device-relevant parameters is needed for online analysis – Inline, non-contact/non-destructive analysis (and control) of third-level metrics, second-level when available, (e.g., V_{OC}) with mapping capability (e.g., lifetime) is needed. Third level metrics are usually more sensitive to final efficiency issues • Evaluate real-time defect identification and mitigation: "locate and remove" (5 votes) – Spatially resolved (x-y) recombination rate is desired to identify losses at shunts, point defects – Cell variation within a packaged module is of key interest – Relationship of cell and microscale measurements to module performance must be understood – Real-time measurements of gas-phase precursors (identity and density) in thin film are needed
RELIABILITY [PREDICTIVE TESTING, STANDARDIZATION]	

Table B.4: Measurement Issues for Amorphous Silicon and Polycrystalline Thin Film PV	
High	• Identify material-specific degradation modes and ways to quantify and predict (7 votes) – ALT is desired that lasts only days and is highly correlated to outdoor test conditions, categorized by technology; current correlated tests require several weeks/months • Improve the kWh/kW ratio of energy produced per rated power (6 votes) • Study standards, certifications, and protocols (5 votes) – Valid reliability testing standards are required including universally accepted accelerated testing protocols – Time required to certify products must be shortened (currently 6-9 months) – Test structures for kinetic studies (adhesion, materials reliability, diffusion, and corrosion)
Medium	• Choose either "two-terminal" or other ways to perform traditional measurements in "laminated" or packaged products (non-destructive, reliable, fast, and conclusive) (3 votes) – Chemical changes in thin films due to aging effects must be understood
Low	• Design highly functional thin film modules for reliability over 20-30 years (1 vote)
Cross-Cutting	
Medium	• Close the loop in establishing the following relationships: process parameters ->material properties ->device/module performance ->stability/reliability (2 vote)

Table B.5: Technical Challenges for III-V Multijunction PV	
Materials	
Low	• Develop new materials that can withstand 5000 x illumination levels – Lack of III-V-VI materials that can handle such levels • Develop low cost materials (1 vote) • Develop stable optical materials without high optical losses upon UV aging (1 vote) • Improve quality of current adhesives (1 vote) • Focus on materials and cell design, characterization, and standards for real-world operating conditions (1 vote) • Obtain lower cost III-V cells by substrate removal and reuse, or growth on lower cost substrates - through developments in processing, bonding, characterization, etc. • Understand effects of in-situ stress during metalorganic vapor phase epitaxy growth of high-PCE, lattice-mismatched cells
Substrates/Growth	
High	• Develop low cost substrates and new chemicals (precursors) for metalorganic vapor phase epitaxial growth, develop liftoff (i.e., reusable substrates) or Si substrates (10 votes) – Inverted metamorphic multijunction cells currently do NOT use techniques similar to those used by LED industry, i.e., liftoff with gallium nitride on sapphire substrates
Low	• Mitigate lattice matching constraints that limit performance – Develop novel epitaxial liftoff approaches, coupled with integration (2 votes) • Establish real-time, in-situ growth monitoring methodologies (2 votes) • Develop flexible/thin substrates • Understand benefits/challenges of different tuning methods of optical properties (e.g., by use of metamorphic approaches compared with use of quantum structures)

Table B.5: Technical Challenges for III-V Multijunction PV	
Cells and Interconnects	
High	• Develop fabrication techniques and novel cell structures for higher efficiency, higher temperature cell operation (10 votes) – New materials, nanostructured cells are required – The number of junctions must be increased – Tradeoff between efficiency, LCOE, and reliability must be understood
Low	• Achieve scalability and cost targets by requiring standardized cell specifications (1 vote) – Cell concentration and cell size must be optimized; the current range of sizes and shapes must be limited to two sizes • Overcome series resistance at higher concentrations • Design techniques for nanoscale and macroscale materials coupling • Optimize cell construction for use under high concentration • Improve material properties and mitigate compatibility constraints, e.g., band gaps, lattice constants, and thermal expansion
Manufacturing Processes	
High	• Develop low cost characterization and production equipment (inline) specific to III-V multijunction (7 votes) – This development should be useful for cells, package, module, assemblies (dish) as well as for MOCVD-based manufacturing
Low	• Develop automated, low-cost manufacturing processes that yield high-performance and highly reliable systems (2 votes) • Identify cheap, reliable, and fast tunnel junction screening methodologies • Ensure economies of scale in manufacturing • Adopt quicker and more accurate characterization methods for cells – Such characterization must provide quicker feedback to cell manufacturers
Packaging (Module)	
High	• Identify technical challenges that keep costs high for components of the CPV system other than the cell (5 votes) – Currently 10-20% of the CPV cost is the cell, and 80-90% of the cost is from other parts of the module – Innovation is needed to lower costs of other parts of module to point where costs split into 50% cell, 50% other
Low	• Overcome lack of affordable ceramic substrates (2 votes) • Study why poor sub-assembly design leads to poor thermal and optical performance • Improve anti-reflective coatings • Protect cells and optics from dirt and water without causing other problems such as overheating • Reduce effects of wind and optical losses in CPV applications • Overcome lack of history of field testing • Improve accuracy in the modeling of thermal effect issues at high concentration: 500 X – 2000 X – Detrimental effects exist on packaging, reliability, and mechanical properties
Optics	
High	• Overcome challenges associated with obtaining optical efficiency improvement, i.e., from 80% to 90% (7 votes)

Table B.5: Technical Challenges for III-V Multijunction PV	
Low	• Study why optical systems can't achieve +/- 1° at 1000 suns (1 vote) • Develop cell coatings that incorporate improved anti-reflective properties, greater protection from elements, and improved transmission of matched spectrum to cell (1 vote) • Expand beyond "classical" optical designs (e.g., Fresnel lenses, mirrors, and prisms) • Reduce cost of optics fabrication • Minimize effects of non-uniform illumination and localized heating
Reliability	
High	• Develop an understanding of known CPV degradation/failure modes, mechanisms, and methods (13 votes), – There exists an inability to accelerate these mechanisms for lifetime testing and standards development and to identify quickly the most problematic weaknesses for specific deployment locations – An understanding is required for quantitative service life prediction (based on location)
Medium	• Simulate long term UV exposure and its effect on adhesives and lenses. (4 votes) – UV capability with advanced light sources must be enhanced • Develop life prediction tools for energy, degradation, failure (2 votes)
Low	• Obtain detailed screening parameters at cell and receiver level to identify and eliminate one-sun failure/reliability risks (1 vote) – The ability to anticipate issues that develop once in capacity is required • Correlate acceleration testing and field system reliability data • Improve understanding of issues affecting lifetime of metamorphic materials (e.g., silver migration) in greater than 500 X concentration – A contrast to lattice matched solar cells, which are better understood • Improve stability of materials in optical path • Identify cells' sensitivity to spectral differences • Identify cells' lack of protection from wind and humidity
Modeling (Cost of Energy)	
High	• Enhance modeling of resource information to optimize structure (12 votes) – Lack of mathematical models for correction of power output under standard conditions and projection of energy output for specific site – Poor existing data of direct normal irradiance with low acceptance angle, aerosol optical depth, and water vapor – Spectral data on hourly average is insufficient – Sum of instantaneous/1 second direct beam time measurements are needed over 1 hour for wider wavelength ranges: 300-2000 nm, i.e., not limited to 1200 nm – Activity will lead to creation of an accurate CPV resource information database

Table B.5: Technical Challenges for III-V Multijunction PV	
Low	• Determine cost-performance-design trade-off space – Higher performing cells may be possible, but at what cost? – At what cost will lower performing cells be of interest? (1 vote) – Can low efficiency III-V CPV be produced at much less manufacturing cost? • Overcome lack of spectral information for modeling (1 vote) – Information is location specific – A multi-year history is required as well as correlation to common environments – It is important to compare such information to existing data from operation sites • Overcome lack of impartial module cost prediction data including optics, cells, and heat sinks (1 vote) • Overcome lack of impartial third party modeling tools for energy harvesting for CPV – Predictions must be based on reliability, degradation curves, and spectrum

Table B.6: Measurement Issues for III-V Multijunction PV	
Growth /Substrate	
Medium	• Develop next-generation diagnostics for real-time monitoring growth (3 votes) – In-situ stress/doping measurements – Optical properties of new alloys materials at high temperatures • Create inline characterization of material and cell performance without use of contacts (2 votes) • Evaluate new in-situ nanoscale, atomic, and chemical characterization methodologies (2 votes) – Important to determine chemical content of specific dopants at growth temperature
Characterization	
High	• Evaluate QE of each current density at operating light levels (> 500 sun) (5 votes) – Peak power (PMAX) operating point of junction, including temperature must be evaluated
Low	• Develop combined optical and electrical measures on embedded nanostructures (i.e., quantum dots, liquid) (2 votes) – Commercial instruments are needed to measure topography, photocurrent generated out of nanostructures in conjunction with thermal measurements • Characterize chemical composition—chemical analysis on nanostructure (with 2–3 dimensional configuration at nanoscale) (1 vote) – Energy dispersive x-ray analysis (EDAX) methods at the nanoscale are of interest • Develop techniques for direct measurement of space-charge region temperature of cell at > 500 suns (1 vote) – Cell temperature gradients must be measured at high concentration and resolved spatially – IR camera capabilities are needed • Characterize/measure cells at high temperatures rapidly as a function of temperature (1 vote) – Full range of temperatures is needed • Develop a more accurate measure of power rating and efficiency – Efficiency should be measured over time and changes differentiated from uncertainty • Characterize material with adequate resolution to probe tunnel junctions • Create minority carrier lifetime measurements in working multijunction devices • Monitor in-situ characterization of formation and motion of dislocations during growth of device • Develop accurate measurement of the spatial and spectral flux distribution across the receiver/cell
Concentrator Solar Cell Simulation Testing	
High	• Create quick, accurate inline (automated) cell test and characterization (10 votes) – Cell measurement tools are required that meet cost targets – High-speed, industrial inline flash tester is required for CPV receiver assembly at concentration – Quick J ratio measurement is required using high intensity pulsed solar simulator or continuous simulator – Measurements are required that indicate or extrapolate cell performance under high concentration using 1X concentration measurements • Develop reliable, adjustable, and accurate simulation of the solar spectrum (single source, multi-source, and filtering) (6 votes)
Low	• Create quick inline characterization of cells, e.g., by electroluminescence – Multiple cameras are required for each cell • Develop high-intensity pulsed solar simulator measurements to determination of the spectrum requirements for n-junction current matched devices

Table B.6: Measurement Issues for III-V Multijunction PV	
Concentrator Module Solar Simulation Testing (divergence)	
High	• Measure and track optical efficiency on modules (15 votes) – Light sources are required that simulate the sun over a large area, including divergence, CSR, etc. – Sun simulator is required for CPV-modules, quality control for manufacturers – Important to understand and relate optical efficiency when it is linked to angular acceptance. – Agreed upon standards and procedures must be included for these measurements – Measurement must be defined first then tracked
Low	• Standardize calibration techniques for CPV module solar simulators (1 vote) • Test simulator capability at CW and pulsed • Calibrate chain, standardize testing • Spectrally adjust and standardize spectral content • Measure spectral response of module • Increase availability of measurement instruments for availability to manufacturers and laboratories
Reliability	
High	• Measure for predictions of degradation rates (10 votes) – Cell, packaging, lens are key components for these measurements – Fail safe/fuse in circuit must be developed to stop/interrupt process to make a digital photogrammetric measurement and understand degradation
Low	• Test weatherometer to simulate humidity and other accelerated weathering conditions (1 vote) • Develop a vision system for automatic detection (and classification) of defects in cells from EL pictures (2 λ) (1 vote) – Point defects and cracks should be classified – A rejection criterion should be developed • Measure bond quality, i.e., chemical properties between materials for the cell to heat sink bond and other bonds in module – Tool must be low cost, inline, and portable – The quality of the die attach bond must be measured • Combine effects tests—test cell while under environmental conditions • Measure UV spectrum for high intensity, high concentration of UV exposure for reliability testing – It is difficult to measure UV dose precisely according to wavelength; current standard UV detectors burn up under high intensity • Develop novel measurement techniques to better understand degradation chemistry – Packaging material is of particular interest • Develop well-characterized reference (for which degradation and soiling is well-understood) CPV system or measurement suite for use as a reference point – The approach could be similar to flat plate reference modules – Family of these reference points are required (for reliability or resource rates) – Source of degradation from system or other factors must be determined
Solar Resource Data	
High	• Develop a simple and low-cost global spectrum monitor (spectroradiometer, spanning the range of 300 nm to ~2000 nm, which measures angular distribution of solar resources) for various locations, multi-year, short term, and long term (11 votes) – Faster time resolution is needed – Real-time monitoring is needed

Table B.6: Measurement Issues for III-V Multijunction PV	
	– Satellite spatial resolution is needed • Develop combined CPV measurement—simple, automated, real-time monitoring, and satellite spatial resolution (5 votes) – Simple/low cost spectroradiometer must be developed for continuous real-time measurement of aerosol optical depth (AOD) and water optical thickness for CPV power plants – Low cost outdoor sensor is needed to measure angular distribution of solar resource
Low	• Identify standard cell/isotype calibration procedures for high concentration (1 vote) – This issue also implies a need to establish linearity of standard cells • Create small package that includes small concentrator system—(Fresnel lenses) for quick on sun testing for multiple suns • Design sensors to prevent environmental contamination (through self cleaning or other methods)
Standards	
High	• Develop measurements to support standards development (7 votes) – Solar resource standards should be developed by NIST (< 1%, 300-2500 nm) – One detector should be used for spectral measurements from 300-2500 nm • Find primary references for concentrator applications (6 votes) – Concentrator isotype cells can serve in this capacity
Low	• Develop quick (on the order of ~ 1 s) QE measurement for multijunction cells – More accurate measurements are required under operating light levels and at P_{max} point of operating junction for each cell design

Table B.7: Technology Challenges for Excitonics and Quantum Structured PV	
Fundamentals	
High	• Improve understanding of fundamentals—interface/surface recombination in nano/quantum/organic materials; improve understanding of low V_{OC}, physics of V_{OC}, charge separation (7 votes) • Improve understanding of organic-organic and organic-inorganic interfaces and their optimization for efficiency and lifetime since these are interface-dominated devices (10 votes)
Medium	• Achieve independent processing control over nanoscale structure, electronic character, and stability (3 votes)
Low	• Improve science of de-coupling of HOMO/LUMO and V_{OC}, which is believed to be coupled • Evaluate Frenkel exciton binding energy—which limits architecture to bulk-heterojunction only • Evaluate market saturation in 20 years at efficiency level of 18% for a single device – Efficiency higher than 18% may not be possible. – Determine the fundamental barriers to surpassing 18% • Determine e-h collision rate – It is of interest to know if collisions occur at rate >> than that predicted by standard percolation theory • Require robustness [driving toward perfection]; accept that chaos exists; embrace non-uniformity • Couple organic materials that are multi-functional to other energy-related properties (e.g., thermo-electric) • Understand quantum dots with internal structure—applying percolation and chaos theories
Materials	

Table B.7: Technology Challenges for Excitonics and Quantum Structured PV	
High	• Improve material stability during processing—increase cost through specialized equipment (5 votes)
Medium	• Develop more materials specifically for multijunctions (4 votes)
Low	• Overcome impurities; either purify cheaply, or use impurities to advantage; overcome lack of understanding of impurities (3 votes) • Increase device stability—need low cost packaging solution (2 votes) • Evaluate current trade-off between ordered materials fabrication and the process cost/energy input of fabrication (1 vote) • Evaluate photostability/morphological stability (1 vote) • Evaluate molecular weight and dispersion control, reproducibility • Evaluate copolymers: difficult and long to make (1 vote) • Consider need for broad spectrum light harvesting polymers or dye-polymer combinations • Begin planning in realization that indium tin oxide replacement may be an issue long term • Difficulty of using polymer substrates—ensure suitability of substrates for preventing moisture, exposure to sunlight • Limit use of dye-sensitized organics in the United States (due to manufacturability and other limitations, e.g., liquid electrolyte) • Improve optical management—overcome barriers in materials • Integrate OPV wiring into textiles (or other geometries) • Understand material limitations, and how different materials interact with surroundings, oxygen, water, temperature, manufacturing conditions • Understand how materials prevent charge recombination • Ensure suitable materials for an effective printing process
Models/Theory	
Medium	• Develop computational mechanics and chemistry, from fundamental physics and chemistry to multi-coupled systems (3 votes) • Model multi-level multi-coupled systems based on first principles (3 votes)
Low	• Develop model degradation mechanisms, decouple differences in substrate electrodes, interfaces, semiconductors, and the packaging barrier (1 vote) • Develop initial rules first, then develop modeling (1 vote) – With OPV, materials are “stumbled upon” • Need multi-scale modeling coupling atomic and molecular properties, device properties • Need dedicated supercomputers – Computational power is coming online, but expensive to access for nontrivial complex uses
Production	
Medium	• Understand basic science of manufacturing at scale for multiple gigawatts of production at high yield and low cost (3 votes)
Low	• Develop architecture for modules that retain efficiency of small area devices (2 votes) • Obtain sustained multi-year research funding for fundamentals of OPV as a nascent field (2 votes) • Develop multi-layer thin film coating technologies (2 votes) • Evaluate the high cost of raw materials: substrate, barrier films, active materials (2 votes) • Develop structures with potential for >20 year life (metal foil) in modules, – Effective light management is required – An understanding of costs are required • Overcome inability to produce OPVs at high speed, low cost (e.g., like the newspaper print industry)

Table B.7: Technology Challenges for Excitonics and Quantum Structured PV	
	• Evaluate the discrepancy between lab experiments and industrially viable production • Develop new paradigms for large installations that are cheaper • Evaluate fast manufacturing and fluid instability • Improve control of crucial interfaces – Solution-based processing is very attractive • Reduce cost of packaging solutions for flexible modules

Table B.8: Measurement Issues for Excitonics and Quantum Structured PV	
Measurement Issues for Excitonics	
High	• Measure and control defect structures (11 votes) • Understand function at the molecule/metal interface—dipole, polarization (8 votes) – In-situ probing is critical • Understand ALT degradation mechanisms and relevance to the field; better real world benchmarking of field vs. laboratory measurements (7 votes) • Develop capability of measuring 3-D nanoscale distribution of domains including size, shape, and connectivity (7 votes) – Capability requires nano-interface imaging • Develop rapid characterization and metrology of morphology and interfaces (8 votes) • Characterize molecular arrangement at internal and external interfaces, including orientation and conformation (5 votes)
Medium	• Evaluate package barrier properties (WVTR, OTR)—correlation to OPV lifetime (4 votes) • Develop 3-D nanoscale device and materials characterization in one tool for inline metrology used in scale-up (4 votes) – Molecular and physical properties of materials are of interest – Measurements of devices will help pinpoint defects, coupled with 2-D probes • Correlate electrical and photoelectrical properties with composition, morphology, processing conditions at nanometer-length scales up to macroscopic (4 votes) • Provide quantitative assessments of surface/interface structure in 2-D or 3-D and relate to recombination parameters (3 votes) • Develop in-situ method to measure nanoscale structure development during solidification (long term) (3 votes) • Create physical property measurement database for model parameterization (3 votes) • Design and build probe for charge carrier dynamics inside a working device (3 votes)
Low	• Develop 3-D field, DOS, and charge carrier distribution in a working device (2 votes) – Online capability is desirable • Identify pinholes—probe devices internally and identify future failure mechanisms during manufacturing (2 votes) • Create online instrument for characterization prior to final product fabrication (2 votes) • Accelerate reliability testing (2 votes) – Testing must be reliable because the result directly impacts ROI and ROI capital investment • Measure relevant HOMO and LUMO levels in the solid state – Measurement is required that provides an alternative to electrochemical and un-interruptible power supply methods (2 votes) • Develop electron spin resonance imaging ~1 nm resolution—magnetic resonance imaging for devices (2 votes)

TABLE B.8: MEASUREMENT ISSUES FOR EXCITONICS AND QUANTUM STRUCTURED PV
MEASUREMENT ISSUES FOR EXCITONICS
• Create faster visualization of dopant distribution in nanostructures and assessment of dopant activation (2 votes) • Determine how multiple excitons are generated, how charge is to be collected, and the type of systems in which it occurs (2 votes) • Standardize device measurement geometrics and techniques (i.e., 2 vs. 3 or 4 point) (1 vote) • Determine effective surface area between donor and acceptor (1 vote) • Determine energy and locations of structural and electronic impurities and defects (1 vote) • Develop capacity measures at 50 micron level • Understand detailed bonding/electronic structure at the bulk heterojunction/contact interface (only 1 molecule thick) (1 vote) • Characterize sub-surface organic/oxide interface composition, in real-world environments (within intact OPVs) (1 vote) • Characterize metrics with high spatial resolution for manufacturing control • Measure charge separation efficiency for donor-acceptor with small LUMO separation, about 0.1 eV • Measure electrical properties of the interface between donor and acceptor regions • Develop single photon sources • Measure the dynamic nature of the interface after device fabrication • Develop computational mechanics to determine spatial properties on controlled volumes • Understand mechanical and electromagnetic properties of multi-layer stacks, e.g., Q-dots, wires • Visualize chemical bonding, structure, and optical properties in a film • Develop measures of optical constants of heterogeneous, nanoscale materials • Create framework to develop polymer blend phase diagrams • Resolve temporal evolution of exciton generation • Characterize complete devices to understand the OPV air stability/thermal stability problem • Measure molecular interactions between additives and active materials – Goal is to understand the influence of additives • Characterize amorphous materials – It is of interest to characterize the chaos: in particular, the structure and location of molecules • Analyze phonon and thermal effects on the nanometer scale • Develop tools to monitor polymer chain movement in the drying process • Develop facile, affordable means to measure carrier lifetimes as a function of chemical nature and spatial extent through the device; characterize/locate recombination centers • Correlate factors that relate ALT testing to outdoor (roof-top) stability – The goal is to predict module lifetime • Develop faster, better, cheaper more tunable lasers • Understand the structure, chemistry, exciton and charge transport behavior of complex organic/organic 3-D nanostructures • Study the impact of thermal and mechanical stresses on all cell and module components • Resolve spatially spin concentration on the 1 nm scale in 3-D • Resolve materials in 3-D on 1 nm scale • Map the donor/acceptor domains • Map coating defects, e.g., pinholes and substrate defects. – Surface energy of different substrate regions may be different • Measure effect of external fields on crystal growth • Determine the chemical potential inside the device (under illumination) • Develop capability of determining complete 3-D image of density of states as in tomography • Characterize J/V behavior at nm length scales (x, y, and z) and correlate with macroscopic

TABLE B.8: MEASUREMENT ISSUES FOR EXCITONICS AND QUANTUM STRUCTURED PV	
MEASUREMENT ISSUES FOR EXCITONICS	
	behavior • Arrive at a no-In solution to transparent conducting oxide • Combine atomic force microscopy/spectroscopy to evaluate phase morphology • Ensure adequate PV device characterization tools at nanoscale (e.g., localized)

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