Preliminary Situation Analysis: Advances in Photovoltaic Technologies

May 2010

Developed as preparatory reading material for the

Workshop on Grand Challenges for Advances in Photovoltaic Technologies and Measurements

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1 INTRODUCTION

The solar industry has seen enormous growth over the past several years and is poised to continue rapid growth over the next decade. Three fundamental drivers for the growth of photovoltaic (PV) technologies are:

- Affordable and reliable energy supplies,
- Energy security for national defense, and
- Environmental sustainability.

These drivers have led to the adoption of favorable policies and stronger federal and state support for research, development, and demonstration, which are key to achieving the objectives shown above.

A pyrheliometer at the SunEdison photovoltaic (PV) power plant measures solar radiation from the sky dome. Photo Courtesy NREL.

To understand the role of measurement in supporting progress in solar energy, the National Institute of Standards and Technology (NIST) is conducting a broad-based effort to identify the technical challenges in the development of advances in PV technologies. As part of these efforts, NIST will host a Grand Challenges for Advances in PV Technologies and Measurements Workshop in Denver, CO on May 11-12, 2010.

The information contained in this situation analysis was collected from available current literature and, therefore, provides a snapshot of reported technology challenges to date. It is intended to serve as preparatory reading material for the upcoming workshop, and, as such, may aid in stimulating ideas, identifying knowledge gaps, and recognizing collaborations related to measurement and technology challenges to advancements in the PV industry. The set of measurement and technology challenges collected from industry experts attending the workshop will be reported in forthcoming documents and used in further analyses.

1.1 Methodology

1.1.1 Defining Advances in PV Technologies

Four technology groupings, listed below, were identified through discussions with industry experts as the technologies expected to play a prominent role in the PV market over the next 20 years. This literature review report and the upcoming workshop focus on the four technology groupings and expected advances within those groups.

1. **Wafer-based crystalline silicon PV** – bulk silicon PV technology with cell thickness of 100 microns or greater
2. **Amorphous silicon (a-Si) and polycrystalline thin film PV** – silicon-film technologies that rely on a supporting substrate, copper indium gallium (di)selenide (CIGS), cadmium telluride (CdTe), or other materials with cell thickness of 100 microns or less
3. **III-V Multi-junction PV** – layered semiconductors in a solar cell, using combinations from periodic table groups III and V, aimed at capturing a broad range of wavelengths
4. **Excitonics and quantum-structured PV** – organic-based, dye-sensitized solar cells, and quantum dot/wire technologies

It should be noted that while quantum-structured PV is called out specifically in the fourth area, nanoscale science and technology is a cross-cutting issue that can also impact the other three technology areas. This cross-cutting issue may be applied where the nanoscale phenomena are secondary to device physics (e.g., light capture, contacts) and is expanded upon in Section 3.5.

1.1.2 Basis for Information

A literature survey was conducted for each of the four technology areas to identify target markets, technology challenges, and measurement issues. The literature surveyed included currently available, major scientific studies, technology roadmaps, and journal articles. Sources used in this report are listed in Section 5.

The extent of information found in the literature for each of these technologies varies widely depending on the stage of development (i.e., some are relatively mature, some emerging, others still in the exploratory or fundamental stages of development). In some cases, where dozens of journal articles or other reports were available, only the most recent or the most comprehensive were cited, due to the preliminary nature and relatively limited scope of this study.

Identifying and understanding measurement issues is particularly challenging because most of the literature does not focus specifically on measurement, but rather on research and development (R&D) barriers that need to be addressed. While many R&D barriers are heavily dependent on measurement science, rarely is the connection clearly defined in the literature. For that reason, many of the measurement issues identified in this situation analysis are not robustly described and require further analysis and insight to define a clear path forward for addressing these issues.

An overview of the current global and domestic solar market and the major trends and drivers (financial, R&D investments) was developed using current market reports and other literature. The information is generally the most current but not necessarily reflective of recently emerging trends in the PV industry.

The current landscape for PV-related standards was reviewed using public sources and information available from a number of standards development organizations. Due to the fragmented development of some PV standards, and the number of organizations involved in multiple standards development efforts worldwide, it is difficult to identify singular gaps in standards development. A preliminary survey of standards, for example, yielded references to hundreds of standards that are currently active or under development. A summary of standards organizations (both international and for the major PV markets) and their solar related efforts is included in Appendix A.

2 ADVANCED PHOTOVOLTAIC TECHNOLOGIES

Today’s PV market consists of mostly wafer-based crystalline modules (~82% of total megawatt [MW]), thin film PV (~17% of total MW), and a small amount of III-V multi-junction PV used mostly in concentrating photovoltaic (CPV) applications. Wafer-based crystalline PV boasts the longest terrestrial usage history and therefore the most long term reliability data. Within the silicon based PV technologies, reduced cost generally corresponds to reduced power conversion efficiency (PCE), with decreasing PCE observed from monocrystalline to multicrystalline to ribbon-based PV. In order of decreasing PCE, the four technology groups discussed in this report are:

- ***III-V Multi-junction PV***: most expensive, used mainly in space applications
- ***Wafer-based silicon PV***: expensive, long terrestrial commercialization history
- ***Thin film PV***: inexpensive, recently introduced to large scale commercialization
- ***Excitonic and Quantum-Structured PV***: inexpensive, not yet widely commercialized for power generation

Next-generation advances hold the potential to reduce the gap between currently achievable PCEs and theoretical PCEs for a given technology. However, technology barriers, including those associated with measurement, hinder both current and future development, as highlighted in the discussions below. In general, technology and measurement challenges are discussed as they relate to increasing PCE, lowering cost, improving reliability, improving understanding of generation and recombination, and improving manufacturing processes or throughput. Generalized ranges of commercial module level efficiency are listed in Table 2.1, with research cell efficiency details charted in Figure 2.1.

Table 2.1
Comparison of Advanced PV Module Efficiencies and Development Status

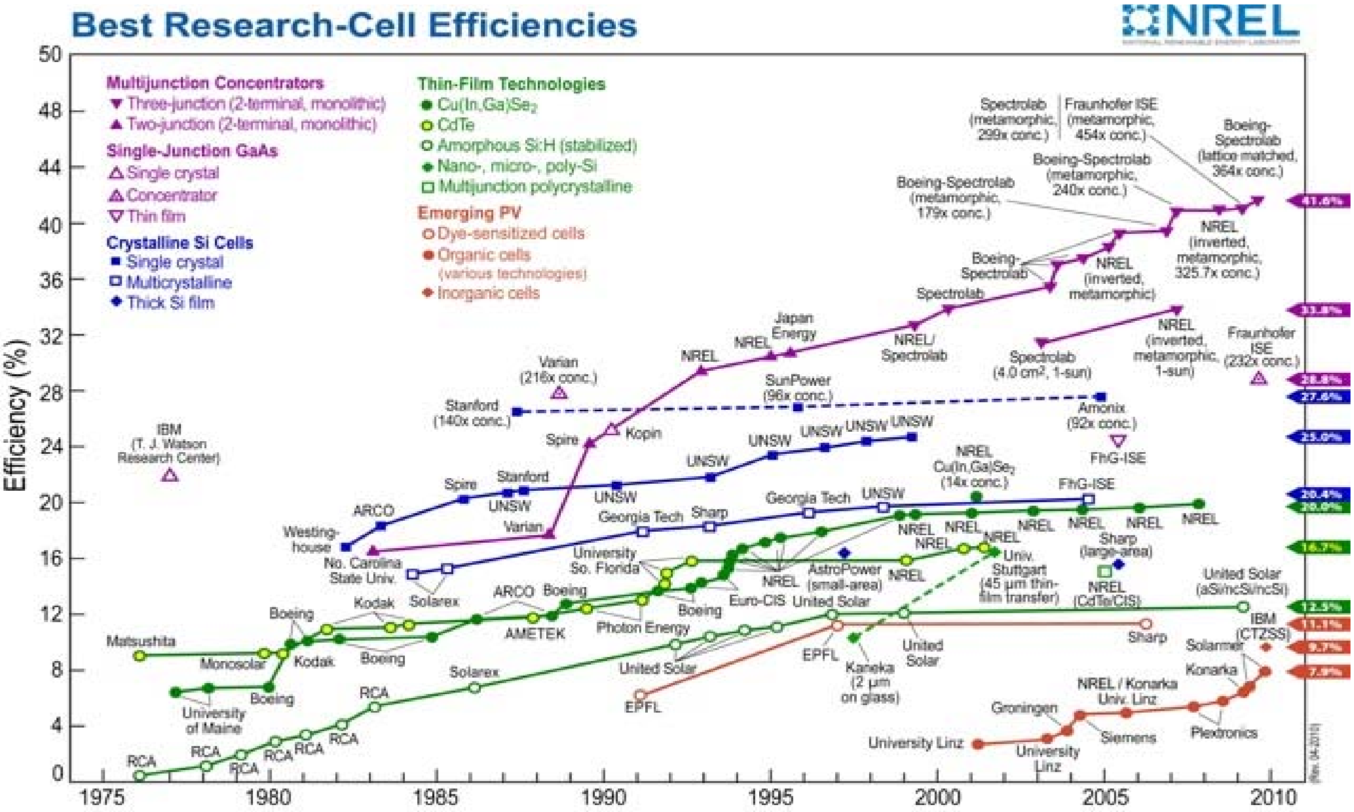
	Wafer-based Crystalline Silicon PV	**Amorphous Silicon and Polycrystalline Thin Film PV**	**III-V Multi-junction PV**	**Excitonic and Quantum-Structured PV**
Module Efficiency	Monocrystalline: 16-22% Multicrystalline: 14-16%	a-Si: 4-7% CdTe: 8-11% CIGS: 7-11% Tandem Si:H: 6-10% Triple junction Si:H: 8%	25%-30%	Organic: 5%-8% Dye sensitized: 8%-11%
General Development Status	Large scale commercialization	Recent large scale commercialization	Main technology for space applications; prototype development and initial manufacturing for CPV	Not widely commercialized for power generation

Sources: NREL, 2010; LBNL, 2009; REW, 2009a; SolarBuzz, 2009.

The following technology discussions are limited to issues up to the module level. While system-level technical and measurement barriers are also critical to the future success of the PV industry, they introduce additional topics such as balance of system (BOS) components and grid interconnection, which are outside the scope of this report and the upcoming workshop.

Figure 2.1

Comparison of Advanced PV Research Efficiencies



The information provided herein is preliminary, based on published literature, and not intended to be all-inclusive. Rather, it is intended that the information will stimulate ideas for the upcoming advances in PV workshop and help identify knowledge gaps in technology and measurement issues.

Note that most of the literature does not focus specifically on measurement, but rather on R&D barriers that need to be addressed. While many R&D barriers are heavily dependent on measurement science, that connection is seldom clearly defined in the literature. For that reason, many of the measurement issues identified in the following sections are not robustly described and will require further analysis and insight to understand the path forward for addressing these issues.

2.1 Wafer-Based Crystalline Silicon PV

Crystalline silicon holds the majority of the commercial PV module market. Its future appeared to be limited when the cost for polysilicon skyrocketed a few years ago. Since then polysilicon costs have more than halved, returning crystalline silicon to an increasing market share position. Associated with its reemergence, much development work is ongoing to reduce costs still further. These activities generally address increasing the PCE of standard cells from 16% to as high as possible with improved processing techniques and cell structures. Also there is a need for further reductions in manufacturing costs through improvements in production yield and module encapsulation. Advanced measurement tools and techniques are required in all of these areas.

2.1.1 Development Status

Wafer-silicon is a mature technology with decades of terrestrial usage. Confidence in wafer silicon technology arises partly from decades of operation, resulting in the best proven reliability. Wafer silicon is expected to comprise a large part of the predicted growth in the solar industry. While PCE has risen from around 6% in early modules up to 22% currently, further improvements are possible with technology advances.

Reduced module costs have historically been mostly due to technological advances in manufacturing and increased manufacturing capacity. However, in recent years, module prices have been greatly reduced by lowered silicon prices, excess supply of modules, and the global economic downturn. Advances in cell efficiencies and yield, and reductions in wafer thickness, may help achieve future reductions in wafer-silicon module pricing. Reductions in module costs have the potential to significantly reduce the overall installed cost since approximately 40-50% of the installed costs are attributed to the modules.

Due to the long commercialization history, global manufacturing capacity is the largest of any solar technology. Substantial momentum in the PV industry has been created by the considerable number of installations and manufacturing capacity. Future performance and cost are likely to follow the 81% wafer silicon learning curve observed in the past. (EERE, 2007a)

2.1.2 Target Markets

Currently, wafer silicon PV dominates the industrial, commercial, and residential PV markets, with approximately 82% of total PV installations using these products. Its future appeared to be limited when the cost for silicon skyrocketed a few years ago. Since then silicon costs have more than halved, returning crystalline silicon to an increasing market share position. Wafer silicon is forecasted to continue a majority share of the market until about 2017. (EERE, 2007a) However, the recent emergence of thin film PV is reducing the market share of wafer-based silicon PV.

2.1.3 Technology Challenges

Although wafer-based silicon PV prices have dropped, ongoing R&D may reduce the costs of this technology still further. Major technology challenges include reduction of feedstock material usage, diminished wafer loss in cell manufacture, development of superior and less expensive feedstock material, reduction of PCE losses (e.g., interconnect shadowing), and development of in-line manufacturing diagnostics (e.g., machine vision tools to inspect cracks, coatings, defects, and soldering between cells). The major technology challenges found in the literature are summarized in Table 2.2.

Table 2.2

Technology Challenges Reported in the Literature for Wafer-Based Silicon PV

Materials/Feedstocks
• Undeveloped impurity and defect engineering • Reducing material cost by developing less-expensive methods to produce feedstock suitable for PV • Glass developed specifically for PV industry use; i.e., glass products that meet required specifications, not arbitrary characteristics, which otherwise may increase costs unnecessarily • Insufficient glass strength in current products to reduce glass thickness and, therefore, material costs • New silicon materials and processing methods needed

Table 2.2
Technology Challenges Reported in the Literature for Wafer-Based Silicon PV

Cells and Interconnects
• Light management for thinner cells (crystalline silicon) due to effective light-trapping • Light management due to reduced metallization shadowing • Control of wafer stress from back contact and thermal balance • Need novel device structures such as heterojunction cells • Lower surface recombination designed to yield cell efficiencies > 25% • Lack of contactless deposition techniques for ultrathin wafers • Cell-contacting schemes: o Reduction of shadowing and percent Si-M contact-area o Developing maskless metallization o Designing advanced metalization schemes o Designing simultaneous front- and back-contact formation o Formulating metallization schemes for low recombination contacts to enable high efficiencies • Innovations to improve manufacturability of cells and interconnects
Manufacturing Processes
• Lack of in-line sensors for various aspects of wafer-based modules production, including microscopic cracks that can propagate during additional processing • Optimization of PCE and yield through manufacturing diagnostics and process modeling, isolating and understanding each process step • Development of techniques to manufacture thinner wafers, while addressing hurdles such as increased wafer breakage • Reducing silicon waste from cutting ingots into wafers (i.e., kerf loss)
Packaging
• Increasing performance of anti-reflection coating • Refining accelerated life testing to predictably replicate failures seen in the field • Development of low and non-imaging concentration optics and associated module design changes

Sources: EERE, 2007a; Energetics, 2008, IEA 2009a

2.1.4 Measurement Issues

Advanced measurement tools and techniques are necessary to overcome these technical challenges to wafer-based silicon PV. The maturity of the wafer-based industry and adaption of technology from the semiconductor industry have resulted in a wide measurement capability portfolio. However, measurement needs still exist, especially with respect to manufacturing and the reduction of wafer thickness. For example, automated wafer crack detection must detect microcracks that do not register errors with current testing but may cause failures with further processing of the wafer. This issue is especially important for thinner wafers that are more susceptible to breakage.

While wafer-based silicon benefits from a long field history, accelerated life time testing is still critical to predict reliability of wafer-based products with new configurations, manufacturing techniques, or materials. Improved measurement techniques resulting in reduced uncertainties in spectral and temperature response functions for PV cell technologies need to be developed. These could include methods to accurately measure the temperature of PV modules during high-speed flash testing.

As noted earlier, measurement issues are not generally the focus of R&D challenges identified the literature, but are an important underlying element. As a result, the measurement issues identified are not necessarily complete or robust. Some of the measurement challenges currently identified in the literature (REW, 2009a) include, in no particular order:

- Automated detection of crack detection for thinner wafers, especially for those cracks that do not register errors with current testing
- Accelerated life testing
- Evaluation of PV products with greater accuracy through flash solar simulators products
- Determination of how grain boundaries and nonuniformities from grain to grain affect the function of solar cells and the measurements of their properties
- Measurement of the kinetics of Si wafer microcrack propagation as a function of processing, which may include in-line imaging capabilities
- Specifications and testing standards for the thinner wafers now being researched
- In-line sensors and manufacturing diagnostics

2.2 Amorphous Silicon and Polycrystalline Thin Film PV

The dominant commercial thin film technologies are CdTe and multi-junction thin film silicon, which are the most mature technologies. They exhibit small area cell PCEs approaching 14% and 16.5%, respectively (Figure 2.1). CIGS is less mature but has the advantage of higher PCE (near 20% in the laboratory). For all three technologies, there exist opportunities for further improvement. Challenges in these technologies include using thinner absorber and window layers, developing higher rate and atmospheric pressure deposition techniques, improving uniformity and control of stoichiometry over large areas, designing new multijunctions, narrowing the gaps between cell and module PCEs, identifying stability issues (from materials to contacts, and water ingress), addressing materials availability/cost issues, environmental concerns, and recycling. Thin films are classified as 2nd generation technologies, but they are showing great promise as disruptive technologies to crystalline silicon PV because of their transformational and technology-driven nature.

2.2.1 Development Status

Development and commercialization status for the three major thin film technologies are discussed below.

a-Si

a-Si products differ from wafer-based in that deposition techniques, such as chemical vapor deposition (CVD), are used to build silicon in very thin layers in a continuous roll-to-roll manufacturing process. This process reduces loss due to cutting, wafer breakage, and microfracture defects. Currently, manufacturing plants use plasma-enhanced CVD for the deposition process. The a-Si technology has improved from initial laboratory fabrication in the 1970’s and is a moderately mature technology, with increasing commercial success.

CdTe

CdTe products have been successfully commercialized with increasing penetration into the market at the expense of wafer silicon products. Today, glass-glass encapsulated thin film CdTe modules appear to be comparable in terms of reliability to conventional Si-based technology. As new approaches are taken to boost PCE, testing must be undertaken to ensure reliability is maintained. While global manufacturing capacity has increased, there is still room for much growth. Although some issues may slow development efforts, such as non-standard manufacturing processes, lack of in-line diagnostics, and availability of raw materials at significantly large production volumes.

CIGS

Commercial production of CIGS products have increased over the past few years but still represent a small share of the overall PV market. Even with lower efficiencies, non-silicon based technologies, such as CIGS and CdTe, become more attractive as silicon prices increase; in turn driving growth of production facilities. In

2008, approximately 40 companies worldwide are involved in CIGS technology development, with less than 10 producing commercially. (Ullal, 2008) Previous predictions estimated that over two gigawatts of production capacity would come on-line in the 2010/2011 timeframe (pv-tech, 2008) when the CIGS market may reach US$1.4 billion. Several deposition methods are used for absorber layer growth including sputter/selenization and coevaporation. Molybdenum is the only back contact used for CIGS and zinc oxide is the usual front contact. The availability of indium may be a limiting factor to increased production of CIGS products. Annual production limits may be in the range of 2,000 to 10,000 MW (EERE, 2007b) based on indium usage and supply. Thinner absorber layers may increase these limits and increase manufacturing throughput by decreasing deposition time. However, issues related to PCE loss, processing robustness, and module reliability need to be resolved. (EERE, 2007b)

2.2.2 Target Markets

In general, thin film PV offers lower costs with the tradeoff of lower PCE. Lower cost and PCE tend to make thin films attractive for smaller systems such as commercial or residential applications and building integrated PV (BIPV). The higher efficiency thin films, CdTe in particular are used for utility scale operations. Flexible thin film products are uniquely situated to satisfy some BIPV design requirements where curvature is desired or required. Whether flexible or rigid modules are selected, however, depends on the application requirements.

Commercial rooftop and large-scale utility, ground-mounted systems are likely to remain the dominant market through 2012. In the near term, rigid products fabricated on low-cost, soda-lime glass substrates are expected to dominate thin film products providing the best opportunity to continue increasing the lead that thin film CdTe has in large PV systems, and allow CdTe to enter the residential rooftop markets.

2.2.3 Technology Challenges

There are many opportunities for further improvement in all thin film technologies. Some of the challenges to thin film PV include the development of thinner absorber and window layers, new architectures that depart from traditional laminar structures, higher rate and atmospheric pressure deposition techniques, improved material uniformity and control of stoichiometry over large areas, design of new multi-junctions, narrowed gaps between cell and module PCEs, stability issues (from materials to contacts, and water ingress), materials availability/cost issues, environmental concerns, and recycling. (EERE, 2007c) Technology challenges found in the literature are summarized in Table 2.3.

Table 2.3
Technology Challenges Reported in the Literature for Thin Film PV

Materials
• Limited understanding of interfaces in CIGS solar cells • Insufficient knowledge of relation between microstructure, composition, and performance • Potential scarcity of Indium in CIGS solar cells • Inadequate control of carrier concentrations in the absorber layer of CdTe solar cells • Need to identify pseudo-binary alloy families that add latitude to device design and development of CdTe solar cells • Undefined role of carrier depletion on individual grain boundaries in polycrystalline Si thin films • Poor theoretical understanding of conduction mechanisms for generation and recombination in CdTe and CIGS solar cells, with no consensus among the recognized experts • Insufficient research efforts on pseudo-binary alloys that add latitude to device design and development of CdTe solar cells

Table 2.3
Technology Challenges Reported in the Literature for Thin Film PV

Cells and Interconnects
• Need to reduce light induced changes in Si:H solar cells
• Problems associated with decrease absorber layer thickness to less than one micron in CdTe and CIGS solar cells
• Lack of well-defined and robust back contacts in CdTe and CIGS solar cells
• Incomplete understanding and adhesion issues of the only known back contact for CIGS, Molybdenum
• Insufficient back-contact stability in CdTe solar cells
• Lack of a capability to accurately model and predict device performance of CdTe solar cells
• Improvements in short-circuit current density in CdTe devices
Manufacturing Processes
• Non-standardization of growth/deposition equipment for optimized absorbers in any of the technologies
• Lack of integrated, off-the-shelf manufacturing systems/components
• High initial manufacturing costs due to customized nature of current systems
• Need low deposition rates for the nanocrystalline bottom cell in micromorph tandem solar cells; high rates compromise the opto-electronic properties of the bottom cell material, which have detrimental effects on the tandem solar cell performance
• High manufacturing cost of a-Si:H based modules due to the use of high vacuum plasma CVD reactor systems
• Inability to control film and junction uniformity over large areas for polycrystalline film modules
• Limited alternative deposition processes for high PCE cells and modules
• Challenge of determining pathways and kinetics for CIGS materials and cell growth
• Empirically optimized process with all junction formation processes interfering with each other
• Lack of in situ characterization tools for next generation deposition techniques
• Limited understanding of the role of cadmium chloride treatments in CdTe solar cells
Packaging
• Optical losses due to limitations of existing anti-reflection coating
• Most clear pathways to higher module PCE are already well explored
• Prevention of moisture ingress for flexible CIGS modules
• Lack of models to predict device performance with CdTe solar cells

Sources: Ullal, 2008; EERE, 2007c; EERE, 2007d; EERE, 2007b; IEA, 2009a; Kurtz, 2009a

2.2.4 Measurement Issues

Some tools and techniques from the manufacturing of other industrial products have been adapted to the solar sector. However, solar specific measurement tools are needed to increase solar manufacturing yield and reduce overall system cost. As noted earlier, measurement issues are not generally the focus of R&D challenges identified the literature, but are an important underlying element. As a result, the measurement issues identified in the literature are not necessarily complete or robust. Some of the reported measurement issues include the following:

- Development of in-line diagnostic tools and systems to enhance process control, such as high speed defect detection

- Advancement of thin film deposition techniques
- General development and standardization of accelerated life testing
- Design of measurement methods that are sufficiently quantitative to determine the moisture permeation rate through barrier layers used to encapsulate large-area, flexible electronics and photonics devices
- Methods and metrics for assessing the value of different device-processing schemes and their scale-up potential
- In-situ, real time thickness and compositional measurement instruments for roll-to-roll systems to allow longer rolls and more production uptime

2.3 III-V Multi-Junction PV

PCEs in the range of 30% are currently achieved in triple-junction solar cells under concentrated solar illumination. There are many core technological challenges, some related to the extreme illumination conditions and others related to concentrators. These include non-uniform illumination, localized heating, solar spectrum modification, current matching for different solar spectra, series resistance, and materials and device fatigue/reliability.

2.3.1 Development Status

III-V multi-junction cells have been widely employed in space applications where the reduced size and weight are top criteria. Their use of the majority of CPV systems in terrestrial applications, has mostly been developed in the last few years. Wide investment in CPV companies only began when installations of fields of PV systems became popular. Thus, the development of CPV systems lags behind that of the other technologies because of the relatively smaller investment. Because of the recent laboratory scale achievement of greater than 40% efficient concentrator cells, and an evolving understanding of the concentrator optics, commercial deployment of CPV using highly efficient III-V cells has been on the rise over the last few years.

2.3.2 Target Markets

Because they are expensive but offer high PCE, III-V multi-junction cells are mostly used in high concentration (>100x) CPV applications (where less PV needed means less overall cost) and space applications (where the high PCE is critical to reduce weight). In terrestrial CPV applications, reducing the amount of required PV cell material results in decreased costs and allows use of high PCE (and expensive) cells. Either refractive (e.g., Fresnel lenses) or reflective (e.g., dish shaped mirrors) are used to focus sunlight onto the relatively small multi-junction solar cell.

Current commercial terrestrial CPV products are most suited to solar farm settings; however, new products are being developed for installation in other locations such as commercial and residential rooftops. Some challenges to CPV designs include dealing with elevated temperatures, optical losses, and misalignment. Expansion of the multi-junction market is limited by manufacturing automation, risks associated with an unproven product, and limited available financing. (Kurtz, 2009b)

2.3.3 Technology Challenges

Some technological challenges reported in the literature are related to the extreme illumination conditions and concentrators. These include non-uniform illumination, localized heating, solar spectrum modification, current matching for different solar spectra, series resistance, and materials and device fatigue/reliability (Table 2.4). Overcoming packaging challenges are also essential to maintain reliability. Packaging must reliably keep water out, be resistant to ultraviolet (UV) light, resist effects of temperature cycling and high temperatures, be inexpensive, and provide a transparent front packaging.

Table 2.4

Technology Challenges Reported in the Literature for III-V Multi-Junction PV

Materials
• Insufficient understanding of the reliability of materials and devices used in CPV systems • No standardization of methods for accelerated optical testing with high concentrations • Minimizing effects of non-uniform illumination and localized heating • Understanding the effect of in situ stress during metalorganic vapor phase epitaxy growth of high-PCE, lattice-mismatched III-V multi-junction solar cells • Understanding of the benefits/challenges of the different ways of tuning the optical properties (use of metamorphic approaches compared with use of quantum structures)
Cells and Interconnects
• Overcoming series resistance at higher concentrations • Acquiring data on cell reliability under concentration • Improving spectral utilization and handling spectral variations • Current matching for different solar spectra • Optimizing cell construction for use under high concentration • Reduction of cell cost fraction of total system cost, possibly by reducing required semiconductor material • Customization of receiver design in CPV applications • Designing techniques for nano- and macro-scale material coupling • Achievement of theoretical concentrator potentials and cost-effective solutions with additional optical research • Identifying cell-mounting strategies that are low cost (manufacturable) but high performance, including high reliability
Manufacturing Processes
• Need automation tools for manufacturing processing and testing • Optics fabrication at reduced cost • Achievement of economy of scale is needed
Substrates
• Need additional suitable substrate materials • Reduction of substrate costs as a fraction of total system cost
Packaging
• Inadequate tests for determining reliability of prototypes; from detailed understanding of individual failure mechanisms to field-testing • Improving anti-reflection coatings • Insufficient approaches for dealing with excess temperature in CPV applications • Need to protect cells and optics from dirt and water without causing other problems such as overheating • Reducing effects of wind and optical losses in CPV applications • Testing of cell bond to heat sink; thermal contact must be maintained to avoid catastrophic failures • Establishing a short history of field testing • Integration of custom-designed receivers with optics in CPV applications • Inadequate stability of materials in optical path

Sources: Kurtz, 2009b; EERE, 2007e.

2.3.4 Measurement Issues

There are a number of measurement challenges that impact the further development of multi-junction cells. These are generally related to device and materials characterization and testing for reliability and performance. As noted earlier, measurement issues are not generally the focus of R&D challenges identified the literature, but are an important underlying element. As a result, the measurement issues identified in the literature are not necessarily complete or robust. Some of the reported measurement issues include the following:

- Lack of tools to measure defect structure and interface phenomena in lattice mismatched materials
- General development and standardization of accelerated life testing
- Need for measurements of spectral and spatial flux distribution at the focal plane/line/point of concentrating solar systems, reducing compounding errors from multiple independent measurements
- Development of concentrating solar simulator approximating solar beam radiation in amplitude and divergence
- Reduction in measurement time and uncertainty of evaluating multi-junction devices at 1-sun; energy production as a function of spectral irradiance, total irradiance, and temperature should be measured

2.4 Excitonic and Quantum-Structured PV

This section includes discussion of solar cells whose absorber layers rely on quantum physics (i.e., confined excitons). At least three different excitonic and quantum-structured solar cell technologies are currently being explored: organic-based, dye-sensitized, and quantum dot/wire technologies. Such solar cells exhibit laboratory PCEs of up to 11%. Numerous challenges exist, both fundamental and technological, to achieving broader commercialization. These include a fundamental understanding of the complex microstructure, photophysical processes, charge separation, charge transport, electronic structure/trapping, contacts and series resistance, spectral matching, and materials and device stability. Other technological challenges include development of processing-property relationships among the molecular structure / microstructure / device performance, and the lack of existing manufacturing base / infrastructure and data on long-term reliability. In general, there is a lack of theoretical models on all levels from device physics to materials processing.

2.4.1 Development Status

These technologies are classified as 3rd generation technologies, with development to commercial-scale beginning to emerge after years of R&D. 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 currently in the 5% to 8% range (Table 2.1), with research scale efficiency recently reaching 9.7% (Figure 2.1). Some limited commercial scale manufacturing of dye sensitized cells is in place; however, more efficient technologies are still in the development stage. Module efficiencies for dye-sensitized cells are in the 8% to 11% range. In general, quantum-structured PV remains in the research phase.

The emerging nature of these technologies has attracted investment from both government and private sources. The DOE, through programs such as the Solar America Initiative and American Recovery and Reinvestment Act, is funding over $40 million to develop excitonic and quantum-structured PV technologies. venture capital and other private investment in this area have yielded over $200 million of investment over the past few years. (GTM Research, 2009)

2.4.2 Target Markets

While organic-based and dye-sensitized PV technology cannot match the reliability and PCE of wafer-based silicon PV, the low-cost, low-weight, and flexibility of these technologies allow for the targeting of a distinct range of burgeoning target markets. These target markets include low-power consumer and commercial electronics (e.g., mobile phones, solar chargers), off-grid applications, outdoor recreational applications (e.g., clothing, tents), and on-grid applications such as BIPV. Organic-based technology is expected to target additional lower power consumer applications, while dye-sensitized PV will target more of the larger area BIPV applications. (GTM Research, 2009)

It is still unclear which of these target markets will fully mature as these technologies increase efficiencies and develop greater technology reliability. Some of the factors that could limit or inhibit growth in these markets include the extent of cost reduction the technology offers (i.e., dollar per watt), the development of a simple and reliable production-scale manufacturing process, and the extent of consumer acceptance or added value to existing products.

2.4.3 Technology Challenges

The literature reports a number of challenges to achieving broader commercialization of excitonic and quantum-structured PV devices (Table 2.5). These include a fundamental understanding in many important areas, such as microstructure, photo-physical processes, charge separation, charge transport, electronic structure/trapping, contacts and series resistance, spectral matching, packaging, and materials and device stability. Other challenges include prediction of device performance, the lack of existing manufacturing base, and limited infrastructure and data on long-term reliability.

Table 2.5

Technology Challenges Reported in the Literature for Excitonic and Quantum-Structured PV

Materials
• Improving understanding of organic materials and device physics including excitons, charge transport, recombination, band structure, and interfaces
• Increasing stability of organic materials by addressing issues such as redox, recrystallization, and temperature fluctuations
• Developing new materials to optimize light absorption, band structure, conducting, and transport properties
• Improving understanding of the fundamentals of material effects on the device physics of dye-sensitized solar cells
• Enhancing temperature stability of electrolyte solution, e.g., freezing, thermal expansion, and volatility issues, in dye-sensitized solar cells
• Reducing UV degradation in dye-sensitized and organic solar cells
• Designing molecular structure to maximize charge transport in excitonic and quantum-structured PV
• Understanding energy level alignments at the donor/acceptor interface
• Characterizing structural and electrical properties, on the atomic and nanometer scale, of nanocrystalline grains, grain boundaries, amorphous tissues, and voids
Cells and Interconnects
• Improving interfacial adhesion and electrical coherence of interfaces to increase PCE and stability of organic solar cells
• Incorporating third-generation mechanisms theoretically capable of exceeding the Shockley-Queisser limit
• Identifying degradation mechanisms in organic solar cells
• Optimizing donor-acceptor morphologies in organic soar cells
• Improving sensitizers, nanostructured architectures, and charge conducting phases in dye-sensitized solar cells
Manufacturing Processes
• Developing high-throughput, large-area manufacturing techniques that maintain small area cell quality
• Development and scale-up of inexpensive bulk manufacturing techniques
Substrates
• Alternative substrate materials to lower the cost or for specific applications

Table 2.5
Technology Challenges Reported in the Literature for Excitonic and Quantum-Structured PV

Packaging
• Understanding packaging requirements needed in organic, dye-sensitized, quantum-structured solar cells • Developing long-term degradation testing and identification of degradation mechanisms in organic solar cells • Optimizing device architecture, including active layer, buffer layers, and conducting oxide materials in organic, dye-sensitized, quantum-structured solar cells • Establishing indoor and outdoor reliability tests to further define failure modes

Sources: EERE, 2007f; EERE, 2007g

2.4.4 Measurement Issues

As is typical of technologies in the exploratory or early research phase, a number of fundamental research and measurements issues remain to be addressed for organic, dye-sensitized, and quantum-structured PV cells. Many of these are related to characterization and assessment of materials, including structure and properties.

As noted earlier, measurement issues are not generally the focus of R&D challenges identified the literature, but are an important underlying element. As a result, the measurement issues identified are not necessarily complete or robust. Some of the measurement challenges identified in the literature include the following:

- Accelerated life testing
- Metrology/infrastructure to support scalable synthesis
- Advanced modeling tools
- Advanced characterization tools (e.g., high brightness synchrotron sources, time-resolved in situ neutron measurements, etc.)
- Data that assess material performance at nanoscale interfaces
- Advanced optical methods (e.g., ultrafast, Raman, and nonlinear spectroscopies) to directly probe carrier dynamics affected by the nanoscale structure and defects in polymeric and mixed-organic films
- In situ characterization to directly establish process, structure and property relationships
- Rapid measurements of nano-structure assembly, disassembly, and response to stimuli
- Better understanding of physical/chemical mechanisms; measurement methods with spatial and temporal resolution for nanoscale structure, combined with spectroscopic/physical parameter measurement are required, to gain insight into charge generation and transport processes in nano-structured materials
- Non-destructive molecular scale characterization methods at interfaces with sufficient depth resolution, chemical resolution, and sensitivity
- Sufficient understanding of defect generation, bias and temperature induced instabilities, wear-out, and breakdown is required to develop new reliability testing and lifetime projection methodologies
- Measurement of prototype reliability for emerging solar PV technology

2.5 Cross-cutting Technical Issues

2.5.1 Nanoscience and Technology

In addition to the quantum-structured PV applications covered under excitonics, nanoscience and technology will be a potential cross-cutting issue for discussion all breakout sessions during the upcoming workshop. These will likely emphasize applications where the nanoscale phenomena are secondary to device physics (e.g., light capture, contacts). Advances in nanotechnology have many applications in the PV industry that could increase performance, among other benefits.

Two cross-cutting approaches are likely: (1) semiconductor quantum structures, such as quantum dots and wells, which may be embedded/incorporated into traditional semiconductor systems (in particular, thin Si:H and III-V's) 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. The use of nano-engineered structures allows one to tune / expand the spectral response, enhance the local fields, excite multiple excitons from a single photon, or upconvert infrared photons, thus providing possible routes individually or in combination toward substantial (revolutionary) gains in PCE.

The properties of quantum wells, quantum dots, and superlattices can be used to alter the relaxation dynamics of photoexcited electrons in PV cells. For example, the Auger mechanism is one method used to cool "hot electrons" (i.e., electrons that have excess kinetic energy equal to the difference between the photon energy and the bandgap). The use of quantum dots in PV cells can lead to quick electron relaxation via the Auger mechanism. (Nozik, 2006)

Nanostructures can also be used to enhance PV cell light trapping ability. For example, a distributed Bragg reflector (DBR) is a wavelength-specific mirror that is fabricated using alternating layers of high and low refractive index material. The DBR can be useful for multi-junction cells in order to reflect any light that is not initially absorbed by the PV cell, allowing the light to be reflected and absorbed. (Marti and Luque, ed., 2004)

3 PHOTOVOLTAIC RELATED STANDARDS

Development of PV standards is in continuous flux, driven by many factors including requirements for addressing novel technologies, lower measurement error tolerances, the need for guarantees of product reliability, and installation safety. Historically, many PV standards were developed by the Jet Propulsion Laboratory Flat-Plate Solar Array Project and were adapted from the Space PV industry, with new standards development activities arising as PV specific issues were identified. Some PV standards are in widespread use and have been created and refined over the decades. New technologies, different applications, and market forces have created unresolved standards needs, which have become increasingly urgent as the industry continues to grow.

PV standards are created by a multitude of standards organizations worldwide. In general, greater numbers of standards exist in areas of the world where the PV industry has been especially active. Standards are created on a local, national, or international level, depending on the mission of the issuing agency, scope of the standard, and level of acceptance. As such, a standards gap existing in one region of the world may not exist in another. The table in Appendix A summarizes the PV related activities of international standards development organizations and those from major PV markets. The table is not an exhaustive list but rather serves as an example of the various organizations involved in PV standards development. One prominent international standards organization in the PV arena is the International Electrotechnical Commission (IEC). The IEC Technical Committee TC82: Solar PV Energy Systems, established in 1981, covers topics such as solar glossary, non-concentrating and concentrating modules, BOS components, and PV system design, construction and maintenance.

Standards organizations generally fall into three categories: a National Standards Board (NSB) organization, a standards developing organization (SDO), and a standards setting organization (SSO). Inclusion of an organization in one of these three categories does not necessarily preclude it from another category. One NSB, which can be either a public or private sector organization, usually represents a country as a member of the International Organization for Standardization (ISO) and participates in international standards setting activities. A SDO, which may be coordinated by an NSB, is usually an industry-based organization that develops and publishes industry-specific standards on a national level. Some international SDOs (e.g., IEEE) may directly affect the development of global standards without going through the NSB.

Due in part to bureaucratic obligations, the standards setting activities of the NSBs and SDOs may not keep pace with an industry's development and needs, spawning the growth of SSOs, which are industry consortia. The SSOs can also promulgate standards to fill an industry's need, which may be adopted locally, nationally, or internationally.

While many organizations have had an interest in developing standards for the

Figure 3.1

Standards Gaps Identified by Solar ABCs

- Accelerated Lifetime Testing
- Code Revisions (e.g., NEC, building and fire)
- Wind Load Issues
- PV Module Rating Tolerance
- Recommended Datasheet and Nameplate Information Formats for PV Modules
- Standard to Certify the Accuracy of Inverter Meters
- Definition of the Procedure for System Energy Rating
- Review of Federal Energy Regulatory Commission's (FERC) Interconnection Screens
- Rate Impact of Net Metering
- Evolution of Net Metering
- Potential Impacts of Advanced Metering Infrastructure on Renewable Energy Policy
- Potential of AMI Data to Reduce the Technical Issues Related to Net Metering
- PV Module Frame Grounding Requirements and Test Methods
- Guidebook to the California State Fire Marshall PV Guidelines

Source: Solar ABCs, 2008

PV industry, some of the efforts have resulted in duplicated standards leading to confusion. Several groups have formed worldwide, such as the Solar America Board for Codes and Standards (Solar ABCs), to coordinate efforts of identification of gaps in PV standards and minimization of duplication; ultimately aiming for a cohesive set of standards for the PV industry. Normally these efforts do not produce a standard but rather recommendations to the standard production organizations discussed previously. These efforts are extremely useful in the coordination of industry professionals from along the supply chain, researchers, governing agencies, and standards organizations.

Many standards organizations develop PV industry standards, resulting in a somewhat fragmented standards landscape. Collaborative efforts between PV stakeholders, such as the Solar ABCs, are identifying and addressing standards gaps including those shown in Figure 3.1.

The standards discussion below has been divided into the following categories along the PV supply chain. While each category has its own unique standards needs, there are also issues that cut across all the categories, such as prediction of long-term product performance and safety.

- Material Standards
- Component Standards
- Module Testing Standards
- Manufacturing Standards
- Installation Standards
- Interconnection Standards

Cross-cutting Issue: Standards for Product Performance

One major issue involves prediction of long-term product performance with sufficient accuracy to forecast project economics. Slight variances in these measurements and the associated errors are compounded throughout the project development process, including determination of project risk and loan interest rates, and can result in variances of millions of dollars in project profit. To correctly determine product performance, a number of standards are needed:

- *module testing standards to determine product performance*
- *manufacturing standards to ensure the inputs and outputs are within acceptable tolerances*
- *installation standards to maximize the potential of the PV product*

Each country or global region presents unique challenges and gaps with respect to PV standards. In the rapidly expanding Chinese market, the Standardization Administration of People’s Republic of China has created 29 voluntary PV standards (and no mandatory ones), most of which are coordinated with IEC standards. In the more mature market, the European Committee for Electrotechnical Standardization adapts or adopts IEC standards to publish European centric standards.

3.1 Material and Component Standards

Material standards encompass not only the raw feedstock materials used in absorber production, but also materials used in all components of the module. Assurance of material quality within required specifications is critical to achieving designed PCE and reliability. Some recently identified deficiencies in material standards which potentially have some relation to absorbers and components include:

- More stringent materials standards to account for open circuit arcing fault failures in polymeric materials

Examples of Component Standards

- IEEE 1547: Standard for Interconnecting Distributed Resources with Electric Power Systems
- ISO 14121: Safety of machinery - Risk assessment
- ISO 13849: Safety of machinery - Safety-related parts of control systems
- UL 1741: The Standard for Static Inverters and Charge Controllers For use in Photovoltaic Power Systems
- UL 508A: Industrial Control Panels
- UL 1740 :Standard for Safety Robots and Robotic Equipment

- Expansion of standards to include direct contact/direct support requirements similar to other Underwriters Laboratory (UL) categories due to increased use of a variety of encapsulants by the PV industry
- Possible adjustment of standards for materials, including backskins/substrates and superstrates and pottants
- Development of standards relating to the impact of PV on roofing materials (EERE, 2009)

In addition to the quality of raw materials used to make PV module components, the quality of the component fabrication and the interconnection between them are also very significant.

3.2 Module Testing Standards

Module testing standards are critical to the rating of a PV product, which has far reaching effects including interest rate determination for project financing. While these tests are critical to the PV industry, many are expensive and require a specialized test facility, such as the National Renewable Energy Laboratory's Outdoor Test Facility. While some standards, such as ISO 17025: Quality Assurance Accreditation, provide for the quality of the lab performing the work, other standards prescribe the procedure to be followed during testing (e.g., ASTM 2236: Standard Test Methods for Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multi-junction PV Cells and Modules).

Accurate accelerated lifetime testing is a major need for all types of PV products. The most common failure modes from installed systems need to be identified and used as input for modifications to accelerated lifetime testing. Identification of potential failure modes allows test procedures to be developed such that potential failures are correctly stimulated. If a potential failure is missed the reliability may be incorrectly assessed. Reliability issues include arcing, interconnection breaks, back sheet crumbling, and junction box cracking.

Examples of Module Related Standards

- EN 50380: Datasheet and nameplate information of photovoltaic module
- IEC 60891: Procedures for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic devices
- IEC 60904: Photovoltaic devices
- IEC 61345: UV test for photovoltaic (PV) modules
- IEC 61646: Thin-film terrestrial photovoltaic (PV) modules
- UL 1703: Standard for flat-plate photovoltaic modules and panels

3.3 Manufacturing Standards

These standards cover the entire manufacturing chain including ingot generation, slicing, deposition techniques, quality control, and equipment interconnection. Manufacturing standards maintain quality between various steps in the manufacturing process. Some major manufacturing standards issues include:

- Purity of silicon feedstock
- Echant materials/gases
- Glass substrates/coatings

Examples of Manufacturing Standards

- BS EN 50513: Data sheet and product information for crystalline silicon wafers for solar cell manufacturing
- SEMI PV1-0709: Test method for measuring trace elements in silicon feedstock for silicon solar cells by high-mass resolution glow discharge mass spectrometry
- SEMI PV2-0709: Guide for PV equipment communication interfaces (PVECI)
- SEMI PV3-0310: Guide for high purity water used in PV cell processing

3.4 Installation Standards

PV installations are regulated in part by the National Electric Code (NEC), building codes, and fire codes, which can vary state-to-state. System designers, installers, and inspectors are vital to proper, safe, and reliable system installations. However, some state codes/regulations conflict with industry standards, leaving the installer to interpret the correct procedure. Improperly installed systems can shorten component lifetimes or have more serious consequences such as instigating a fire with potential harm to life and property.

Due to double and triple digit solar concentrations, CPV also presents unique issues for safety (e.g., potential vision damage to humans and animals) and testing (e.g., deployed systems usually operate at much higher temperatures than used in regular test procedures). One comprehensive CPV safety standard does not exist. CPV standard IEC 62108 prescribes the evaluation of extended exposure in specific climates by measurement of electrical, mechanical, and thermal CPV system characteristics. International CPV safety standard efforts aim to create standards compatible with IEC 62108.

Although many existing standards govern PV installations, either by specifically targeting PV or as part of broader codes such as NEC, there are several gaps that need to be addressed, including:

- Requirements for grounding PV equipment
- Life time reliability testing of grounded components
- Fire safety of PV systems, whether ground mounted or integrated into a building structure
- Test methods for arcing
- Integration of PV installations into building codes and material standards
- Distinction in the standards between reliability and durability
- Unique challenges of BIPV, building applied PV, and other direct-adhered PV

Examples of Installation Standards

- NFPA 70: National Electric Code (and state or local amendments)
- IEC 62108: Concentrator photovoltaic (CPV) modules and assemblies
- State and local codes relating to buildings, fire, or safety (e.g., California Code of Regulations, Title 24, the California Building Standard Codes or California Health and Safety Code Section 13869.7 for Fire Protection Districts)

3.5 Grid Interconnection Standards

Interconnection standards regulate technical, legal, and bureaucratic obligations for connecting a PV system to the electrical grid. These country specific standards usually include technical specifications, contractual stipulations, and rate agreements to which PV owners and utilities must comply. In the U.S., state public utility commissions usually set standards for PV systems connected at the distribution level, while transmission level connections are regulated by the FERC. Approximately 38 states plus the District of Columbia and Puerto Rico have adopted interconnection policies, 13 of which only apply to net-metered systems. Compatibility issues between regulations, policies, and interconnection standards must be addressed as the PV industry grows. Interconnection standards are very important to achieve compatibility and ensure the safety of electrical grid workers. In addition, BOS components have been added to this category.

Related standards creation efforts are underway for issues peripheral to PV but that definitely have an effect on the PV industry. One example is the NIST Framework and Roadmap for Smart Grid Interoperability Standards (NIST, 2010), which aims to standardize rapidly developing smart gird technologies, and incorporates renewable energy sources such as PV.

Examples of Grid Interconnection Standards

- IEC 61727: PV systems - characteristics of the utility interface
- IEC 62116: Test procedure of islanding prevention measures for utility-interconnected PV inverters
- IEEE 1547: Standard for interconnecting distributed resources with electric power systems
- IEEE Standard 929-2000, Recommended practice for utility interface of PV systems
- UL 508c: Power conversion equipment
- UL 1741: Inverters, converters, controllers and interconnection system equipment for use with distributed energy resources

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5 ACRONYMS

a-Si	amorphous silicon
BIPV	building integrated PV
BOS	balance of system
CdTe	cadmium telluride
CIGS	copper indium gallium (di)selenide
CPV	concentrating photovoltaic
CVD	chemical vapor deposition
DBR	distributed Bragg reflector
FERC	Federal Energy Regulatory Commission
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
MW	megawatt
NIST	National Institute of Standards and Technology
NSB	National Standards Board
PCE	power conversion efficiency
PV	photovoltaic
R&D	research and development
SDO	standards developing organization
Solar ABCs	Solar America Board for Codes and Standards
SSO	standards setting organization
UL	Underwriters Laboratories
UV	ultraviolet

APPENDIX A: PHOTOVOLTAIC STANDARDS EFFORTS

The table below contains a partial listing of organizations involved in developing standards for the PV industry.

Organization	Solar Related Efforts	URL	Solar Contact / e-mail
American National Standards Institute (ANSI)	ANSI represents the U.S. within ISO. As such, they are involved with the coordination and development of PV standards.	http://www.ansi.org/	Not available
ASTM International	E44.05 Solar Heating and Cooling Systems and Materials; E44.09 Photovoltaic Electric Power Conversion; E44.20 Glass for Solar Applications	http://www.astm.org/COMMIT/COMMITTEE/E44.htm	Committee Manager: Christine DeJong cdejong@astm.org
Deutsches Institut fur Normung (DIN)	The DIN formed a technical committee DKE/K 373: Photovoltaische Solarenergie-Systeme to address PV standards needs.	http://www.dke.din.de/cmd?level=tpl-untergremium-home&committeeid=54738887&search_grem_akt=54758548&subcommitteeid=54758548&languageid=en	Arno Bergmann
European Committee for Electrotechnical Standardization (CENELEC)	Technical Body CLC/TC 82: Solar photovoltaic energy systems, aims to support the accelerated market PV introduction through harmonization of standards. CLC/TC 82 works with IEC TC 82 and the National Committees to develop PV standards especially where there are special European Concerns.	http://www.cenelec.eu/Cenelec/Homepage.htm	Not available
Fraunhofer-UMSICHT	Fraunhofer UMSICHT develops applied and custom-made process engineering technologies.	http://www.umsicht.fraunhofer.de/englisch/	Not available
Institute of Electrical and Electronics Engineers (IEEE)	IEEE SCC21 – Standards Coordinating Committee on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage	http://grouper.ieee.org/groups/scc21/	SCC21 Chair Richard DeBlasio Dick.DeBlasio@nrel.gov
International Electrotechnical Commission (IEC)	Technical Committee 82 Solar Photovoltaic Energy System (TC-82). Five working groups: 1) glossary; 2) modules, non-concentrating; 3) systems; 6) balance-of-system components; 7) concentrator module. A joint committee working group on decentralized rural electrification also exists.	http://www.iec.ch/dyn/www/f?p=102:7:0::::FSP_ORG_ID:1276	Chairman Mr Heinz Alexander Ossenbrink (DE)

Organization	Solar Related Efforts	URL	Solar Contact / e-mail
International Organization for Standardization (ISO)	TC180. Scope: Standardization in the field of solar energy utilization in space and water heating, cooling, industrial process heating and air conditioning.	http://www.iso.org/iso/iso_technical_committee?commid=54018	Secretary Mr. Max Maffucci max.maffucci@standards.org.au
IPC - Association Connecting Electronics Industries	The IPC Solar Standards Committee was formed in 2009 to focus on the following issues: 1) Acceptability guidelines for solar panel lamination; 2) Specification for materials used in tabbing and stringing; 3) Acceptability criteria for tabbing and stringing; 4) In-process test methods for solar panels; 5) Visual acceptance criteria for solar panels - final module assembly; 6) Guidelines for final test with an emphasis on flash test; 7) Design guidelines for tabbing and stringing.	http://www.ipc.org/ContentPage.aspx?PageID=IPC-Standards-Development-Efforts-Radiate-Into-Solar-Industry	Anthony Hilvers IPC vice president of industry programs (847) 597-2837 AnthonyHilvers@ipc.org.
Japanese Industrial Standards Committee, Ministry of Economy, Trade and Industry	This committee represents Japan within the ISO and is an observer member of ISO TC 180 for Solar Energy.	http://www.jisc.go.jp/	Not available
Japanese Standards Association (JSA)	Publishes standards for the PV industry.	http://www.jsa.or.jp/default_english.asp	Not available
National Electrical Code* (administered by National Fire Protection Association)	Article 690 of the NEC (NFPA-70) is dedicated to PV systems. However, the majority of the NEC also applies to PV system installation.	http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=70&cookie%5Ftest=1	James W. Carpenter, Chair International Association of Electrical Inspectors, TX
PowerMark Corporation	PowerMark was formed to provide PV manufacturers with a certification program to certify the module's quality, through the process of product labeling, licensing manufacturer to use a Certificate of Conformity, laboratory accreditation, and a program based on U.S. and international standards.	http://www.powermark.org	Not available
SAC (Standardization Administration of China)	The SAC represents China within the ISO and was authorized by the State Council of China to coordinate standardization work within China. As such, solar standards will be	http://www.sac.gov.cn/templet/english/	Not available
Semiconductor Equipment and Materials International (SEMI)	Current Standards Activities: Equipment Automation Hardware (E), Equipment Automation Software (E), Facilities (F), Flat Panel Display (D), Gases (C), Materials (M), MEMS (MS), Microlithography (P), Packaging (G), Photovoltaics (PV), Process Chemicals (C), Safety Guidelines (S), Silicon Materials & Process Control (MF), Traceability (T).	http://www.semi.org/en/Standards/index.htm	North America Representative Bettina Weiss bweiss@semi.org

Organization	Solar Related Efforts	URL	Solar Contact / e-mail
Spanish Association for Standardisation and Certification (Asociación Española de Normalizción y Certificación)	Develops solar standards for Spain in conjunction with international efforts.	http://www.aenor.es/desarrollo/inicio/home/home.asp	Not available
State Grid Electric Power Research Institute of China (SGEPRI)	Will partner with UL to advance standards and development practices for solar energy (along with renewables in general). SGEPRI will establish a National Solar Energy R&D Center, and undertake standards development, testing capabilities as well as technical evaluation and certification, and training.	http://njqiaoyou.com/html/about7.shtm	Not available
Underwriters Laboratories (UL)	Partnering with other countries to develop standards, including a recent agreement with China to develop PV standards.	http://www.ul.com	Not available