Foundations for Innovation:

Photovoltaic Technologies for the 21st Century

December 2010

Report of the Steering Committee for Advancing Solar Photovoltaic Technologies

STEERING COMMITTEE FOR ADVANCING PHOTOVOLTAIC TECHNOLOGIES

This report was prepared through the collaborative efforts of the individuals noted below. It reflects their expert contributions as well as the many excellent ideas generated at the *Grand Challenges for Advanced Photovoltaic Technologies and Measurements Workshop* held on May 12-13, 2010 in Denver, Colorado.[1]

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[1] *Workshop Summary Report: Grand Challenges for Advanced Photovoltaic Technologies and Measurements*. July 2010. http://events.energetics.com/NISTGrandChallenges2010/pdfs/AdvPV_WorkshopReport.pdf

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INTRODUCTION

Solar energy is the most abundant renewable energy resource on the planet. The solar energy that reaches the Earth's surface in less than one hour would be sufficient to satisfy the energy requirements of all human activities for more than one year.

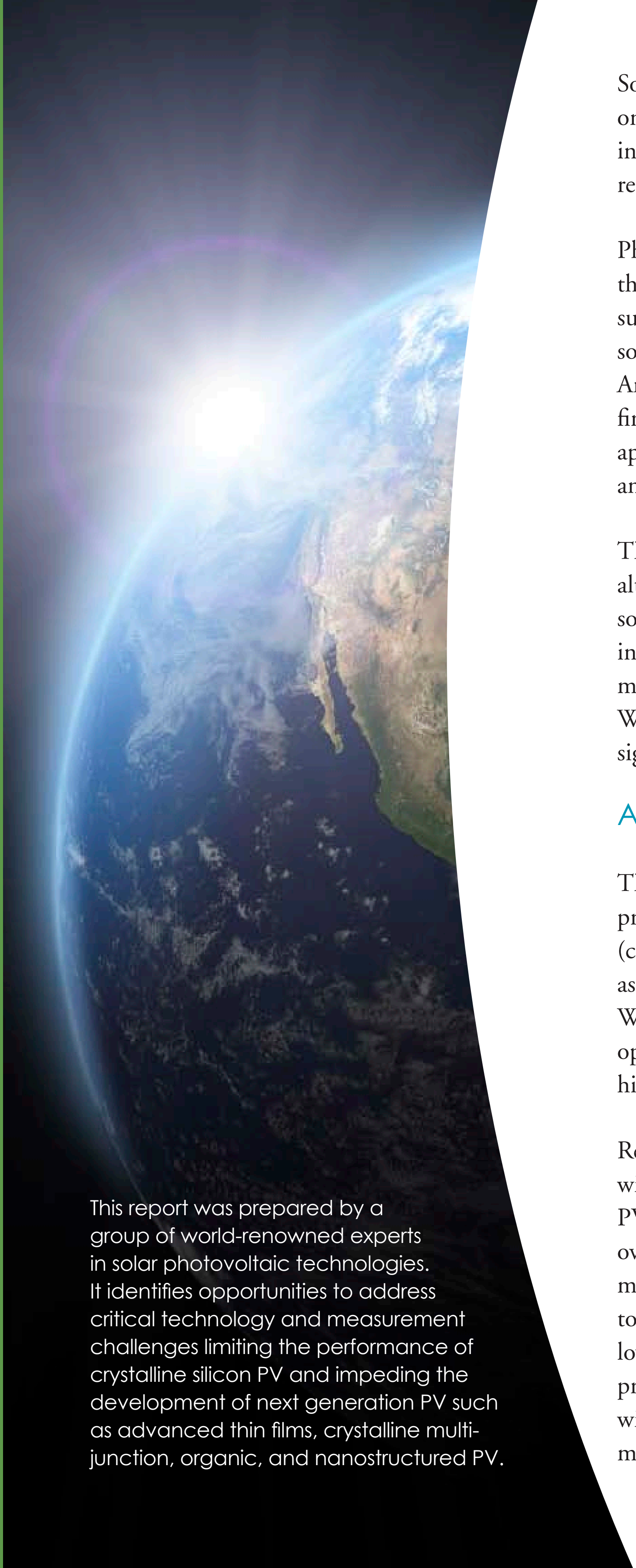
Photovoltaics (PV) refers to the generation of electric power through the use of PV or solar cells to convert the photons of sunlight directly into electric current. The modern form of the solar cell was invented in 1954 at Bell Telephone Laboratories. Arrays made from interconnected cells powered America's first space satellites. Today, PV modules in their terrestrial applications provide power for homes, commercial buildings, and industrial plants.

The limitless supply of solar energy makes PV an ideal alternative for power generation. At the same time, the use of solar energy avoids emissions from combustion of fossil fuels in power plants. Solar power generation is readily distributed, meaning greater security for the sources that supply the grid. With these attributes, PV technology has the potential for significant growth in nearly all regions of the globe.

A CALL TO ACTION

The future promise of PV is substantial. Conservative projections put worldwide annual capacity at 200 GW in 2020 (capacity increase of about 17% per year); others estimate as much as 300 GW in 2025 (IEA 2009, GreenTech 2011). While the U.S. share of this market today is small (about 8%), opportunities exist to grow this market share to 10%–20% or higher—as much as 15–20 GW.

Realizing the enormous economic potential from growth in PV will not be simple. While significant progress has been made in PV technology, a number of major challenges remain. While overall costs have been reduced, PV is not cost-competitive in most electricity markets. Advanced technologies will be needed to supply increased efficiency and overall higher performance at lower cost, and enable greater product diversity. Manufacturing processes will also need substantial improvements to keep pace with much higher product volumes. These advances are vital for meeting the unprecedented market expansion that is predicted.



This report was prepared by a group of world-renowned experts in solar photovoltaic technologies. It identifies opportunities to address critical technology and measurement challenges limiting the performance of crystalline silicon PV and impeding the development of next generation PV such as advanced thin films, crystalline multi-junction, organic, and nanostructured PV.

Next-generation technologies currently operate well below theoretical power conversion efficiencies (PCEs), but dramatic gains are possible if key problems can be solved. This may require a deeper fundamental understanding of the relationships between materials and performance, resulting in entirely new low-cost materials and approaches. As advanced technologies emerge, predictable ways of ensuring performance over module lifetime will be needed to gain market acceptance.

While technology is an integral driver, policy measures such as tax credits and renewable electricity credits will continue to provide stimulus for U.S. solar markets. Many states are now adopting portfolio standards that require 25% or more of their power to come from clean, renewable energy, and this will likely increase domestic demand. Compliance with state mandates is estimated to require about 9 GW of new solar capacity by 2025 or more than 550 MW per year—more than all U.S. PV installations in place today (LBNL 2010, SEIA 2010).

This report outlines a set of opportunities and "grand" technology and measurement challenges that must be addressed to ensure the widespread commercialization of PV technologies. Meeting these challenges head-on will help to ensure the place of PV in our nation's energy future.

> "By tapping America's entrepreneurial spirit and longstanding leadership in technology innovation, we can set a course for a prosperous sustainable economy —and take control of our energy future."
>
> *A Business Plan for America's Energy Future*. American Energy Innovation Council, June 2010

THE PHOTOVOLTAIC CELL

Photovoltaic (PV) cells, also called solar cells, are electronic devices that convert sunlight directly into electric power. The modern solar cells invented at Bell Telephone Laboratories in 1954 were made from crystalline silicon semiconductors, and crystalline silicon remains the dominant PV material. However, other semiconductors, including those deposited as thin films, are gaining a considerable share of the PV market.

Because solar cells are low-voltage devices, they are connected in a series string to yield a useful voltage. The string of cells is sealed in a weather-proof package called a module (or panel). PV products are sold in the form of modules, and not as individual cells.

A one-square-meter crystalline silicon module will produce about 150 watts of power under full or one-sun conditions. Two or more modules connected together form an array. Residential rooftop arrays are usually 2–6 kilowatts in size. Utility-scale arrays can be hundreds of megawatts (MW). Worldwide PV shipments in 2009 were about 7900 MW. Shipments in 2010 were about 17,300 MW, a year-over-year increase of 119% (Navigant 2011). In its early years, terrestrial PV was deployed only for remote applications, which usually required battery storage. Today, most PV is directly tied to the power grid.

> "The nation that leads the clean energy economy will be the nation that leads the global economy."
>
> *President Barack Obama, State of the Union Address, February 2008.*

REAPING THE BENEFITS OF PV

Expanding U.S. production capacity for clean, renewable energy technologies—of which PV is an essential component—will create unique opportunities for enduring, skilled jobs while ensuring that sustainable, secure energy options are available. Globally it is expected that the renewable energy industry will be worth trillions of dollars within the next 20 years.

Clean energy is an engine for economic growth and job creation. One study estimates that more than 42,000 existing U.S. manufacturers could experience growth based on an increasing demand for clean energy components (Blue Green Alliance 2010). The potential for new jobs is also impressive. A recent census shows 93,000 solar power industry jobs in the United States as of August 2010, and projects job growth of 26% over the next year compared with the 2% growth expected economy-wide. This represents about 24,000 net new jobs (Solar Census 2010).

Today, PV is one of the world's fastest growing energy technologies. In 2009, the global solar PV sector (modules, systems components, and installation) was valued at nearly $39 billion. Over the last decade the market has experienced an exciting growth rate of nearly 40% annually (Clean Edge 2010, IEA 2009).

Progress made to date in PV technology is impressive. Through the process of "learning by producing," the typical module cost has continued to decrease by 20% with every doubling of manufacturing output. Conventional PV technologies (primarily wafer silicon-based technologies such as polycrystalline thin film cadmium telluride) are now approaching grid parity at less than 10 cents per kilowatt-hour levelized cost of energy[2] for grid-connected systems. However, reaping the future benefits of PV will require new scientific insights, next-generation technologies, and automated manufacturing that advance today's state of the art—and thus improve the ability of the United States to compete in global markets.

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[2] Levelized cost of energy takes into account complete costs. These include installed system price and associated costs such as financing, land, transmission, operation and maintenance and insurance.

RISING TO THE COMPETITIVE CHALLENGE

Capturing a greater share of PV markets has become a competitive challenge for the United States. While domestic production has been growing rapidly, the United States today accounts for only 8% of global production, compared to 44% in 1996 (see Figure 2) (PV News 2010). The erosion of U.S. market share is largely the result of aggressive and subsidized production capacity ramp-up in Europe, Japan, China, and Taiwan. In Europe, where 77% of the PV market now resides, about 74% of total installed PV is imported; 50% of that is provided by China and Taiwan (SB 2010). Many countries are now investing heavily in renewable energy and manufacturing technology in general, with the hopes of gaining market leadership (Pew 2010, Breakthrough 2009).

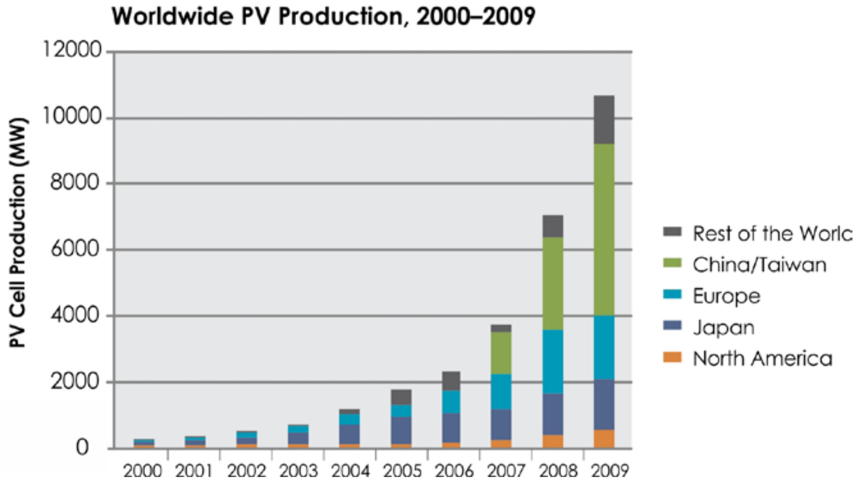
The predicted future growth of PV worldwide represents an extraordinary opportunity for the United States to create economic growth and new jobs, and gain a share of export markets. Advances in technologies must be pursued to realize these opportunities. When expansion occurs, those countries ready to step in with better technology and increased, cost-effective production capacity will be the best positioned to capture new markets.

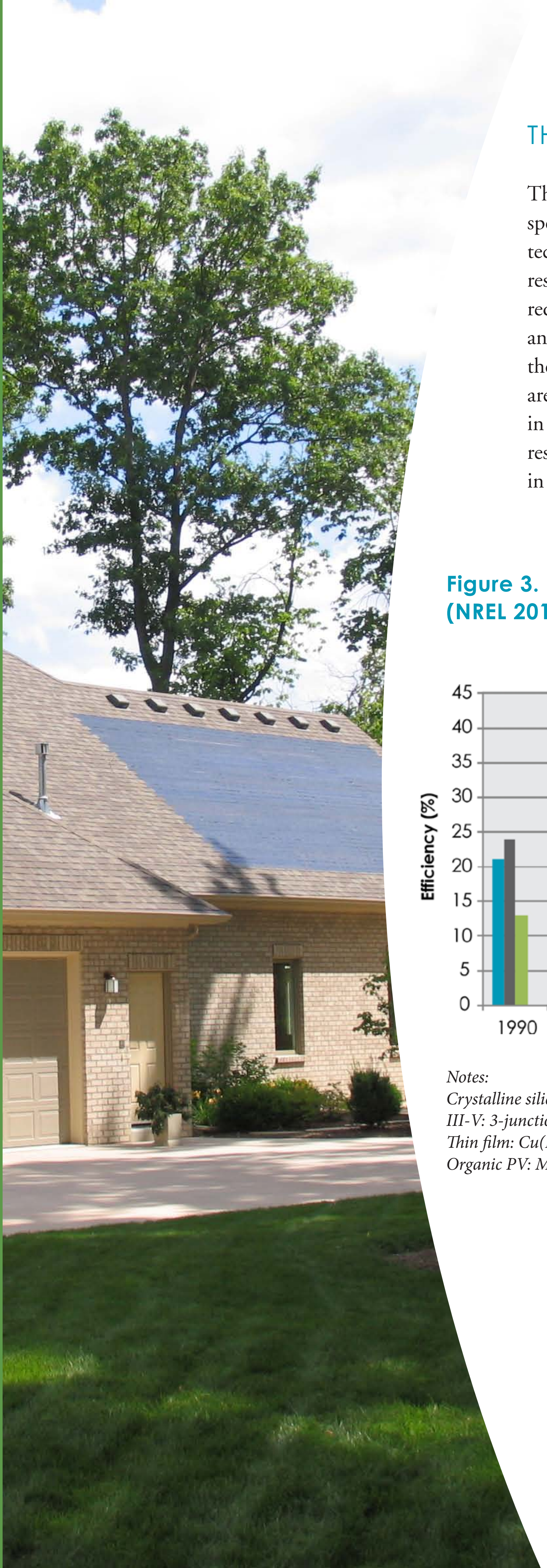
The pace of growth in PV shows little signs of slowing. Steps taken today to overcome the technical challenges of tomorrow—those impeding development of next-generation PV—will enable the United States to regain PV manufacturing leadership and be well-positioned to help meet world demand. Acting today, in anticipation of the massive worldwide expansion in PV installation, will help move the United States to the forefront.

The United States today accounts for only 8% of global PV production compared with 44% in 1996.

Global competition and market growth—a growing challenge and opportunity for U.S. PV manufacturers

Figure 2. Global PV Production (PV News 2010)

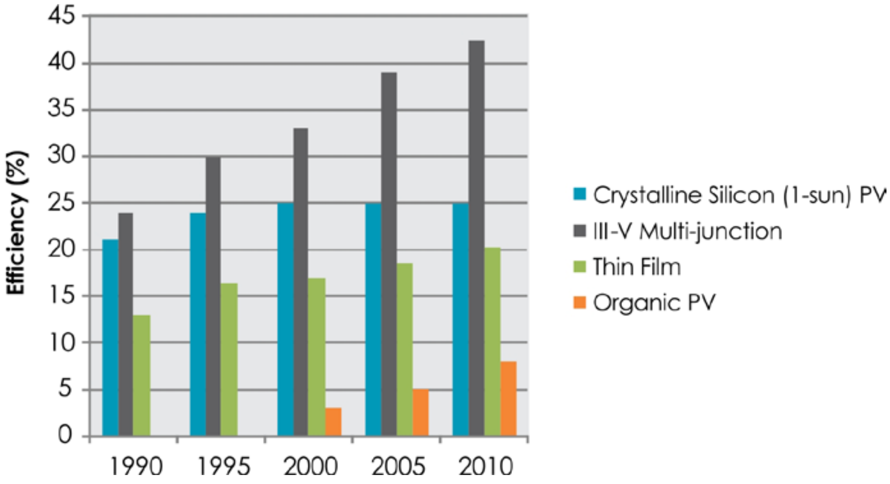




THE STATE OF PV TECHNOLOGY TODAY

The technology areas shown in Table 1 represent the full spectrum of the PV industry and are in varying stages of technology readiness, from commercial products to early stage research. All are undergoing efforts to improve performance and reduce manufacturing cost. However, the fourth area, excitonics and quantum-structured PV, is in a nascent stage. While still in the early stages of development, this next-generation technology area holds great promise for potentially disruptive improvements in performance and/or cost. Figure 3 illustrates the impacts of research efforts over the last two decades to improve efficiencies in all types of PV technologies.

Figure 3. Improvements in Best Research Cell Efficiencies (NREL 2010)



Notes:
Crystalline silicon PV: single crystal silicon
III-V: 3-junction from 2000-2010 and 2-junction in prior years, under concentrated light
Thin film: Cu(In, Ga)Se$_2$ *(CIGS) technology only*
Organic PV: Mix of technologies

TABLE 1. CHARACTERISTICS OF PV TECHNOLOGIES

	Wafer-based crystalline silicon	Amorphous silicon and polycrystalline thin films	III-V multi-junction[1]	Excitonics & quantum-structured
Efficiencies (%)				
Research Cell	Monocrystalline: 25 Multicrystalline: 20	a-Si:H: 13 CdTe: 17 CIGS: 20	42	OPV: 8 DSSC: 11
Best Module Prototypes	Monocrystalline: 20–21 Multicrystalline: 17–18	a-Si:H: 10–11 CdTe: 13 CIGS: 13-14	30	OPV: <5 DSSC: 10 (specialty products)
Commercialized Module	Monocrystalline: 16–20 Multicrystalline: 13–16	a-Si:H: 6–10 CdTe: 8–11 CIGS: 7–12	27-30	OPV: 3 DSSC: 6–8 (specialty products)
Applications and Stage of Development				
Applications	Flat panel arrays used in homes, commercial buildings, and utility-scale plants	Building integrated PV such as roof shingles and building coverings; flexible products; commercial roof tops (a-Si:H); utility-scale power plants (CdTe on glass rapidly meeting demand)	Concentrating PV; utility-scale deployment; technology of choice for outer space applications (flat-plate configuration)	Small lightweight consumer applications (OPV) and some building integrated prototypes (DSSC)
Stage of Development	Most widely used technology with approximately 85% of the global PV market A long track record of use exists, including historical reliability data	Second largest market share, much of which is in CdTe on glass for utility-scale applications Many products are still in development to increase efficiency and quantify reliability	Slow adoption for terrestrial applications due to system cost and requirement for clear sky environments, such as U.S. Southwest	Mostly in the research stage OPV and DSSC are in limited early-stage commercial production for specialty consumer and building products

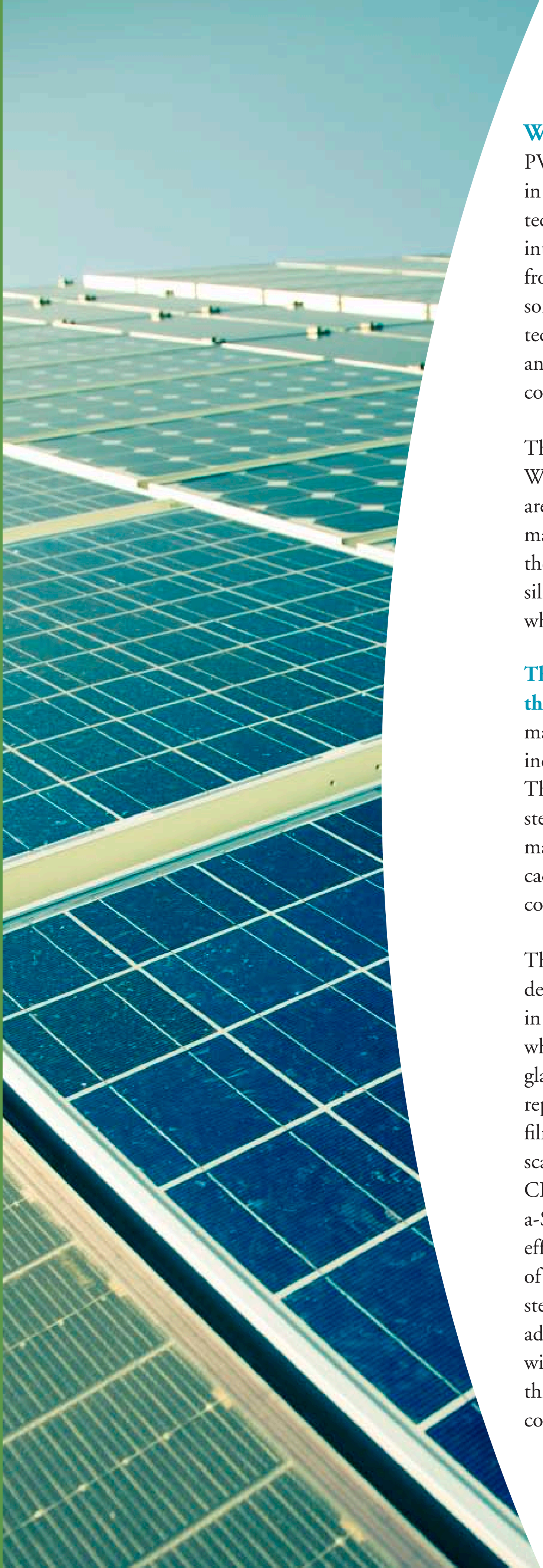
1. Reported multijunction efficiencies are under concentration.

Sources: Crystalline Silicon: Schott 2010; Sun Power 2010; NREL 2010; Navigant 2010.
Thin Films: NREL 2010; Spire 2010a.
III-V Multi-junction: Spire 2010.
Excitonics and Quantum-structured PV: Nano 2010; NREL 2010.

PV research and development at the U.S. Department of Energy

The U.S. Department of Energy (DOE) Solar Energy Technologies Program supports R&D in PV science and technology with a goal of achieving grid parity by 2015. To reach this goal, DOE is investing in approaches across the development pipeline—from basic material science and cell technologies to manufacturing scale-up and total system development. The Next Generation PV Program, for example, supports high-risk, high-payoff projects that focus on revolutionary PV approaches that would enable power generation at significantly lower cost than grid electricity. In this program, the expectations are to realize prototype cells and processes by 2015 and achieve full commercialization in the 2020–2030 time frame (DOE 2010).

The DOE Office of Science supports the Energy Frontier Research Center for Solar Fuels and Next Generation Photovoltaics. This university-led effort is exploring scientific concepts for breakthroughs in generation of fuels and electricity from sunlight (BES 2010).



Wafer-based crystalline silicon PV—Crystalline silicon PV is the most commonly used technology today and is found in solar panels atop roofs and in large field arrays. This PV technology 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. The silicon wafer technology has the longest track record of all PV technologies, and is the most commercially advanced. Crystalline silicon wafers compose about 85% of the global PV market (Navigant 2010).

The PCE of modules in production ranges from 13%–20%. While widely commercially available, continued cost reductions are possible if high-volume manufacturing can be advanced and material challenges can be overcome. These include advances in the processes of ingot sawing, which must be designed to reduce silicon waste, and metal tabbing to interconnect wafers (cells), which must be strung together and sealed in a rigid module.

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. The substrates are sometimes flexible (e.g., polymer or stainless steel ribbon). Absorber layer material technologies include cells made from multijunction amorphous silicon, polycrystalline cadmium telluride (CdTe), and rapidly emerging polycrystalline copper indium-gallium diselenide, or $Cu(In,Ga)Se_2$ (CIGS).

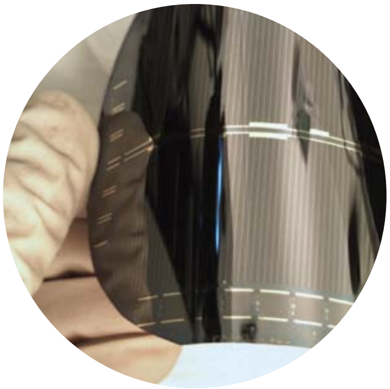
The PCE of modules now in production ranges from 6%–12%, depending on the material and substrate. The lowest efficiency in this range is associated with a-Si:H on flexible substrates, whereas the highest efficiency is associated with CIGS. CdTe on glass, a product that has surpassed 1 GW in annual production, reports the lowest cost and highest manufacturing volume. Thin film technologies have found application ranging from utility-scale PV (e.g., CdTe on glass), to building integrated PV (e.g., CIGS on flexible steel foil), to portable PV power (e.g., thin a-Si:H on polymer). While thin film PV tends to have lower efficiency than crystalline silicon, it requires only small amounts of semiconductor material per cell and fewer manufacturing steps with the potential for fully automated production. These advantages result in lower costs and make thin films competitive with wafer-based silicon in many markets. Recently, some thin-film CdTE products have been very competitive with conventional crystalline silicon PV.

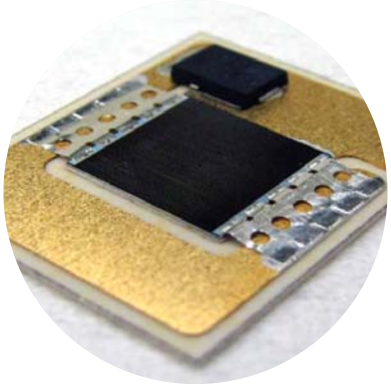
III-V multijunction PV— The layered structure of this technology consists of single crystalline semiconductors from groups III and V of the periodic table, such as gallium arsenide (GaAs). These layered semiconductors, due to their varied band gap energies, absorb different portions of the solar spectrum, and in conjunction with the high crystalline quality, result in the highest cell efficiencies of any type of PV cells.

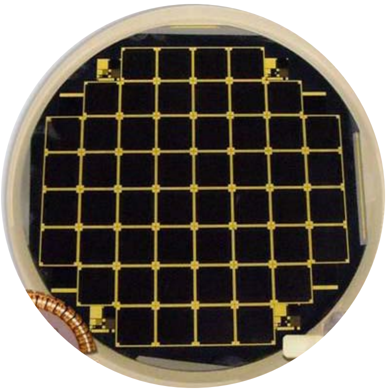
Current research cell efficiencies, under high concentration, are greater than 40%, compared with greater than 25% and 20% for crystalline Si and thin film (CIGS) PV technologies, respectively. While its efficiency is high, the III-V cell is among the most expensive to produce. Such cells were first used in space applications where higher costs were outweighed by the high efficiency and improved radiation resistance, enabling smaller array areas and lower overall system mass. Today these cells are finding terrestrial applications in concentrating photovoltaic (CPV) systems, using optics to concentrate sunlight to intensities in the range of 300–1500 suns. High concentration lowers cost by allowing the use of a small-area cell under a large-area inexpensive plastic or glass optic. However, markets for CPV systems are geographically restricted because they use only direct sunlight (clear skies). These limitations will be greatly reduced with higher multijunction cell efficiency of greater than 40%.

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. These third-generation technologies seek to achieve very high efficiencies by overcoming the thermodynamic limitations of conventional (crystalline) cells, or by lowering production costs using materials amenable to extremely high-rate deposition.

Solar cells exploiting quantum structures may exceed the thermodynamic limit of crystalline cells by optimally extracting energy attached from each photon with predicted efficiencies as high as 66%. However, these high-efficiency approaches remain primarily in the basic materials research phase. Organic PV (OPV) technologies have achieved recent success on the research scale, leading to low-level pilot production of modules at low cost. Module prototype efficiencies of OPV are under 5%, with small-cell-area research efficiencies reaching 8%. If successfully developed, OPV promises low-cost production. Dye-sensitized solar cell technology is starting to transition to manufacturing, providing low-cost products, but issues of stability, lifetime, and reliability still need to be addressed.







BROAD CHALLENGES FOR PHOTOVOLTAICS

PV technologies continue to face broad challenges reflecting a range of technical (i.e., scientific and engineering), market, infrastructural, and institutional issues. Barriers arise throughout the stages of technology development, beginning with basic science and progressing through applied R&D, demonstration, manufacturing, and deployment. Addressing the most critical of these barriers will help ensure that PV technologies take their place as a prominent choice of power for the nation.

TECHNICAL CHALLENGES

The broad technical barriers below impact all types of PV technologies by contributing to existing limitations in cost, performance, and reliability. These factors influence the development and widespread adoption of PV in the United States as well as the potential size of export markets. The current limitations of measurement science and technology are a common thread through these challenges. Many of the measurements required may be destructive to materials and devices, may be expensive or time consuming, and may require years—even decades—of data collection.

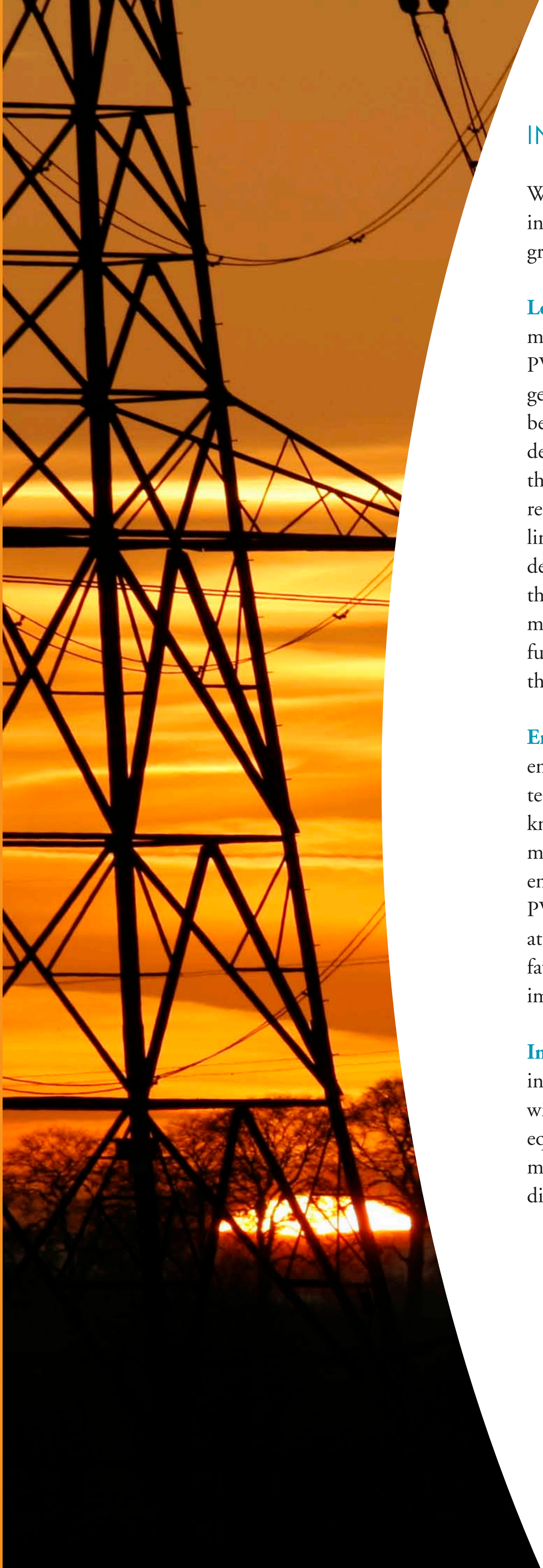
Materials to device analysis—A basic understanding of the relationships between PV device processing and fundamental materials properties on the atomic scale and their impact on performance is essential to advancing all PV technologies in the future. Such fundamental knowledge is critical for the development of more efficient solar cells and the reduction of manufacturing costs. An in-depth understanding of processing-property-performance relationships may enable measurement of materials properties on the production line, and then application of that information to control processing for optimum performance and maximum yield and throughput of the fabricated devices. Fundamental materials to device analysis assists in inventing, developing, and scaling new technologies, and is critical to understanding the physics behind advanced PV concepts.

In-line manufacturing tools— All PV technologies can benefit from analysis tools for inline, real-time measurements to advance manufacturing. Whereas the methodologies and requirements may differ according to PV technology, the common goals include increasing performance, yield, and throughput, and thereby lowering manufacturing cost per watt. The throughput of PV manufacturing is likely to increase continuously in the future and place even higher demands on the speed of such in-line measurements. 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.

Reliability characterization—PV producers currently lack the ability to accurately predict reliability over the lifetime of the PV system, and thus lack standards for such predictions among their PV products. Investment confidence depends in large part on the reliability (e.g., system lifetime, expected performance over lifetime) of PV products. The lack of accurate reliability data measured using accepted methodologies, such as standardized accelerated lifetime tests, impacts more than just the ability to market PV products, for example, to system integrators and installers. It also increases the risk to investors, as the income generated by the PV system is less certain.

A 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. Thus, an important challenge is creating universally accepted standards, protocols, and certifications within the time frame necessary to meet industry needs and expected increases in demand. This challenge covers a range of issues that must be addressed, including solar resource and energy output measurements, system reliability, accelerated life testing, and product certifications.

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. Power density measurement granularity as small as 100 meters will be particularly important for the incorporation of highly distributed PV in the future smart grid environment. Benchmarked solar resource data with specified uncertainty levels would also reduce uncertainties in system and operating costs and support financing. High penetration of PV will also require accurate forecasting of weather to balance PV availability with other utility assets.



INSTITUTIONAL AND OTHER CHALLENGES

While not the focus of this report, there are a number of broad infrastructural, institutional, and other challenges impeding the greater deployment of existing and emerging PV systems.

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 electricity generation, the raw materials used by that technology must be Earth-abundant and available. Whereas there was a severe deficiency of electronic-grade Si feedstock in the early 2000s, this availability limitation has now been resolved. The accessible resources of materials such as indium and tellurium may also limit the scale-up of thin film technologies to meet a larger demand. The availability of new, low-cost material substrates that enable improved efficiency could be a barrier for III-V multijunction cells. Studies are needed to more fully understand future materials limitations on abundance and availability and the impacts on next-generation technologies.

Environmental impacts of emerging technology. The environmental impacts of conventional and emerging technologies are not well understood. Issues include a limited knowledge of the toxicity of nanomaterials and other novel materials; potential release of materials from PV systems into the environment during and after their useful life; safe operation of PV manufacturing plants; and cost-effective recycling of modules at the end of their useful life. While life-cycle analysis typically favors PV over many energy technologies, these analyses must be improved to better capture all environmental impacts.

Interconnect rules and fees. Excessive standby and interconnection charges will prohibit integration of PV systems with the grid. 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. Financing of projects would need to move beyond tax equity markets to meet expected targets for dramatic growth.

Regulation, permitting, and policy. Many of the permitting requirements in the United States are cumbersome or create disincentives, making deployment more complex and costly. For example, in some cases the cost of the building permit is tied to the value of the project. Streamlining of the permitting process could potentially facilitate PV implementation.

Policy measures that include tax credits, capital expenditure grants, incentives for generation, and renewable electricity credits are expected to continue to be important drivers for U.S. solar markets for the next few years. While solar costs are decreasing, policies are also being implemented by federal and various state governments, and the combination could result in more rapid growth in commercial, utility, and residential solar power (Bloomberg 2010).

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 accurate information enabling them to evaluate the performance and payback period of PV systems over time.

STRATEGIC OPPORTUNITIES

A number of strategic opportunities were identified as critical to accelerating progress in PV technologies. These are illustrated in Table 2 and are described in depth on the following pages. The strategic opportunities are recurring themes that appear in multiple technology areas and consequently could have far-reaching impacts if addressed. Within these opportunities are a set of technology and measurement priorities where action is urgently needed. Additional details on the priorities can be found in the workshop summary on which this report is based (NIST 2010).

Measurement science and technology emerges as a recurring theme within the priority challenges to be addressed. Throughout the innovation and commercialization process in PV, advanced measurement capabilities are crucial. As technologies mature, fundamental improvements must be increasingly driven by an in-depth understanding of the relationships between material properties (down to the atomic scale) and device performance. As a result, measurement science impacts all technology areas from the current generation of wafer-based crystalline silicon PV to future generations of quantum and nanostructured PV.

ENABLING SCIENCE AND ENGINEERING

Opportunity
Greater understanding of performance from atomic to system level

A fundamental understanding of materials properties and device behavior at multiple scales, from atomic to cell and system levels, is critical for realizing the promise of innovative, high-efficiency PV technologies. A strong scientific foundation will accelerate development of PV products with higher performance, more predictable and longer life, and lower cost to consumers. Energy rating systems that accurately describe how various PV products perform are needed to help consumers make informed choices.

A major challenge in understanding performance is developing the capability for comprehensive analysis of materials properties from the nanoscale to macroscale, and correlating these properties with PV device performance. This capability is lacking today, creating a gap between conceptualization and demonstration of next-generation technologies. The approaches for acquiring fundamental knowledge of materials properties will vary according to technology. All PV products, however, would benefit from improved analytical capabilities for chemical, structural, optical, and electronic properties characterization.

A better understanding of product performance leading to a more accurate assessment of its value would enable consumers to make informed choices about PV products and encourage more widespread adoption. Consumers must be confident in making wise energy selections based on consistent and comparable information about a diverse slate of products, including system outputs, longevity, and suitability for specific applications. The lack of energy ratings or other comparative characteristics affects the commercialization and marketing of new PV technologies as well as the financing of these systems.

Three-dimensional analysis from nanoscale through macroscale

- ***Three-dimensional (3-D) analysis from nanoscale*** through macroscale is a critical capability for more fully characterizing, validating, and ultimately simulating a variety of properties important to PV performance.

- Tools are needed for the ***3-D tomography of chemical composition, structure, optical electric field, and charge carrier recombination,*** from the micron (µm) scale to less than 5 nanometers (nm), to provide a detailed understanding of device behavior. Tools to visualize composition, impurities, defects, grain boundaries, voids, and other inhomogeneities are required to better understand existing limitations on PV efficiency. These capabilities would benefit current technologies, by providing better diagnostic tools, as well as emerging technologies, by helping develop an understanding of fundamental phenomena that affect

Opportunities

Understanding performance from atomic to system level

Low-cost and highly automated manufacturing with high yields

Long and predictable product lifetimes

Widespread adoption of PV through low-cost and diverse product offerings

WORKSHOP ON GRAND CHALLENGES FOR ADVANCED PHOTOVOLTAIC TECHNOLOGIES AND MEASUREMENTS

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

A workshop was hosted by the National Institute of Standards and Technology (NIST) in May 2010 to identify the critical technology and measurement barriers impeding advances in these PV technologies. The workshop was attended by more than 70 world-renowned experts from industry, national laboratories, and academia. The ideas they generated form the basis for this strategic opportunities report (NIST 2010).

Table 2. Strategic Opportunities and Priority Challenges

PRIORITY CHALLENGES FOR PHOTOVOLTAICS	PV Technologies: Wafer-based crystalline silicon	Thin film	III-V multi-junction	Excitonics and quantum-structured	Broad Impacts on PV
Greater Understanding of Performance from Atomic to Device Level					Science and Engineering Foundations
Three-dimensional (3-D) analysis from nanoscale through macroscale • 3-D tomography of chemical composition, structure, and optical electric-field • 3-D tomography of electronic structures at variable length scales		●		●	
Multi-scale modeling for simulating materials growth, structure, optical and electronic properties, and device performance			●	●	
Assessment of module performance and energy output • Accurate solar resource assessment and solar spectrum simulation • Accurate prediction of system energy output • Measurements to support standards for spectral response	●	●	●		
Low-Cost and Highly Automated Manufacturing with High Yields					Manufacturing Scale-up and Production Capabilities
In-line monitoring of source materials, wafers, substrates, and layers throughout processes of cell fabrication and module packaging • Process monitoring and control from materials to wafer to cell • Real-time and in-line measurements enabling closed loop control for thin films • Affordable, automated, in-line production and characterization equipment for III-V multijunction devices and modules • In-line tests for cell/packaging defects and failure mechanisms for excitonics and quantum-structured cells	●	●	●	●	
Improved interconnection of cells into modules • Improved interconnection schemes for thin (50 micron) silicon cells • High throughput measurement of wafer mechanical integrity • Cost-effective interconnection of III-V cells	●		●		
Long and Predictable Product Lifetimes					Market Development and Sustainability
Measurements of accelerated life testing and degradation modes for accurate prediction of module output over its lifetime • Measuring and predicting the degradation of materials • Accelerated lifetime and reliability testing for thin films, concentrating PV, and quantum-structured technology	●	●	●	●	
Widespread Adoption of PV through Low-Cost and Diverse Product Offerings					
Increasing the performance of materials and their interfaces, and screening for new abundant and compatible materials • Overcoming crystalline wafer efficiency limitations through materials monitoring and control, including materials and device compatibility measurements • Materials screening to enable stable, manufacturable low-cost thin film modules • Materials growth monitoring and control for higher efficiency multijunction cells • Application of fundamental knowledge to increase efficiency in excitonic and quantum-structured cells	●	●	●	●	

performance. As a specific example, 3-D structural tomography would enable the design and evaluation of optical light-trapping structures that increase the number of photons available for absorption and consequently the utilization of smaller volumes of source materials in higher throughput cell fabrication. Finally, detailed analyses of the roles of impurities and structural and electronic defects can also be applied to enhance understanding of degradation mechanisms. Analysis of 3-D nanoscale chemical and structural characteristics would support optimal device design and accelerate novel technology development for excitonic and quantum-structured devices.

- ***3-D tomography of electronic structures at variable length scales*** in bulk and at interfaces is needed to improve understanding of device physics, which could lead to better design of materials, interfaces, and device architectures—all of which impact performance and cost. This is particularly important for emerging excitonic and quantum-structured cells. Challenges include improving sensitivity for photoelectrons spectroscopy, developing high resolution probes for conductivity, and measuring multiple parameters simultaneously.

Multi-scale modeling for simulating materials growth, structure, optical and electronic properties, and device performance

- ***Multi-scale modeling for simulating materials growth, structure, optical and electronic properties, and device performance*** is needed to support stages of development from theory to prototype for many advanced device concepts, including III-V multijunction, organic PV, and nanowire cells. Predictive models are imperative for the accelerated design and development of new materials. Multi-scale measurements and models to analyze or simulate molecular and quantum-scale properties and their impacts on macroscopic device performance are currently lacking. Multi-scale models are needed that address complex systems from nanoscale to microscale to macroscale, and then link results to system performance. This capability would help predict how different materials and devices actually perform—providing a new route for higher power conversion efficiency, as well as longer lifetime and improved stability and reliability, based on scientific understanding rather than trial and error. For III-V multijunction cells, current modeling capabilities for simulating material growth, material structure, electronic properties, and device performance are insufficient and limit the ability to increase efficiency.

Assessment of module performance and energy output

- All PV technologies would benefit from the development of more ***accurate solar resource assessment and solar spectrum simulation.*** This could be achieved through high-performance, broadly functional instrumentation for measurement of the direct and global solar spectrum. The objective is to obtain diverse satellite and weather data from multiple locations

Better understanding of materials properties is improving efficiency in thin film PV

The Advanced Deposition Research System for Photovoltaic Materials is under development at Colorado State University under the direction of Dr. Walajabad Sampath. The new machine could ultimately double or triple the efficiency of thin film solar panels produced by Abound Solar. The machine is designed to boost thin film efficiency by adding active layers incorporating cadmium, magnesium, and tellurium and by enhancing the efficiency of the existing CdTe active layer (CSU 2010).

Dr. Walajabad Sampath of Colorado State University.

over multiple years, incorporating factors of humidity, aerosol optical depth, wind speed, and temperature. The challenges lie in developing low-cost instrumentation with sufficient accuracy, coordinating data from many diverse sources, and creating new models that correlate solar spectral characteristics and module performance. With accurate solar assessment data, PV products can be optimized for location, with lower associated financial risk based on predictable performance—both leading to greater market share. Solar spectrum simulation is especially important in III-V technologies, which seek to match the properties of incoming solar radiation in the design of concentrating optics, cell configuration, and other system properties.

- ***Accurate prediction of system energy output*** is a major challenge and the current capability is inadequate for all PV products. An advanced capability would enable development of an improved Module Energy Rating System covering field performance under differing climates, incorporating spectral effects, mounting strategies, operating temperatures, and degradation. A neutral third party rating system, which validates system performance, would have tremendous value for encouraging and accelerating PV deployment by boosting both consumer and investor confidence. The investor needs to know how much electricity the PV array will produce over its lifetime to understand the value of the investment.

- ***Measurements to support standards for spectral response*** are needed to accelerate all types of PV development and lower costs through more accurate assessment of performance. Major barriers include establishing the uniformity of the beam, addressing thermal issues, and improving the speed of measurement. The goal is to achieve spectral response measurements in fewer than 10 minutes, with evaluation of spectral response uncertainties of less than 1% over the 250–2,500 nm range at one-sun or higher concentration.

ADVANCES IN MANUFACTURING

Opportunity
Low-cost and highly automated manufacturing with high yields

Improved manufacturing processes are needed to promote high-volume manufacturing of PV products and lower overall costs. Manufacturing challenges vary according to the unique characteristics of the PV technology, the basic material components used for energy conversion, and their compatibility and stability.

An expansion of the existing set of inspection and process control tools used in PV manufacturing is required to enhance cell and module performance and to reduce production costs. Without a sufficient complement of in-line tools, it is difficult to detect—early in the manufacturing process—the wide variety of defects that can degrade the quality and performance of the finished product. This limitation is a major barrier to high-volume production of PV modules. Addressing the challenges as described below for each technology would enable significant progress toward high-yield, high-volume, and thus lower-cost production of high-performance PV products.

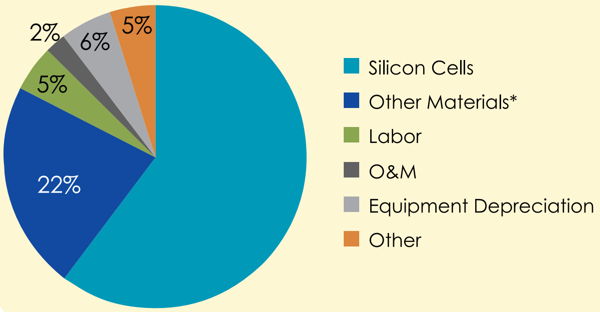
In-line monitoring and control of source materials, wafers, substrates, and layers throughout processes of cell fabrication and module packaging

- New in-line tools are needed for ***process monitoring and control from materials to wafer to cell,*** including the steps for crystal growth, wafering, junction formation, and passivation. A key goal would be the development of intelligent process controls based on in-line monitoring, in conjunction with physical models, leading to improved crystal growth and correlations with electrical performance. These capabilities would enable a faster return on capital expenditures and improve the competitive position of manufacturers by integrating measurements, models, and controls for all processing steps.

Manufacturing Costs

On average, materials and materials processing account for more than 80% of the cost of manufacturing a crystalline wafer Si module.

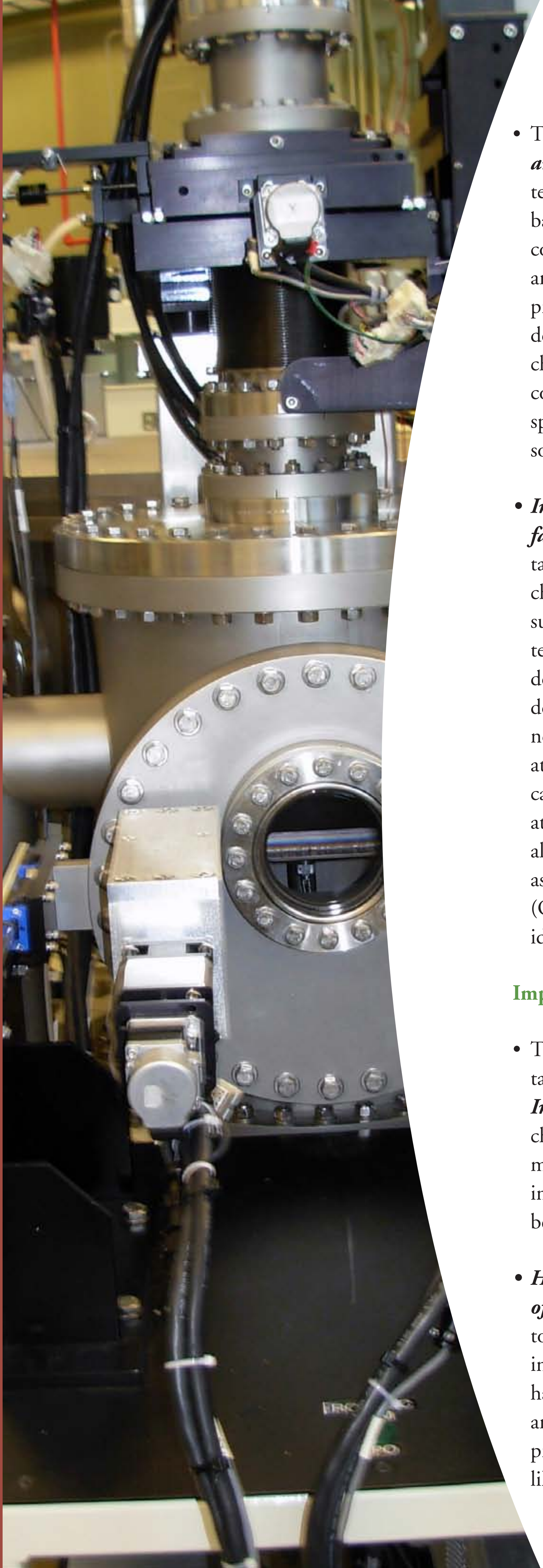
Average Distribution of Manufacturing Cost for Crystalline PV Modules



Source: IEEE 2010

**Module materials (glass encapsulants, backsheet, junction box, frame)*

- ***Real-time and in-line property measurements enabling closed loop control*** are lacking for the analysis of the multi-layered components. Developing a diverse set of techniques for mapping the physical and chemical characteristics of layer thickness, composition, impurity concentrations, as well as the microstructural, optical, and electronic properties could dramatically improve process understanding and help to identify process deviations that affect performance, yield, throughput, and reliability. The objective is in-line measurement technologies that provide high-speed, non-destructive analysis; are compatible with continuous, automated manufacturing processes; and enable high performance, yield, and throughput, for example, via enhanced rates of deposition.



- The lack of ***affordable, automated, in-line production and characterization equipment*** for III-V multijunction technology, including cells, packaging, and modules, is a major barrier. Testing equipment that can detect and potentially correct defects in real time would increase throughput and yield and mitigate reliability concerns, all contributing to lower-cost production. The challenge in multijunction PV technology is to develop test equipment and methods with less than 10-minute characterization times, and that account for less than 5% of cell costs. Possible technologies include electroluminescence, generic spectrum single or multijunction tests, and high-concentration solar simulation tests.

- ***In-line tests for cell and packaging defects and associated failure mechanisms*** (e.g., pinholes, scratches) specifically tailored toward organic PV products are needed. Cell characterization is one of the most pressing challenges for successful implementation of excitonic and quantum-structured technologies, which are still in the early stages of manufacturing development. As new high-throughput manufacturing is developed (e.g., roll-to-roll OPV processing), tests will be needed to detect defects in the nanometer to micron scale at very fast (i.e., 300 meter/minute) coating speeds. These capabilities will increase yield, enabling technology maturation at very low production cost. These new testing capabilities could also be applied to other printed electronics applications such as organic thin film transistors, organic light emitting diodes (OLEDs), displays, solid state lighting, and radio frequency identification.

Improved interconnection of cells into modules

- Thin crystalline silicon cells (<50 microns) will need special tabbing or interconnection methods to avoid breakage. ***Improved interconnection schemes*** would require new chemistries for liquid precursors used in non-contact metal printing, a flexible circuit approach for module-level interconnection, and mechanical supports to allow thin cells to be interconnected.

- ***High throughput measurement of the mechanical integrity of silicon wafers*** is a specific capability for which adequate tools are lacking and will be needed to develop improved interconnection schemes. Key challenges include automated handling of thin wafers and in-depth understanding of stresses and cracks that enables prediction of failure in subsequent processing. ***Cost-effective interconnection of III-V cells*** is also likely to be a long-term issue.

RELIABILITY

Opportunity
Long and predictable product lifetimes

Characterizing and demonstrating the reliability of PV materials, modules, and systems are both important steps toward gaining consumer confidence. It is important to be able to predict service life in geographic locations, guarantee lifetime warranties, predict annual degradation rates, and develop new and improved products with longer life through an understanding of degradation mechanisms.

Although each type of PV technology faces unique challenges in reliability, a number of issues are universal. These issues include the limited availability of robust instrumentation for measurement of key properties that impact reliability, the lack of tools and tests for simulating and verifying outdoor combined environmental conditions under accelerated time scales, and inadequate understanding of degradation and failure mechanisms under operating conditions. All result in a lack of accurate predictive capability for reliability. Because the tools for consistently measuring product lifetime, including accelerated lifetime testing (ALT), are fundamentally lacking, the degradation and failure mechanisms over the lifetime of the PV products and in various environments are not fully understood, making mitigation of these effects difficult to address.

An example of the challenges related to device reliability is characterization of packaging barrier properties, including water vapor and oxygen transmission rates. Because water and oxygen can reduce the stability of device materials, correlations of these parameters with module lifetime are needed.

Universally accepted standards for accelerated lifetime protocols and reliability are needed for all PV products. Standards help promote confidence in technology, enable advanced engineering solutions for more stable products, and control costs via more predictable system output. Standards and protocols are important to today's commercial technologies and will be vital to the deployment of newly emerging and next-generation PV products. Demonstrating reliability is especially important for emerging technologies that do not have as many years of demonstrated field performance.

Some general and technology-specific challenges to achieving long and predictable product lifetimes are presented below.

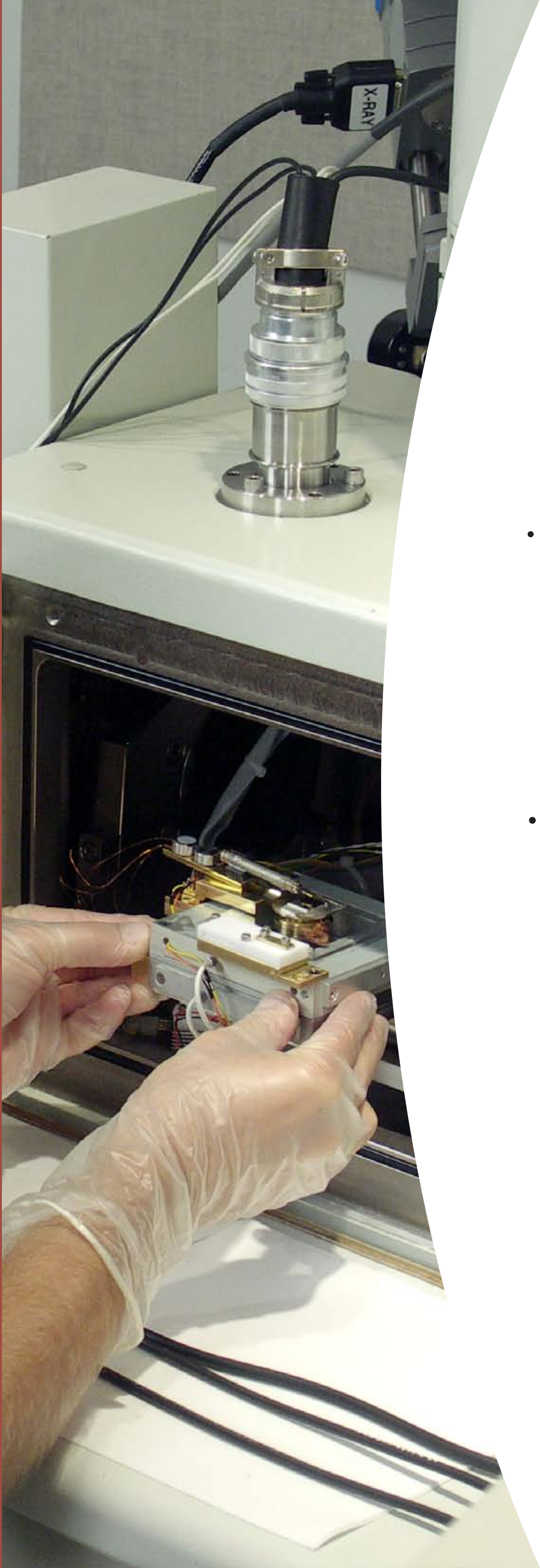
Measurements of accelerated life testing and degradation modes for accurate prediction of module output over its lifetime

- ***Measuring and predicting the degradation of materials*** provides important information about lifetime performance of PV modules and systems. Measurement of polymer degradation in modules during field performance is a major challenge for all technologies. Discoloration resulting in a loss of solar insolation is a potential degradation mode that can affect all technology types. Degradation of the semiconductor material itself can also occur in some PV modules. For example, the performance of active layers of thin film silicon modules

Guaranteeing lifetime warranties for solar PV

A PV module has no moving parts and its operating life is thus largely determined by the stability—under operating conditions—of the materials from which it is constructed. Today, manufacturing warranties for PV products vary from 10 to 25 years. However, a number of failure modes and degradation mechanisms exist that may reduce the power output or cause the module to fail. Nearly all of these mechanisms are related to light exposure, water ingress, or temperature stress.

Many companies guarantee a minimum power produced by the PV system for a certain number of years, which depends on the technology and the rated peak power of the PV system (usually a minimum of about 80% of the rated power).



are affected by metastable light-induced defects. Potentially all solar cells may be degraded by interaction between materials at interfaces and resulting instabilities, and in thin films by diffusion of atmospheric contaminants along grain boundaries and through voids. The causes of degradation and instabilities are, in many cases, poorly understood. For example, some thin film modules have been observed to increase in efficiency when exposed to light, whereas others decrease in efficiency. A detailed understanding of these issues may require the development of techniques that can measure chemical and structural characteristics at the atomic level. This is a very high priority for grain boundaries of thin films, tunnel junctions of multijunction cells, and for quantum-structured PV in general.

- Knowledge gained through understanding of polymer degradation, such as that produced by ultraviolet radiation, will enable faster development and deployment of new materials that could survive in the field potentially as long as 50 years. To support this effort, new methods for precisely measuring UV radiation according to its wavelength will need to be explored and developed, as well as methods for measuring bond stability and degradation chemistry, all necessary for accurate accelerated UV reliability testing.

- ***Accelerated lifetime and reliability testing for thin films, concentrating PV, and quantum-structured technology*** are needed to gain investor confidence. Accelerated stress tests that quantitatively correlate with field performance would aid in understanding failure mechanisms, improving reliability, and increasing lifetime. While outside the scope of this report, the primary reliability issues of PV systems have been consistently related to trackers (for systems that use trackers) and inverters or other balance-of-system components. Ironically, the monitoring equipment that is so helpful in quantifying reliability is also a key source of failure. Lifetime is also closely tied to degradation, and tests are needed to simulate conditions occurring over many years in the field. More precise measurements are needed to enable detection of small changes after tests or in-sun hours.

  For quantum-structured PV, research is needed to identify and model failure mechanisms and to direct the development of specialized analysis methods to detect changes at the quantum scale. Demonstrating reliability for these entirely new, as yet unproven products will be critical to gaining consumer and investor confidence and moving excitonic and quantum-structured PV into the mainstream. In fact, many of the barriers that thin film PV technologies have faced (and continue to face), in particular metastable defects, interface interdiffusion, and reactivity to the atmosphere are expected to be encountered to an even greater degree in excitonic and quantum-structured PV.

SUSTAINABLE MARKETS FOR PHOTOVOLTAICS

Opportunity

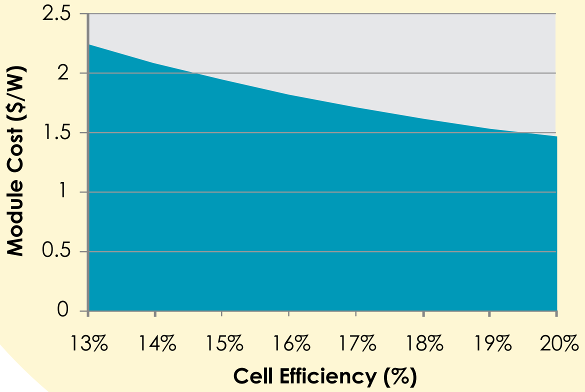
Widespread adoption of PV through low-cost and diverse product offerings

One of the major challenges to expanding the use of PV is its high cost. Lowering the cost of PV systems to consumers and consistently demonstrating the value of PV to end users is critical for broadening its adoption. Cost-effective PV technologies that enable a more diverse mix of products for use in a greater number of applications will help expand and create new markets both here and abroad.

Efficiency Directly Impacts PV Module Cost

While the efficiency of today's multi-crystalline silicon cells is typically around 16%, efficiencies are expected to increase with future device improvements. As shown below, a 2% increase in cell efficiency from 16%–18% decreases the module cost by more than 10%, assuming cell costs are fixed.

Impact of Efficiency Increases on Crystalline PV Module Cost

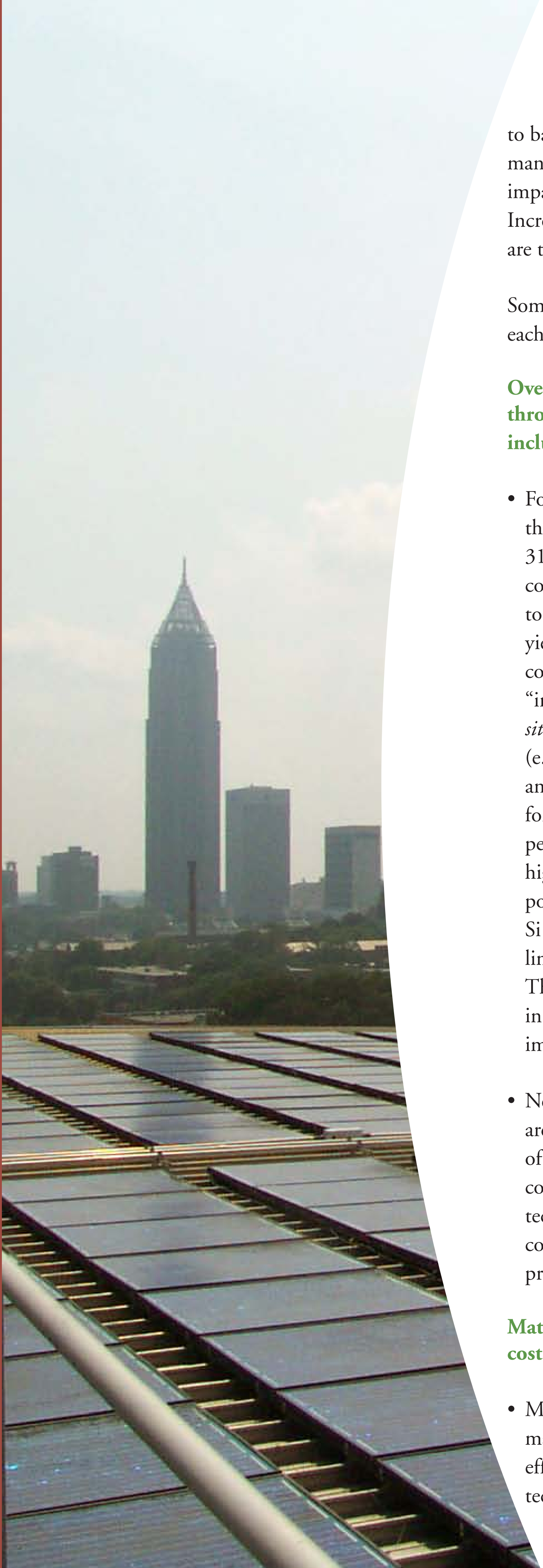


Source: IEEE 2010

Many factors affect the overall cost of PV, including market price of raw materials, capital expenditures for manufacturing equipment, the price of project financing, and the supply of modules to the market. The PCE of PV cells, which varies with technology type, directly impacts the cost to the consumer. Higher efficiency produces more power per unit area and reduces overall costs related to area (e.g., installation costs and balance of systems mechanical components). Achievable target module efficiencies range from ~10% for organic PV to ~40% for III-V multijunction PV.

Conversion efficiency is limited by absorber material bandgap and material quality, device design, and processing details. Different factors may affect the PCE of the various technologies. Crystalline cell efficiency tends to increase with concentration and decrease with temperature. The efficiency of polycrystalline thin film PV would be significantly enhanced by the successful development of a monolithic tandem structure. The efficiency of III-V cells in concentrators is sensitive to spectral changes as the sun moves across the sky, and advanced designs must account for these changes. Organic PV efficiency may be improved largely by the development of new materials and by control of blend morphology.

Today, PV products are used in a variety of applications, from satellites for space power to utility-scale fields for terrestrial power



to battery chargers for consumer products. However, there are still many opportunities to expand PV products into other markets that impact everyday life, such as the generation of transportation fuels. Increasing efficiency and lowering the cost to produce PV products are two pathways toward expanding their potential applications.

Some of the top challenges to achieving high target efficiencies in each technology area are described below.

Overcoming crystalline silicon wafer efficiency limitations through materials monitoring and control of crystalline wafers, including materials and device compatibility measurements

- For conventional crystalline silicon wafer technology, the theoretical limiting efficiency under one-sun illumination is about 31%, so efficiency improvements focus on increasing optical collection and reducing defects in the material that contribute to electrical losses. Thus, a key objective is to achieve high yields of high-quality silicon, which allows the highest possible conversion efficiency. To meet this objective, effective *in situ* (or "in place") monitoring of materials production is needed. *In situ* monitoring of both material and cell production processes (e.g., ingot growth, wafering, junction formation, passivation) is an essential capability for improving quality and efficiency and for reducing the occurrence of defects. Such capability would permit direct control of final product quality while ensuring high yields, throughput, and thus lower costs. It may also be possible to achieve other advances, such as making crystalline-Si based multijunctions and thereby increasing the theoretical limit similar to the approach in III-V multijunction technology. The incorporation of special quantum-engineered structures in crystalline silicon cells, with potential major efficiency improvements, is also being researched.

- New methods for characterizing materials and their compatibility are needed to ensure production of the highest possible quality of silicon wafers with reduced impurities. Understanding compatibility of materials for devices will require advanced techniques for characterizing device performance under variable conditions and relating this performance to the properties and processing of material components.

Materials screening to enable stable, manufacturable, and low-cost thin film modules

- Materials screening to enable development of a stable, manufacturable, and low-cost thin film module with 20% efficiency would open up a wider range of markets for this technology. Challenges to achieving this are characterization and understanding of: (1) the physics and chemistry of defects and how they can be controlled through processing; (2) the interaction of materials at the interfaces; and (3) the compatibility of materials for effective charge transport throughout the device. Rapid screening of new PV materials (e.g., absorbers, dopants, window and buffer layers, and transparent conducting oxides) must be developed to optimize performance, resulting in increased efficiency. Reaching the 20% efficiency level will likely involve overcoming such challenges for multijunction polycrystalline thin film modules.

Materials growth monitoring and control for higher efficiency multijunction cells

- Incorporating additional junctions in III-V multijunction cells has the potential to enhance collection of the solar spectrum and enable operation beyond the thermodynamic limit. Material growth monitoring and control are needed for ensuring the target values of additional layer thickness and composition. A major challenge exists in real-time analyses of epitaxial[3] growth of the crystalline layer and predicting how growth processes impact the ultimate performance of the device. Addressing this challenge would greatly facilitate rapid development of optimized cell designs with low optical losses and near-perfect electronic quality, both of which are needed to increase efficiency.

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

- Excitonics and quantum-structured PV are possible game-changing technologies with the potential for dramatic increases in efficiency as high as 66%. As they are primarily in the research and development stage, increasing the efficiencies of these PV cells presents challenges related to the creation and application of basic scientific knowledge. Efficiency could be improved through materials design and development to identify materials with optical and semiconductor properties that optimally absorb the solar spectrum and deliver the photocurrent at a high voltage. Efficiency could also be improved by morphology characterization and control to optimize the delivery of the photocurrent to the outside circuit. The development of low-cost barrier technologies is essential to reduce degradation and retain the initial efficiency. For organic PV, there is a need to achieve efficiency and stability improvements through advanced materials. In quantum-structured devices, however, the focus is on controlling the architecture of the cell to utilize quantum effects that maximize the conversion of photon energy to electrical energy and extend the thermodynamic limit.

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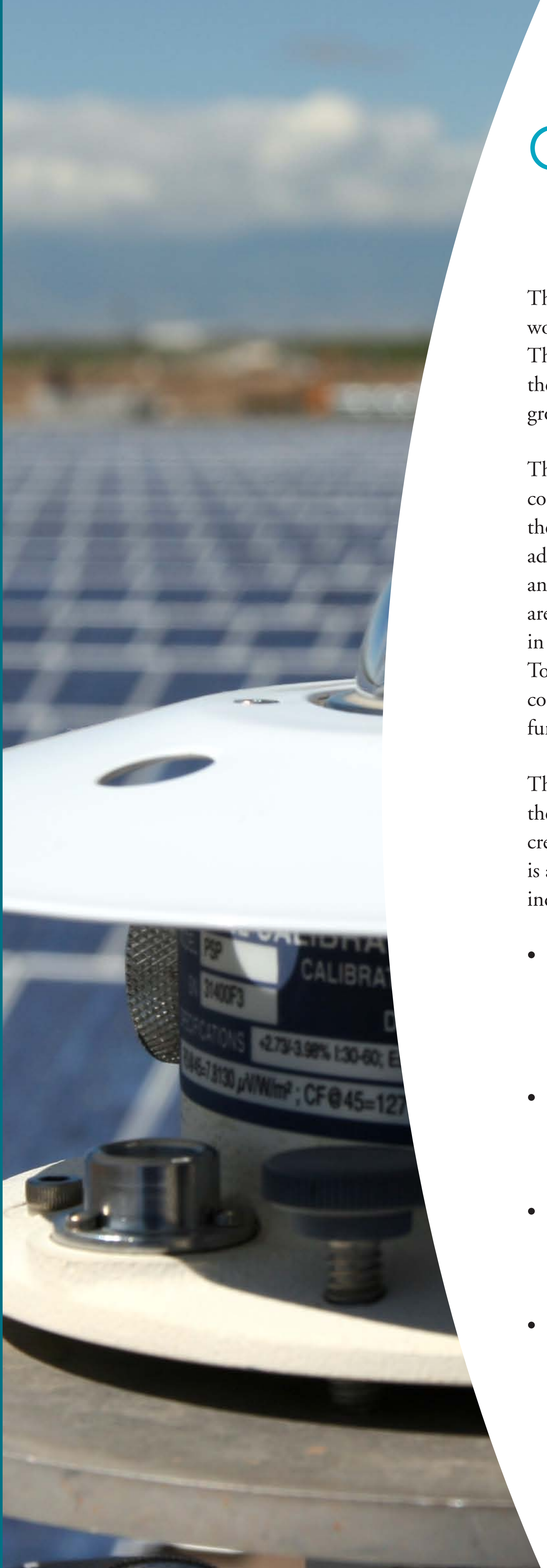
[3] Epitaxy or epitaxial refers to any process by which a single crystal layer of a material is grown on top of a substrate.



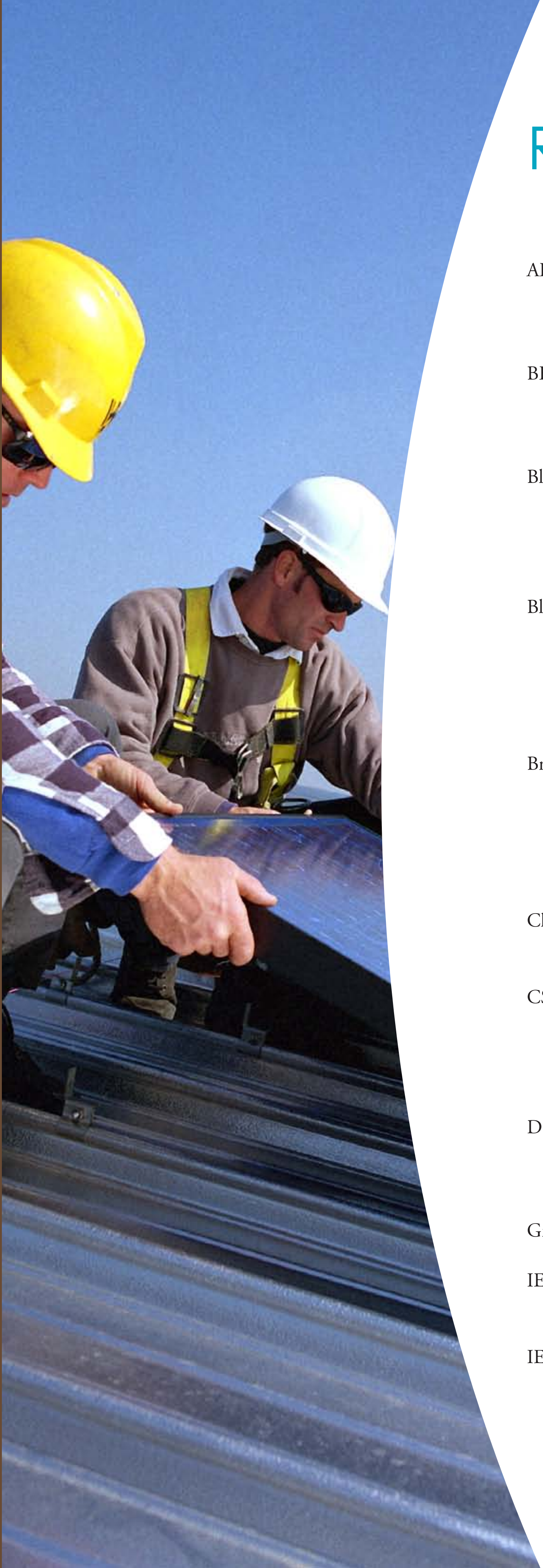
CONCLUSION

The PV industry is experiencing remarkable growth worldwide, and great strides have been made in technology. There are enormous opportunities for the United States to reap the benefits through industry growth, new jobs, and capture of growing export markets.

The companies that are positioned with new technology and cost-effective production capacity will be the most likely to gain the bulk of expanding markets. This will require technology advances that go beyond the state of the art to provide lower cost and increased performance. Many countries around the globe are already investing heavily and subsidizing PV technology in the hopes of gaining market leadership for their industries. Today, the U.S. PV industry supplies only 8% of the market, compared with 44% fifteen years ago, and is at risk of falling further behind.

This report is a call to action. Progress has been made, but there are many challenges ahead. Overcoming these challenges creates exciting opportunities to ensure that the United States is a technology leader with a competitive edge in the global PV industry. Significant challenges detailed in this call include:

- **Understanding performance from atomic to systems level**—key to understanding the fundamental relationships of materials properties to system performance and advancing the state of PV technologies;
- **Low-cost and highly automated manufacturing with high yields**—essential for ramping up production to meet dramatic projections for worldwide growth;
- **Long and predictable product lifetimes**—required for investors to understand the income and value of PV products over their lifetime; and
- **Widespread adoption of PV through low-cost and diverse product offerings**—made possible through technology innovations that increase efficiency, lower cost, and broaden the spectrum of PV applications.



REFERENCES

AEIC 2010. *A Business Plan for America's Energy Future.* American Energy Innovation Council. June 2010. http://www.americanenergyinnovation.org/

BES 2010. U.S. Department of Energy, Office of Science, Basic Energy Sciences. http://www.science.energy.gov/bes/EFRC/CENTERS/UNC/efrc_UNC.html

Bloomberg 2010. "US Solar Poised for $100bn Growth Surge" Bloomberg New Energy Finance. Business Wire, New York, October 25, 2010. http://www.bloomberg.com/news/2010-10-25/us-solar-poised-for-100bn-growth-surge.html

Blue Green Alliance 2009. *Building the Clean Energy Assembly Line: How Renewable Energy Can Revitalize U.S. Manufacturing and the American Middle Class.* BlueGreen Alliance. November 2009. http://www.bluegreenalliance.org/admin/publications/files/BGA-Phase-II-Report-PRINT.pdf

Breakthrough 2009. *Rising Tigers, Sleeping Giant: Asian nations set to dominate the clean energy race by out-investing the United States.* Breakthrough Institute and the Information Technology and Innovation Foundation. November 2009. http://thebreakthrough.org/blog/Rising_Tigers.pdf

Clean Edge 2010. Clean Energy Trends 2010. Clean Edge, Inc. 2010. http://www.cleanedge.com/reports/pdf/Trends2010.pdf

CSU 2010. Photo Courtesy of Walajabad Sampath, Colorado State University. See also *Denver Post,* July 2, 2010. "Colorado State professor working on a more efficient solar cell." http://www.denverpost.com/headlines/ci_15424561

DOE 2010. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Program. http://www1.eere.energy.gov/solar/photovoltaics_program.html

GreenTech Media 2011. Personal communication. March 2011.

IEA 2009. Technology Roadmap: Solar Photovoltaic Energy. 2009. http://www.iea.org/papers/2010/pv_roadmap.pdf

IEEE 2010. Roger Little, Michael Nowlan, Robert Bradford, and David Hebert. Spire Corporation, Bedford, MA. "The solar breeder factory: minimizing the cost of photovoltaic energy generation." Presented at the 35th IEEE PV Specialist Conference, June 2010, Honolulu, Hawaii http://www.ieee-pvsc.org/PVSC35/

LBNL 2010. Ryan Wiser and Galen Barbose. *Supporting Solar Power in Renewables Portfolio Standards: Experience from the United States.* Lawrence Berkeley National Laboratory and Ed Holt & Associates, Inc. October 2010. LBNL-3984E. http://eetd.lbl.gov/ea/emp/reports/lbnl-3984e.pdf

Nano 2010. Recent Trends in Dye-Sensitized solar Cell Technology. Professor Ashutosh Tiwari, University of Utah. AZoJono-Journal of Nantechnology Online. March 15, 2010. http://www.azonano.com/details.asp?ArticleId=2542

Navigant 2010. PV Technology Shipments. Navigant Consulting, Inc. PV Services Program. August 2010.

Navigant 2011. Solar Outlook. March 2011.

NIST 2010. *Workshop Summary Report: Grand Challenges for Advanced Photovoltaic Technologies and Measurements*. July 2010. http://events.energetics.com/NISTGrandChallenges2010/pdfs/AdvPV_WorkshopReport.pdf

NREL 2010. Best Research Cell Efficiencies. Compiled by Lawrence Kazmerski, National Renewable Energy Laboratory. 2010. http://www.nrel.gov

Pew 2010. *Who's Winning the Clean Energy Race? Growth, Competition and Opportunity in the World's Largest Economies: G-20 Clean Energy Factbook.* 2010. http://www.pewtrusts.org/uploadedFiles/wwwpewtrustsorg/Reports/Global_warming/G-20%20Report.pdf

PV News 2010. PV News, Volume 29, Number 5, May 2010. Archived data at http://www.gtmresearch.com/report/pv-news

SB 2010. "Solarbuzz Reports World Solar Photovoltaic Market Grew to 7.3* Gigawatt in 2009" http://www.solarbuzz.com/Marketbuzz2010-intro.htm March 15, 2010.

Schott 2010. Press Release October 12, 2010. "Schott Solar PV, Inc. Produces World's Highest Multicrystalline Module Efficiency of 17.6% with High Performance Cells and Innovative Manufacturing." Schott Solar, Inc. http://www.schottsolar.com/us/

SEIA 2010. *U.S. Solar Industry: Year in Review*. April 15, 2010.

Solar Census 2010. National Solar Jobs Census 2010. October 2010. Solar Foundation with Cornell University, Green LMI Consulting, Inc., BW Research Partnership, Inc., The Energy Foundation, Solar Electric Power Association, and Solar Energy Industries Association. http://www.thesolarfoundation.org/

Spire 2010. Press Release October 6, 2010. "Spire Produces World's Most Efficient Solar Cell." http://www.spirecorp.com/

Spire 2010a. Personal communication with Spire Corporation. October 2010. http://www.spirecorp.com/

SunPower 2010. "SunPower panel reaches record 20.4% total-area efficiency." PV Tech. October 26, 2009. http://www.pw-tech.org/lib/printable/6501/

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