

DOE Solar Energy
Technologies Program **FY 2006**

ANNUAL REPORT



U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Cover Photos

Front cover, clockwise from upper left:

GE manufactured this 2.4-kW PV system, which is installed on the roof of the Highlands Patrol HQ building at the Aspen Mountain Resort in Aspen, CO, at an elevation of 11,000 feet. *Aspen Skiing Co., PIX14729.*

In February 2006, President George W. Bush toured UNI-SOLAR's PV manufacturing plant in Michigan to highlight his Solar America Initiative. *United Solar Ovonic, PIX14727*.

Arizona Public Service began initial operation of a 1-MW concentrating solar power (CSP) trough plant in FY 2006—the first commercial CSP plant built in the United States since 1991. *Arizona Public Service.*

This manufacturing line is at Shell Solar Industries in Camarillo, CA, a partner in the PV Manufacturing R&D Project. *Shell Solar Industries, PIX13855.*

The Science and Technology Facility at NREL, completed in FY 2006, is a 71,000-square-foot, state-of-the-art facility designed to help accelerate the development and commercialization of promising new energy technologies. *Patrick Corkery, PIX14765.*

NREL researchers use hot-wire chemical vapor deposition to produce high-efficiency PV devices for testing and study. *Richard Matson, PIX14602.*

Back cover:

Series of photos showing activities and events of the Solar Decathlon, which was held on the National Mall in Washington, D.C., during October FY 2006. Upper-right photo: Secretary of Energy Samuel W. Bodman (center) and Under Secretary of Energy David Garman (right) congratulate Jeff Lyng, a student leader of the victorious University of Colorado team.

DOE Solar Energy Technologies Program

The Solar Energy Technologies Program, within the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), is responsible for developing solar energy technologies that can convert sunlight to useful energy and make that energy available to satisfy a significant portion of our nation's electricity needs in a cost-effective way. The Solar Program supports research and development that addresses a wide range of applications, including on-site electricity generation, thermal energy for space heating and hot water, and large-scale power production.

In the body of this report, you will read about R&D and achievements from across the Solar Program. The work performed at the participating DOE national laboratories—National Renewable Energy Laboratory (NREL), Sandia National Laboratories, Oak Ridge National Laboratory (ORNL), and Brookhaven National Laboratory—is highlighted, along with the vital contributions of our industry and university partners.

An Expanding Industry

The recognition by the U.S. public—and our national, state, and local leaders—that domestically produced solar and other renewable energy options are synonymous with energy security and economic prosperity grows more palpable each day. The demand for solar energy systems is soaring. Backing that demand is a strong commitment to allocate Federal research dollars to continuing to advance the science underlying solar technologies and move those technologies to the marketplace.

Based in large part on 30 years of accomplishments within the Solar Program's research facilities and partnerships, photovoltaic (PV) systems are being installed in the United States and around the world at a record pace. In 2006, we opened the Science & Technology Facility at the National Renewable Energy Laboratory (Fig. 1). This building represents a new paradigm of laboratory scientists working side by side with members of the PV industry to ultimately produce the most efficient and cost-effective PV systems possible.

With the commissioning of Arizona Public Service’s 1-MW trough plant in 2006, the concentrating solar power (CSP) industry produced the first commercial CSP plant built in the United States since 1991. Following that, construction began on Nevada Solar One, a 64-MW trough plant (that subsequently went online in June 2007). Both projects use a solar collector that was developed collaboratively by Solargenix and the Solar Program.

Fig. 1. U.S. Secretary of Energy Samuel W. Bodman (center) cuts the ribbon with Colorado Congressman Bob Beauprez (left) and Colorado Senator Ken Salazar (right) to open the DOE National Renewable Energy Laboratory's Science & Technology Facility, in Golden, CO.

Solar America Initiative

Early in 2006, the Solar America Initiative (SAI) was announced in support of the President's Alternative Energy Initiative, laying the groundwork for SAI activities to begin in FY 2007. The Solar Program leads and implements the SAI.

The SAI is quite simply a new way of doing business for the Solar Program. It ramps up DOE's business strategy of partnering with U.S. industry to accelerate commercialization of improved PV systems that can meet aggressive cost and installed capacity goals. The initiative has two areas of emphasis:

- *Research and Development* focuses on PV component R&D and system designs, including low-cost approaches for manufacturing.
- *Market Transformation* centers on non-R&D activities aimed at reducing market barriers and promoting market expansion and complements the core R&D and engineering activities.

SAI will employ public-private partnerships to pursue component and system technologies. Industry-led project teams will demonstrate manufacturing approaches that deliver low-cost, high-reliability commercial products. Ultimately, by 2015, the efforts of the SAI will contribute to making PV electricity cost competitive with traditional energy sources in all U.S. sectors.

Mission and Goals

We in the Solar Program are committed to developing solar technologies that provide the country with economic energy options and help U.S. industry remain the world leader in these technologies. Research, design, and development of technology are combined with value analysis, an integrated-systems approach, and partnering to attain the Solar Program's goals and objectives.

Our mission is to improve America's security, environmental quality, and economic prosperity through public-private partnerships that bring reliable and affordable solar energy technologies to the marketplace. Our goals are to reduce the cost of solar energy to the point that it becomes competitive in relevant energy markets (e.g., buildings and power plants) and for solar technology to reach a level of market penetration to enable a sustainable solar industry.

Program Areas

In FY 2006, the Solar Program consisted of three subprogram areas. The first two, Photovoltaics and Solar Thermal, are technical and cover five key activity areas:

Photovoltaics

- Fundamental Research
- Advanced Materials and Devices
- Technology Development

Solar Thermal

- Concentrating Solar Power
- Solar Heating and Lighting

The third subprogram, Systems Integration and Coordination, covered crosscutting activities that reflected a Systems-Driven Approach to managing the Solar Program. This subprogram provided a framework and the analysis tools to explore alternative pathways and identify critical technology needs to guide planning and management of the entire solar portfolio.

Awards and Patents

Among the nation's premier awards for technological innovation are those presented by *R&D Magazine*. In FY 2006, Solar Program researchers at ORNL received an R&D 100 Award for their hybrid solar lighting (HSL) system. The system uses a roof-mounted solar collector and small fiber optics to transfer sunlight to hybrid fixtures with electric lamps. A control system enables sunlight to power the light and illuminate about 1,000 square feet during sunny daylight hours while clouds and darkness allow the system to revert to providing regular electrical light.

Developing intellectual property, and acquiring patent protection for the work, is another critical component of the Solar Program's role in moving technologies into the marketplace. In FY 2006, the Electronic Materials and Devices project at NREL led the entire laboratory in generation of new intellectual property, filing 12 patents, which is more than a third of all of the records of invention from NREL. During the year, four of the inventions reported in earlier years were granted patents.

The Future is Now

FY 2006 got off to a rousing start with the Solar Decathlon, which was competed in October 2005 (Fig. 2). Following on the success of the first Solar Decathlon in 2002, the event featured teams of college students vying to design and build the most effective solar-powered house. With more than 100,000 visitors touring the homes on the National Mall in Washington, D.C., and hundreds of news stories in national and local media, the event captured the attention of the American public. It put solar technologies on center stage for several weeks before, during, and after the competition. More to the point, the two Solar Decathlons, and the next one slated for October 2007, have opened the door to new technologies and a new generation of young people schooled in the ways of energy-efficient building and the freedom inherent in solar-powered homes.

Fig. 2. Early in FY 2006, hundreds of college students from the United States and around the world celebrated their moment in the sun at the Solar Decathlon. "Every one of these houses is a marvel of engineering and design, and a model of creativity and innovation," said U.S. Secretary of Energy Samuel W. Bodman.

Halfway through the year came new opportunities and the beginning of an action plan for expanding domestic solar energy production under the Solar America Initiative. By year's end, we saw this as a transitional year for the Solar Program, leading to a fundamental change in our way of doing business for FY 2007 and beyond.

So what do the coming years hold in store? Our plans are ambitious—and directed toward markets whose potential size can be measured in gigawatts rather than megawatts. We must meet levelized energy cost goals for solar energy that will open those markets, and the Solar America Initiative provides a roadmap for doing that.

We will continue to use analytical techniques and models, based on the Systems-Driven Approach, to optimize our research portfolio. We will invest in partnerships with the private and public sectors, using the balance of near-, mid-, and long-term research and related activities that will have the most impact on gigawatts installed. Risk is being factored into this analysis, as well as the use of outside experts to ensure our analysis is robust.

As in the past, our annual operating plan and subcontracts will contain robust milestones, as defined in the stage-gate model for both commercialization and research paths. But added to this will be a new emphasis on next-generation technology and open-ended, outside-the-box research. Workforce development is also a major priority to get the pipeline flowing with people who can help bring the technologies to the next level.

We'll be on the lookout to knock down barriers to installing solar energy systems, such as integrating solar energy systems with the power grid. We want solar power to be affordable, but also easy to get and use. Under the Market Transformation component of the SAI, such as the Solar America Cities activities, we will address these issues.

All of this is marching toward our ultimate goal of zero energy homes and buildings that are self-contained and self-sustaining from an energy perspective. We have them now, but they are not yet affordable. Our goal is to improve the efficiency of the building by 70% so the solar power goes further.

Based on 30 years of success, we are fortunate to be here at the right time and place. We plan to get more and more solar out there—for energy security and to make a huge difference in the future for climate change.

Steven Chalk
Solar Energy Technology Program Manager (acting)
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

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Photovoltaic R&D Subprogram Overview

Richard J. King, Team Leader, Photovoltaic R&D

The majority of the Photovoltaic Subprogram's activities are carried out through two primary research centers: the National Renewable Energy Laboratory (NREL) in Golden, CO, and Sandia National Laboratories (SNL), in Albuquerque, NM. Brookhaven National Laboratory (BNL), in Upton, Long Island, NY, provides program support in the area of environmental health and safety. NREL, SNL, and BNL are all partners in the National Center for Photovoltaics (NCPV), which provides guidance to DOE PV research efforts. In addition, the DOE Golden Field Office (GO), in Golden, CO, administers and manages contracting activities assigned by headquarters.

PV Subprogram research is focused on increasing domestic capacity by lowering the cost of delivered electricity and improving the efficiency of modules and systems. We emphasize long-term innovative research, thin-film development, manufacturing R&D, and systems development and reliability. Long-term research is focused on "leapfrog" technologies such as polymers and nanostructures. In thin films, new levels of efficiency and stability in prototype modules have been achieved, as well as higher laboratory cell efficiencies. Near-term research is focused on reducing cost through manufacturing advancements and by improving system reliability.

Goals and Objectives

The goals of the PV Subprogram follow the lead of the Solar America Initiative. The aim is to reduce the cost of PV technologies to the point that PV-generated electricity is cost competitive with conventional electricity sources by 2015. Specifically, the 2015 PV goals are to reduce costs to 8¢–10¢/kWh in the residential sector, 6¢–8¢/kWh in the commercial sector, and 5¢–7¢/kWh in the utility sector. Achieving these goals will require reducing installed PV system costs by 50%–60% between 2005 and 2015, from $5.5–$8.50/Wp to $2.25–$3.50/Wp in 2005 U.S dollars.

Results and Accomplishments

July 7, 2006, marked the ribbon-cutting ceremony for NREL's new Science & Technology Facility. The 71,000-square-foot, state-of-the-art facility is designed to help accelerate the development and commercialization of promising new energy technologies, particularly in solar, hydrogen, and building-related energy technologies. The facility has space for 75 full-time researchers and features an 11,500-square-foot Process Development and Integration Laboratory, which will allow NREL and industry researchers to work together to develop new PV manufacturing processes. This cooperative research will help reduce the time it takes to move new technologies from the laboratory bench to commercial manufacturing.

In existing research areas, laboratory researchers made rapid performance improvements on a variety of fronts. Crystalline silicon heterojunction solar cells with amorphous silicon (a-Si:H) layers were deposited by hot-wire chemical vapor deposition. The research team achieved an NREL-confirmed conversion efficiency of 17.83% for a 1-square-centimeter cell with both a front heterojunction emitter and a back heterojunction contact fabricated entirely below 200°C at NREL. This is the best published cell efficiency on a p-type Si wafer by the a-Si:H/c-Si heterojunction technology. Researchers also fabricated high-efficiency (19.52% confirmed) copper indium gallium diselenide (CIGS)-based solar cells using a single-layer, NREL-developed, chemical-bath-deposited CdZnS buffer layer. NREL has been the world leader in fabricating the most efficient CIGS thin-film solar cells since 2002.

Boeing Spectrolab demonstrated a 40.7%-efficient GaInP/GaInAs/Ge cell that was verified by NREL at 236 suns. Researchers have been working toward the "40% barrier" for the past two decades. In the 1980s, multijunction solar cells achieved about 16% efficiency, and NREL broke the 30% barrier in 1994. Today, most satellites use these multijunction solar cells, and

Spectrolab, a subsidiary of The Boeing Company, recently produced its two millionth solar cell using this multijunction technology. The new Spectrolab cell, developed with DOE funding, could lead to more affordable solar power systems, costing as little as $3/watt to install and producing electricity at a cost 8¢ to 10/¢kWh.

The Thin Film PV Partnership supported manufacturing advances of key thin-film technologies during the fiscal year. This is viewed as the Partnership's most important activity in the short term, because it will help establish thin films in the marketplace, improve their chances of future growth and success, and help define the transition of technologies that have been successfully developed by DOE funding to the private sector. Two Technology Partners expanded manufacturing facilities in the United States (First Solar 85 MWp and Uni-Solar 60 MWp). A third Technology Partner, Global Solar, announced plans to expand in 2007. Production of thin films in the United States grew from 12 MWp in 2003 to an estimated more than 70 MWp in 2006.

The PV Manufacturing R&D Project completed the development (achieved manufacturing-line-ready status) of at least three in-line diagnostic processes initiated in FY 2002 awards from "In-Line Diagnostic, Intelligent Processing (IDIP) Solicitation." At least five of the U.S. PV industry partnerships involved in the IDIP solicitation reported a minimum of 22 in-line diagnostic processes that have been implemented on U.S. PV production lines.

Solar Program staff members are also active participants in developing the codes and standards so critical to the safety and consumer acceptance of PV systems. As part of this work, the 2005 National Electrical Code was published with the 42 changes proposed by the SNL "Industry Forum" with new allowances for ungrounded PV arrays and improved disconnect requirements.

In California, one the world's largest markets for PV systems, the Los Angeles Department of Water and Power revised its solar energy rebate program from one providing a rebate amount based on system size to one based on the estimated energy output predicted by NREL's PVWATTS model. Consequently, rebate amounts will now depend on parameters that determine energy production: size, tilt, azimuth, fixed or tracking, and location of the PV system.

Professional Recognition

A mark of the impact of a research group is the contribution its members make to the broader scientific community. Scientists, researchers, and managers within the NCPV are active, working members of numerous professional organizations and are widely recognized for their roles. Citing only a few examples from 2006, Sally Asher was elected a chair of the Applied Surface Science Division of the American Vacuum Society (AVS) and is program committee co-chair for the 54th AVS International Symposium. Pete Sheldon was elected a director of the AVS. David Ginley served as general chair of the Fall 2005 Materials Research Society Meeting; subsequently he was selected to be secretary of the society. Timothy Coutts served as program chair of the 4th World Conference on Photovoltaic Energy Conversion; he has been selected to be general chair of the 33rd IEEE Photovoltaics Specialists Conference.

Finally, Lawrence Kazmerski received two prestigious awards in 2006. Pennsylvania State University honored him with the Nelson W. Taylor Award for Materials Science. He also received the World PV Award at the Fourth World Conference on Photovoltaic Energy Conversion for his outstanding contributions to the worldwide advancements of PV science and technology. The award, sponsored by professional organizations from the European, Asian-Pacific Rim, and U.S. PV communities, recognizes superior and sustained leadership in solar photovoltaics. Kazmerski is director of the NCPV and was the first staff member hired to do PV research for NREL's predecessor, the Solar Energy Research Institute.

Fundamental Research

Fundamental or basic research investigates the physical mechanisms of charge carrier transport, band structure, junction formation, impurity diffusion, defect states, and other physical properties of photovoltaic and photoelectrochemical materials. This area also includes solar resource characterization and environmental health and safety.

Among the research topics are innovative ideas and technologies with the potential to “leapfrog” current approaches. This high-risk research leads to new, nonconventional concepts that could dramatically improve cost effectiveness in the long term.

Fundamental research is key to the continued advancement of photovoltaic technology necessary to meeting the 2015 goal of achieving $0.05/kWh to $0.10/kWh battery-free, grid-tied systems. Industry and university researchers work in partnership with national laboratories to improve the efficiency of cell materials and devices by investigating their fundamental properties and operating mechanisms. This teamed research approach works to identify efficiency-limiting defects in cell materials and analyze their electrical and optical properties.

FY 2006 marked a host of accomplishments in the Fundamental Research area, including:

Measurements and Characterization

- Provided measurement support in the areas of analytical microscopy, surface analysis, electro-optical characterization, and cell and module performance to more than 70 PV research partners in industry, academia, and NREL.
- Maintained International Standards Organization accreditation for primary and secondary cell and module calibrations.
- Relocated staff and characterization labs (Surface Analysis, Electro-Optical Characterization, and Analytical Microscopy areas) to the new Science and Technology Facility.

Solar Resource Characterization

- Completed a draft 15-year National Solar Radiation Data Base (NSRDB) and distributed for review. Completed plan for final NSRDB update and began final validation and production.

Environmental Health and Safety

- Promoted and established international collaborative life-cycle environmental assessments of PV energy technologies, enhancing the quality and quantity of PV environmental assessments.

Crystalline Silicon Project

- Achieved a record efficiency for p-wafer silicon heterojunction solar cells with a confirmed efficiency of 18.2%. This 1 cm^2 cell has a-Si contacts on both sides and an open-circuit voltage of 0.667 V.
- Modeling showed that 18%–20%-efficient low-cost cells with screen-printed contacts using 100 to 200 µm-thick c-Si wafers can reduce the levelized cost of electricity to 5–10 ¢/kWh.

Electronic Materials and Devices

- Applied for six patents on the direct printing of precursors for CIS solar cell absorbers and metallization for Si solar cell contacts.
- Achieved 19.52%-efficient CIGS/CdZnS solar cell; 17.1%-efficient, 1-µm, thin CIGS solar cell; and 15.02%-efficient thin CdTe solar cell.

High-Performance Photovoltaics

- The Institute of Energy Conversion demonstrated an 11.9% CIGSS (1.5 eV) top cell material of the polycrystalline thin-film tandem.
- Boeing Spectrolab demonstrated a 40.7%-efficient GaInP/GaInAs/Ge cell that was verified by NREL at 236 suns.

Measurements and Characterization

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Peter Sheldon, 303-384-6533, peter_sheldon@nrel.gov

DOE HQ Technology Manager: Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2006 Budget: $6,728K

Objectives

- Provide routine and specialized measurement and characterization support for PV program research and industry teams.
- Lead and contribute to collaborative research that addresses critical issues in PV technologies.
- Develop and implement novel measurement techniques that enhance the ability to understand and advance fundamental PV research and development.

Accomplishments

- Provided measurement support in the areas of analytical microscopy, surface analysis, electro-optical characterization, and cell and module performance to more than 70 PV research partners in industry, academia, and NREL.
- Maintained our International Standards Organization (ISO) accreditation for primary and secondary cell and module calibrations.
- Completed capability to evaluate multiple-junction concentrator cells and modules to 1000X with lowest possible uncertainty.
- Investigated the structural properties of site-selected c-Si/a-Si interfaces in Si heterojunction cells with new record efficiencies.
- Investigated local open-circuit voltage (V_{oc}) and local current flow in amorphous and nanocrystalline mixed-phase silicon solar cells.
- Conducted study correlating composition and structure of moisture barrier layers grown on flexible substrates with growth conditions, water vapor transport rates, and adhesion properties.
- Studied the reaction kinetics of nanoscale Cu_xTe films, an important component of back contacts in CdTe-based devices.
- Organized the *16th Workshop on Crystalline Silicon Solar Cell & Modules: Materials and Processes.*
- Developed models to help understand crack propagation and wafer breakage in Si wafers.
- Applied spectroscopic ellipsometry to facilitate improvement of Si heterojunction solar cells.
- Relocated staff and characterization labs (Surface Analysis, Electro-Optical Characterization, and Analytical Microscopy areas) to the Science and Technology Facility (S&TF). Fitted up new laboratories and restored to operational status.

Future Directions

- Provide measurement support in the areas of analytical microscopy, cell and module performance, electro-optical characterization, and surface analysis to at least 70 PV research partners in industry, academia, and NREL.
- Maintain ISO accreditation for primary and secondary cell and module calibrations.
- Develop integrated plan to provide priority support to Solar America Initiative (SAI) Technology Pathway Partnership (TPP) awardees that meets their R&D needs within the context of available resources.
- Investigate the atomic structure of the c-Si/a-Si interface and the thickness and crystallinity of the a-Si layer in Si heterojunction cells as a function of cell processing conditions.
- Develop luminescence mapping capability for industrial silicon wafers.

- Organize the *17th Workshop on Crystalline Silicon Solar Cell & Modules: Materials and Processes*: identify priority R&D issues for the Si PV industry.
- Improve understanding of CdTe back contact reaction kinetics by developing a quantitative model for surface-segregation phenomena.
- Investigate materials chemistry of copper indium gallium diselenide (CIGS) on flexible substrates, leading to an improved understanding of long-term reliability.
- Complete study of the kinetics of microcrack propagation and improve our understanding of how thermal profiling and mechanical stresses, associated with conventional processing, impact propagation.
- Assess the technical shortcomings of minority-carrier lifetime measurement techniques used to determine material quality of mc-Si; apply improved understanding to facilitate better measurements of material quality for the PV industry.
- Develop enhanced cell and module measurement capabilities that improve measurement turn-around time and uncertainty necessary to support the SAI (requires capital equipment funding).

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1. Introduction

The Measurements and Characterization Division provides test, measurement, and analysis support and research for the National Photovoltaics Program. It supports all PV material technologies and involves essential collaborations with external research partners in university and industry laboratories, PV manufacturers, and internal research groups. Each year, this project assists clients with the test and analysis of thousands of materials and device samples, helping them to understand and direct work on their research and commercial product development.

These activities address one or more of the three areas crucial to meeting the EERE goal of reducing the levelized cost of energy for PV to $0.06/kWh by 2015. The three areas are (1) improving device and module performance, (2) reducing manufacturing costs, and (3) improving device/module reliability. This is accomplished by selecting projects that address key issues for a broad spectrum of technologies, including c-Si, a-Si, thin Si, copper indium diselenide (CIS), CdTe, III-Vs, and future-generation materials.

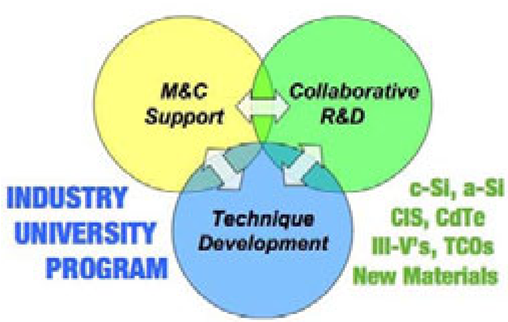


Fig. 1. Schematic showing Measurements and Characterization research areas of emphasis.

As shown in Fig. 1, for each technology, we allocate resources to: (1) provide routine and specialized measurement and characterization support for research and industry partners; (2) lead and contribute to collaborative research that addresses critical issues in these PV technologies; (3) develop and implement novel measurement techniques that enhance our ability to understand and advance fundamental PV R&D.

2. Technical Approach

The project is composed of four core competency research tasks and a management/coordination task. The four research tasks are Analytical Microscopy, Cell and Module Characterization, Electro-Optical Characterization, and Surface Analysis. The major *non-support* research activities pursued in FY 2006 are outlined below by task. *Although a significant portion of our work involves working with industry to solve research and manufacturing problems in a timely manner, these activities are not reported in this document because of their proprietary nature. Nevertheless, during the past year, we have collaborated with well over 70 research groups from industry, universities, and national laboratories.* FY 2006 priority milestones in each task are listed below.

2.1 Analytical Microscopy Task

- Investigate the structural properties of site-selected c-Si/a-Si interfaces in record-efficiency Si heterojunction cells.
- Investigate local V_{oc} and local current flow in amorphous and nanocrystalline mixed-phase silicon solar cells.
- Complete investigation of screen-printed contacts on industrial Si Cells.

- Commission a focused ion beam (FIB) workstation and develop transmission electron microscopy (TEM) sample preparation techniques for PV thin films.
- Relocate a portion of research operations to the S&TF.

A summary of progress on these milestones is outlined in section 3.1.

2.2 Cell and Module Performance Task

- Complete capability to evaluate multiple-junction concentrator cells and modules to 1000X with lowest possible uncertainty.
- Maintain ISO 17025 accreditation for primary and secondary cell and module measurements.

A summary of progress on these milestones is outlined in section 3.2.

2.3 Electro-Optical Characterization Task

- Organize the *16th Workshop on Crystalline Silicon Solar Cell & Modules: Materials and Processes*.
- Develop models to help understand crack propagation and wafer breakage in Si wafers.
- Apply spectroscopic ellipsometry to facilitate development of improved Si heterojunction solar cells.
- Relocate a portion of research operations to the S&TF.

A summary of progress on these milestones is outlined in section 3.3.

2.4 Surface Analysis Task

- Study relationship between moisture barrier deposition fundamentals and ultimate barrier performance characteristics.
- Study the reaction kinetics of nanoscale Cu_xTe films.
- Conduct studies of wet-chemical processing of PV material surfaces leading to better control of deposition processes.
- Design and specify a cart-based Auger electron spectroscopy tool for use at S&TF.
- Relocate a portion of research operations to the S&TF.

A summary of progress on these milestones is outlined in section 3.4.

Budget allocations by task are provided below.

Task Title	FY 2006 Budget ($K)
Analytical Microscopy	1,708
Cell and Module Performance	1,268
Electro-Optical Characterization	1,692
Surface Analysis	1,380
Management/Maintenance	680

3. Results and Accomplishments

Research results outlined in this section address only FY 2006 priority milestones, which represent only a portion of all support and research activities within the division. A more complete summary of all division research activities can be found in our bimonthly reports. Highlights for each task are outlined below.

3.1 Analytical Microscopy Task

Investigation of the structural properties of site-selected c-Si/a-Si interfaces in Si heterojunction cells with new record efficiencies:
In collaboration with NREL's Si Group, the structural properties of site-selected c-Si/a-Si interface in Si heterojunction (SHJ) cells with new record efficiency of 18.2% were investigated. These cells have the best published cell efficiency in a p-type Si wafer by the a-Si:H/c-Si heterojunction technology and exceeds NREL's FY 2006 AOP milestone of 18%. The improvement over the previous best cell (17.8%) results mainly from achieving a thinner amorphous silicon emitter that reduces parasitic absorption losses. The thickness and uniformity of the a-Si layer and the quality of the a-Si/c-Si interface were examined by site-selected TEM preparation using our new FIB and high-resolution transmission electron microscopy (HRTEM). Because the cells are textured, cross-sectional TEM samples must be prepared along certain directions and at specific areas. This was achieved by using dual beam FIB milling.

Figure 2(a) is a scanning electron microscope (SEM) image of a site-selected cross-sectional TEM foil made from a 18.2% Si device, showing three different areas: (112) facets, (111) top, and (111) bottom. These three areas correspond to the textured surface structure. The Ag layer is the contact layer. Figure 2(b) is a HRTEM image from a (112) facet area, showing that the a-Si layer is very uniform and around 4.2 nm thick, which is much thinner than that in the previous record Si cells (about 5–6 nm). Figure 2(c) is a HRTEM image taken from a (111) top area. The dashed line indicates the location of the a-Si layer. However, the a-Si layer is not seen. Instead of an a-Si/c-Si interface, an In_2O_3/c-Si interface is observed. The HRTEM images taken from the (111) bottom areas showed similar features.

In summary, we developed an approach that enables thinner a-Si layers than in previous SHJ

Si cells, resulting in higher efficiency devices. In the (112) facet areas, the a-Si layer is uniform in thickness and the c-Si/a-Si:H interface is atomically abrupt. However, the a-Si layers at the top and bottom (111) facet regions are not clear and no abrupt a-Si/c-Si interfaces were observed, providing guidance for future cell improvement.

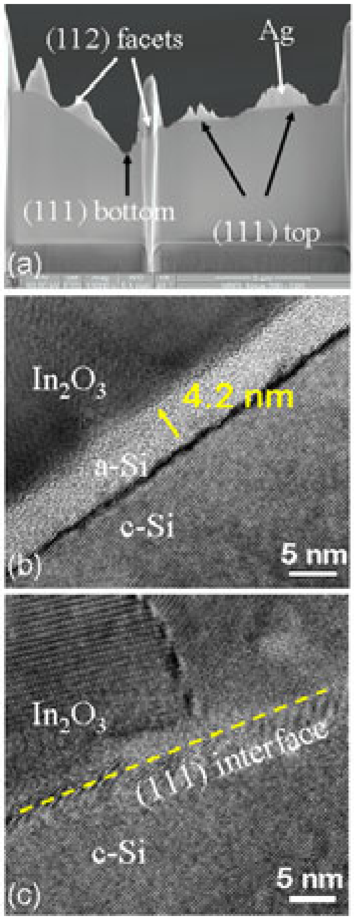


Fig. 2. (a) SEM image of a site-selected cross-sectional TEM foil made from a Si cell with 18.2% efficiency, showing three different areas: (112) facets, (111) top, and (111) bottom; (b) HRTEM image from a (112) facet area; (c) HRTEM image taken from a (111) top area.

Investigate local V_{oc} and local current flow in amorphous and nanocrystalline mixed-phase silicon solar cells:

Amorphous silicon (a-Si:H) solar cells made close to the transition from amorphous to nanocrystalline phases, but still in the amorphous regime, show an improved initial performance and stability. On the other hand, nanocrystalline silicon (nc-Si:H) solar cells made close to the transition, but in the nanocrystalline regime, also show good performance. The devices made in the transition region are called mixed-phase solar cells. In collaboration with United Solar, Inc., we have measured the microelectrical properties of local V_{oc} and local current flow in the mixed-phase *n-i-p* silicon solar cells by scanning Kelvin probe microscopy (SKPM) and conductive atomic force microscopy (C-AFM). Figure 3 shows the SKPM electrical potential and AFM topographic images, and a line profile of the V_{oc} distribution along the arrow shown in Fig. 3(a).

From both the SKPM and AFM images, we observed that the nc-phases aggregate in the a-Si:H matrix. Each aggregate is ~500 nm in size and contains many small nanometer-sized grains. Under illumination of 1.85 eV laser light, reduced V_{oc} is observed when probing the nc-Si:H aggregates. V_{oc} gradually increases, over a distance of 1 µm, as one probes farther away from the aggregate into the surrounding a-Si:H matrix. The minimum V_{oc} values in the nc-Si:H aggregates, in the mixed phase, is larger than the V_{oc} of the nc-Si:H single-phase device. This and the V_{oc} changes observed could be caused by charge redistribution near the a-Si:H/nc-Si:H boundary in the *i*-layer bulk. Although there is some lateral electrical interaction, a clear distinction between the amorphous and nanocrystalline regions has been observed.

We also measured local current flow or local conductivity by using C-AFM. We found that the local current value of the nc-Si:H phase is much larger than that of the surrounding a-Si:H matrix, and the transition interface between the high and low currents is sharp. The forward biased C-AFM images show that the current is very low over the entire surface of the fully a-Si:H region. High current spikes are observed in the mixed-phase region, where the current spikes correspond to nc-Si:H aggregates. The density of the current spikes increases from the mixed phase to the heavy nc-Si:H regions. A thick a-Si:H buffer layer, inserted between the *p* and *i* layer, significantly reduced the magnitude of the current spike in the nc-Si:H region. The C-AFM and the SKPM measurements suggest that the mixed-phase cells can be considered as a two-phase, parallel-connected diode structure.

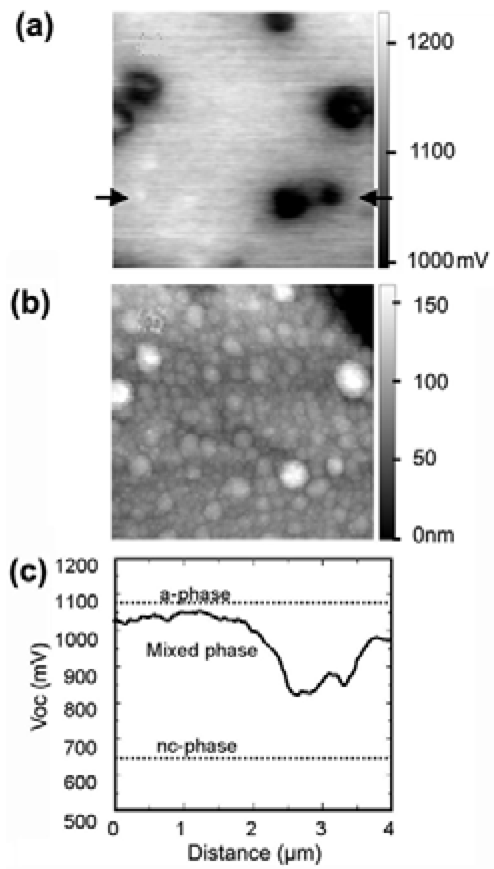


Fig. 3. (a) SKPM image and (b) the corresponding AFM image taken on a-Si:H and nc-Si:H mixed-phase solar cells. (c) is an example local V_{oc} line profile along the arrows in (a), as deduced from the SKPM measurement.

Electron backscatter diffraction (ESBD) studies of thin-film Si:

EBSD is based on the fully automated acquisition of diffraction patterns produced by backscattered electrons under diffraction conditions in scanning electron microscopy. EBSD provides maps of the orientation of crystalline phases with very high resolution and can be used to investigate the misorientation of individual grain boundaries (GBs), identification of special boundaries, grain distribution, preferential orientation, deformation, and strain.

In collaboration with NREL's Si Group, we have investigated the microstructure of Si thin-film devices as a function of deposition and post-deposition processing conditions. These films are based on the recrystallization of amorphous silicon films in the solid phase. We studied the impact of rapid thermal annealing (RTA) and hydrogen passivation. The RTA was performed at 900°C for 4 minutes, while the hydrogen passivation was carried out at 550°C. We performed EBSD measurements on both the aluminum-induced crystallization (AIC) seed layers and the epilayers at different stages of the processing (1) after deposition, (2) prior to post-deposition treatments, (3) after RTA, and (4) after hydrogen passivation. Figure 4 illustrates the results of the EBSD measurements for the AIC seed layer prior to post-deposition treatments. A map of the band contrast calculated from the diffraction pattern reflects the microstructure of the film far better than standard secondary-electron imaging. Below this, a map shows the grain boundary distribution. To the right, the orientation maps along the in-plane and out-of-plane directions are shown.

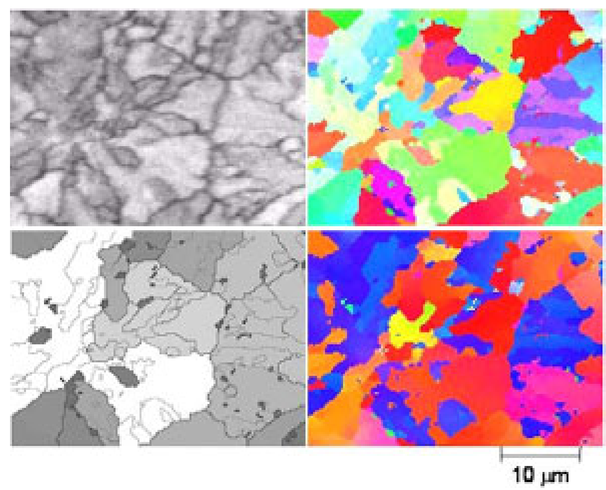


Fig. 4. (Top left) The microstructure of an Al-induced crystallized Si seed layer. (Bottom left) Map outlining the grain boundaries. Orientation maps along the in-plane (X) and out-of-plane (Z) directions are shown in the top right and bottom right, respectively.

Prior to post-deposition treatments, the seed layer exhibits nearly perfect bimodal distribution toward <100> and <111>, as indicated by the pole figures. We find that most of the GBs on the orientation map are Σ3 and Σ9. These are twinning boundaries and they are regarded as intra-grain boundaries. After these special boundaries are dismissed, grain diameters in the 10-μm range are standard for the seed layer. The epilayer develops larger grains than the underlying seed layer and is preferentially oriented toward <100>; the domains remaining <111>-oriented result from twinning.

After RTA, the seed layer shows the <100>/<111> bimodal distribution. The RTA treatment stimulates the generation of twinning boundaries and other boundaries in what seems to be previously well-developed grains, resulting in smaller grains. On the epilayer, the angle spread along <100> is slightly higher than before RTA, suggesting local recrystallization. After hydrogen passivation, the bimodal distribution in the seed layer is not as well defined as before. The results for the epilayer after hydrogen passivation are similar to those obtained after RTA.

Investigate screen-printed contacts on industrial Si cells (in collaboration with BP Solar, Ferro, and Applied Materials):
SKPM and C-AFM, combined with SEM, were used to investigate the firing temperature effect on cast Si solar cells with screen-printed Ag front contacts and Al back surface field (Al-BSF). We analyzed samples with firing temperatures lower and higher than the estimated optimal temperature. For the samples with low firing temperatures, the SKPM measurements indicate that the p-n junction is located 400 nm below the surface of the wafer. Both under and beside the screen-printed Ag contact, the electric field induced by a reverse bias voltage of –1 V is 1.1E4 V to 1.4E4 V/cm and spreads over 900 to 1100 nm. In comparison, for the samples with the high firing temperatures, the p-n junction is located 500 nm below the surface of the wafer and the electric field induced by a –1 V bias voltage is 1.3E4 V to 1.6E4 V and spreads over 1100 to 1500 nm. The C-AFM combined with SEM analysis of the Ag/Si interface reveals that the bulk of the screen-printed contact consists of a mixture of conductive (Ag) and insulating (glass frit) parts. Further, SEM analysis using the doping contrast mode were performed to investigate the depth of the Ag penetration toward the p-n junction and to confirm the location of the p-n junction. For the low-firing-temperature samples, SKPM measurements at the Al-BSF side indicate a p/p+ junction 200 nm below the Al/Si interface. Under a forward-bias voltage of 1 V, the electric field induced at this junction is 1E4 V/cm. These data are being used to help formulate improved contacting inks and optimize firing parameters to yield higher performance contacts.

Commission a focused ion beam (FIB) work station and develop TEM sample preparation techniques for PV thin films:
We have commissioned a FEI Nova 200 NanoLab dual-beam SEM/FIB. This dual-beam instrument consists of an FIB column and a SEM column on the same platform. Supporting other analytical tools such as TEM, the dual-beam FIB performs precise, site-specific sample preparation for both TEM and SEM. This technique allows the preparation of electron transparent TEM samples from thin-film/substrate material combinations that were either extremely difficult or not possible using previous preparation techniques.

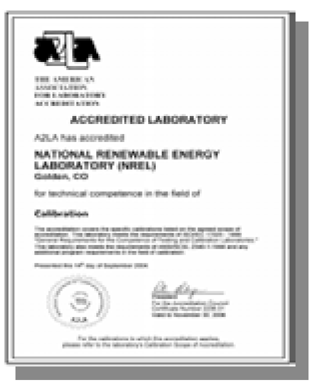
3.2 Cell and Module Performance Task

Complete capability to evaluate multiple-junction concentrator cells and modules to 1000X with lowest possible uncertainty:
The capability of the Spectrolab high-intensity pulsed solar simulator (HIPSS) has been enhanced, by expanding the current ranges; spectral adjustment (through lamp voltage adjustment); and intensity adjustment (through variable apertures). The test device's current range was expanded to 0.1A–60A full scale, and the single fixed-range reference cell channel was expanded to two reference cell channels with current ranges from 0.005A to 2A. This allows the I-V characteristics to be measured from 1 sun to 2,000 suns for all PV technologies of interest. Other options were also investigated to enhance the test bed capabilities, such as modifying the sweep circuit to be able to reverse the sweep direction to detect bias rate artifacts or using filters to further adjust the spectrum. The spatial nonuniformity was also mapped to understand and minimize uniformity-related error sources. A stage-gate analysis was performed with the conclusion that additional funds for a spectrally adjustable solar simulator would be required to further reduce the uncertainty for high-efficiency cell designs where the current matching of more than the top two junctions is required.

Maintain ISO 17025 accreditation for primary and secondary cell and module calibrations. Complete periodic audits, maintenance of quality systems, calibrations, softwar,e and documentation to meet A2LA requirements:
Quality calibration plays a critical role in the product-manufacturing process. ISO accreditation provides our customers with confidence that the performance reported for these products is verifiable and internationally accepted. Many of our PV industry partners currently have ISO 9001 quality programs in place. These companies rely on NREL for calibrations of reference cells and modules they use to measure their products. Certified module-qualification facilities such as

Arizona State PV Testing Laboratory and Florida Solar Energy Center (FSEC) require their reference cell calibrations to be traceable to a certified laboratory. All PV calibrations performed by the group are traceable to primary reference cells calibrated by NREL. NREL is one of four calibration laboratories in the world certified to perform world Photovoltaic Scale Primary reference cell calibrations. For this reason, it was critically important that NREL attain an ISO accreditation for the reference cells we calibrate for the PV community. The ISO 17025 accreditation provides NREL with international credibility and recognition.

This process took two years to complete and involved establishing a very structured quality system, detailed work procedures, detailed document control methodology, formalized record-keeping process, rigorous management review process, corrective action plan process, and an instrument calibration validation process. Implementing and maintaining an ISO 17025 program is a significant and critically important task. Test beds within the PV performance team that produce numerical results for customers that are not within the scope of A2LA certificate 2236.01 are required to be in calibration as if part of the scope and the software is subjected to the ISO 17025 software review process.


ACCREDITED LABORATORY

A2LA has accredited

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)

Golden, CO

for technical competence in the field of

Calibration

Fig. 5. NREL A2LA accreditation certificate #2236.01

Other activities in support of the DOE PV program: PV cell and module calibration service. Performed 5,285 standardized spectral responsivity, linearity, and current-versus-voltage calibrations on 1,620 different cells and modules of all technologies in support of the DOE PV program. Thirteen concentrator prototype modules from six companies were evaluated, generating more than 77,592 current-versus-voltage curves with accompanying irradiance and other meteorological data. Direct-beam spectra also accompany the data set for 15 sunny days.

Consolidated concentrator cell characterization activities from two buildings to a single laboratory, leading to improved operational efficiencies.
American Society for Testing and Materials (ASTM) and International Electrotechnical Commission (*IEC) standards* – Attended committee meetings and participated in standards development. Shepherded standards for linearity determination, rating concentrator modules and systems, and spectral responsivity measurements.
Underwriters Laboratories (UL) Cooperative Research and Development Agreement – UL approached NREL and requested assistance in performing portions of Module Qualification and Certification tests. Customers requesting certification interact with UL. NREL performs tests for UL. The Cell and Module Performance group performs all current-voltage (I-V) measurements required at various stages of test sequence. This required that the capability be developed to measure following IEC standards 61646 and 6215 to measure the I-V characteristics at 0.2 suns and at normal operating cell temperature (NOCT). Options for measuring module temperature coefficients outdoors following IEC 60904 standards were also evaluated.

3.3 Electro-Optical Characterization

Organize the 16th Workshop on Crystalline Silicon Solar Cell & Modules: Materials and Processes: The 16th Workshop on Crystalline Silicon Solar Cells and Modules was held in Denver, Colorado, August 6–9, 2006. Participants came from 14 different countries and the workshop was attended by 157 scientists and engineers from 39 research institutions, DOE HQ and GO, 34 international PV and semiconductor companies, and two DOE national laboratories (SNL and NREL).

The 3.5-day workshop is geared to help the PV-Si industry by (1) bringing together the industry, research, and academic communities, (2) disseminating scientific and technical information by nurturing collective views on critical research areas, and (3) providing feedback to NREL/DOE on important research tasks, as perceived by the PV community. This is achieved at the workshop through a combination of oral presentations by invited speakers, poster presentations, and discussion sessions. This year's sessions reviewed recent advances in crystal growth technologies, impurities and defects in semiconductors, feedstock issues, solar cell processing, thin-film Si and heterojunction devices, solar cell metallization, and module reliability issues. The theme of the workshop—"Getting More (Watts) for Less ($i)"—reflected the growing need for maximizing the use of silicon to obtain the largest amount of PV energy. A rump session, "Toward 100 μm Wafer Thickness and Beyond," was held on the evening of August 6, which allowed attendees to discuss the issues and potential solutions to reducing the wafer thickness for increased cell efficiency and lower Si consumption.

Develop models to help understand crack propagation and wafer breakage in Si wafers: Wafer breakage is the most crucial issue in current commercial, low-cost solar cell production because typically about 10% of the wafers break during cell fabrication. It is now recognized that wafer breakage primarily arises because of the presence of microcracks either on the edges or the surfaces of the wafer. Figure 6 is a SEM micrograph of a crack typically seen on the edge of a wire-sawn and textured PV-Si wafer. Similar, but typically smaller, microcracks also exist on the wafer surfaces. Stresses produced by wafer handling or cell processing can propagate an existing crack or initiate (and then propagate) a new crack.

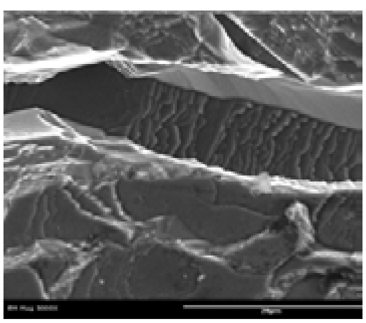


Fig. 6. A SEM photograph of a microcrack in wire-sawn and textured multicrystalline PV-Si wafer.

We have developed a new technique for screening wafers that have fatal cracks. In this technique, controlled stresses (representative of those experienced by a wafer during cell fabrication) are applied to a wafer to determine the propensity of the wafer for breakage. We have built a rudimentary machine to establish a proof of concept. Initial results are very positive. The wafer-screening machine is also an excellent tool for performing experiments to understand the mechanics of wafer breakage, the focus of our current work. Experimental results obtained in this machine can be combined with theoretical modeling to learn how microcracks propagate under various stress distributions produced by wafer processing, handling, and encapsulation.

Because wafer breakage is directly related to the kinetics of microcrack propagation, we are developing a theoretical model, which can be used to investigate propagation of microcracks under various stress distributions that are prevalent in solar cell processing. Such stress distributions occur in wafer handling (using various pick and place methodologies) and during high-temperature solar cell fabrication steps.

The new modeling software is a combination of a thermal modeling program that we developed for the study of dislocation generation by thermal stresses in silicon and the COMSOL Multiphysics, finite element modeling package. Figure 7 illustrates calculated results from this model. Figure 7a shows von Misses stress distributions around a microcrack of 2 μm, in a 125-mm x 125-mm silicon wafer under a tensile stress of 100 MPa. It is seen that large stresses exist near the crack tip. Figure 7b shows stress distributions for a 20-μm crack. The calculated stress intensity factor (SIF) values for the crack sizes of 2 μm and 20 μm are 0.28 MPa $m^{1/2}$ and 0.98 MPa $m^{1/2}$, respectively. A rule of thumb in fracture mechanics is that when the SIF reaches fracture toughness, the crack will become unstable and the wafer will break. The fracture toughness of a silicon wafer has a value of 0.9 MPa $m^{1/2}$. Hence, the wafer with a 20-μm crack size will break under a tensile stress of 100 MPa.

Our model is also applicable to stresses produced by thermal processing. The end result of this project will be a methodology that the PV industry can use to minimize wafer breakage. Such a methodology will include treatment of the wafers (e.g., etching) and optimization of temperature profiles during cell processing to minimize thermal stress effects, and establishing stress distributions that can be least harmful to the wafer/cell and prevent its breakage during wafer handling.

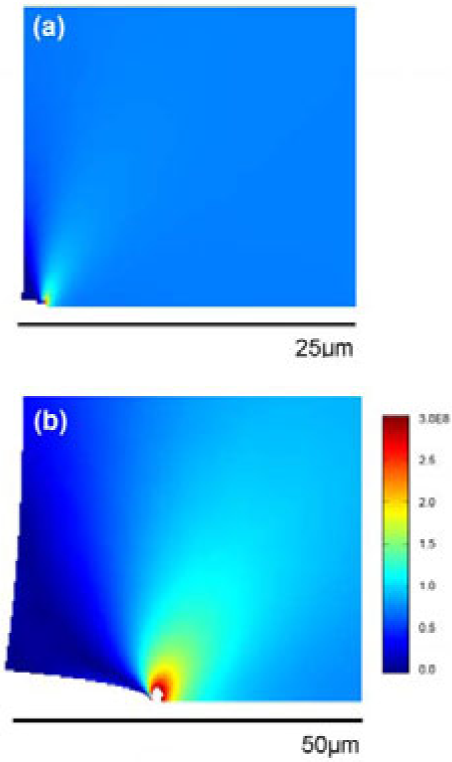


Fig. 7. Calculated stress distributions in 125-mm x 125-mm silicon wafer caused by the presence of microcracks, in response to a tensile stress of 100 MPa. Figures (a) and (b) correspond to microcracks of 2 μm and 20 μm, respectively. Figure (a) shows a 25-mm x 25-mm section, and (b) shows a 50-mm x 50-mm section in the vicinity of the cracks. The deformation of the wafer in both micrographs is magnified by a factor of 100.

Metallization firing and SiN:H studies (in collaboration with BP Solar, Ferro, and Applied Materials):
Metallization firing is the most complicated process step of a Si solar cell fabrication. A firing process step performs three separate functions: (1) dissolution of SiN:H by the front metallization followed by Si-Ag interactions at the front contact; (2) diffusion of hydrogen from the interface into the bulk of the cell for impurity and defect passivation; and, (3) alloying of the back Al contact to form a back surface field (BSF). To achieve the highest efficiency, each of these functions must be maximized. We are studying each of these functions to establish one process cycle that can maximize all of them to produce the highest efficiency cells. These studies require a furnace with a capability to apply a controlled optical flux as a function of time, a method to monitor the temperature distribution in the cell (in particular, under the metallization), and ability to characterize fired samples under different process conditions. To accomplish these, we have built an optical processing furnace with a capability to exhaust effluent, monitor the temperature distribution of the entire solar cell using multiple thermocouples attached to the cell itself, and control the entire process cycle. Characterization of fired cells is done by various groups in the M&C Division and is facilitated by a new procedure that we have developed for cross-sectioning a large area of a solar cell, using chemical mechanical polishing. Two important findings were that: (1) for a given optical flux, screen-printed cells exhibit a large temperature difference between regions with and without front metallization. For example, using an optical flux density profile that produced a maximum temperature of 812°C, away from the buss bar, yielded a temperature of 786°C under the buss bar (this represents near optimum firing conditions). Perhaps more significant is that these temperatures are far below the eutectic point of Ag-Si (835°C) and the melting point of Ag (961.9°C), yet they yield low-resistance ohmic contacts. This can only be explained by invoking mechanisms that can depress the eutectic melting point of Ag-Si, such as the presence of other metals and interface energy. It also suggests a need for carefully designed temperature measurements during solar cell processing.

Applied spectroscopic ellipsometry to facilitate development of improved Si SHJ solar cells:
Among the highest-efficiency PV modules commercially available today are Sanyo's HIT™ modules, which are based on silicon heterojunction technology. NREL's silicon materials team is rapidly developing the technology to challenge Sanyo's lead in the SHJ area. In FY 2006, the team achieved 18.2% efficiency on a p-type float-zone silicon wafer. One of the challenges in SHJ R&D is measuring the film thickness and material properties of the extremely thin (2–6 nm) amorphous silicon (a-Si) layers used in SHJ devices. Because the material properties are both thickness- and substrate-dependent, the only reliable way to measure them is to measure the films incorporated into the actual devices. We have applied *in-situ* and *ex-situ* spectroscopic ellipsometry to provide accurate and timely measurements of film thickness and optical and electronic properties of a-Si films used in SHJ devices. *In-situ* real-time spectroscopic ellipsometry (RTSE) has been used to gain insight into the film growth mechanisms, as well as how the material properties change with changes in the

deposition conditions. *Ex-situ* variable-angle spectroscopic ellipsometry (VASE) has been used to measure the properties of the a-Si layers in partially or fully completed SHJ devices. By measuring the thickness and absorption coefficient of the i-, n-, and ITO-layers in a SHJ device, we are able to calculate the optical absorption in these layers. This information can be used to pinpoint efficiency losses and targets for improving efficiency. Figure 8 shows a comparison of the optical losses that are due to absorption in the i- and n-layers with the difference in quantum efficiency between two devices that are identical except for the presence of the i- and n-layers forming the front junction. The agreement between these two disparate measurement techniques is excellent, indicating that light absorbed in the i- and n-layers does not contribute to the photocurrent in the SHJ cell.

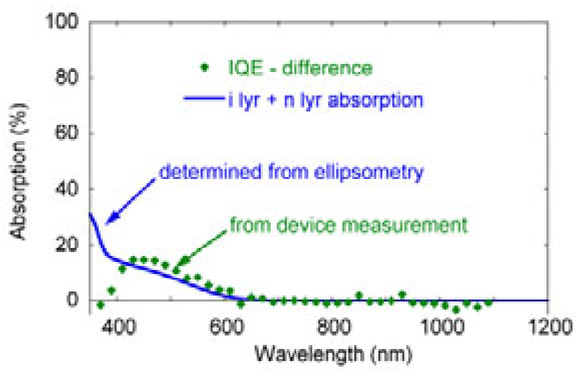


Fig. 8. Green diamonds; difference in internal quantum efficiency (IQE) between standard diffused junction Si PV cell and equivalent SHJ cell. Blue line; absorption in i- and n-layers determined from ellipsometry.

Apply Dessis 2-D device modeling software to elucidate fundamental limitations in crystalline and polycrystalline photovoltaic device designs:
Solar cell modeling has generally been limited to one-dimensional models that calculate simple current-voltage curves. A new effort within our group has focused on developing fully two-dimensional solar cell modeling with the ability to simulate multiple experiments or measurements including current-voltage, quantum efficiency, time-resolved photoluminescence, near-field scanning optical microscopy, electron-beam-induced current, and cathodoluminescence. This computational effort has been applied to diverse solar cell problems in FY 2006.

For example, in CdTe solar cells the electric field of the CdTe/CdS junction can quickly alter the spatial profiles of the excess electrons and holes, thereby distorting recombination rates and lifetime measurements. Simulations of time-resolved photoluminescence (TRPL) experiments on completed CdTe solar cells tracked the complex carrier dynamics following a short laser pulse into a junction and indicated the conditions under which meaningful lifetime values can be extracted. This led to a CdTe model that simultaneously reproduces experimental current density voltage (J-V) data, TRPL data, and trends between device performance and lifetime. CdTe device modeling also indicates how lifetime measurements are affected by grain boundaries and surface recombination, and conversely, to what degree lifetime measurements can resolve the impact of these different recombination mechanisms on device performance.

In another thin-film technology area, researchers have recently proposed that $CuInGaSe_2$ solar cells are composed of nanodomains caused by compositional fluctuations and/or phase separation. These nanodomains may form a three-dimensional network of p-n regions that separate charge, alter solar cell operation, and possibly improve device efficiency. Figure 9 illustrates a 2-D calculation of the hole current density under short-circuit conditions for a hypothetical CIGS device with micron-sized n-type domains embedded within p-type material. Additional calculations using much smaller domains (ranging from 10 nm to 1 µm) are currently being evaluated to determine how charge separation, band offset, and ultimately solar cell performance changes for different-sized domains. This is part of a larger ongoing effort to explore if there are two-dimensional device designs that can be exploited to enhance solar cell efficiency.

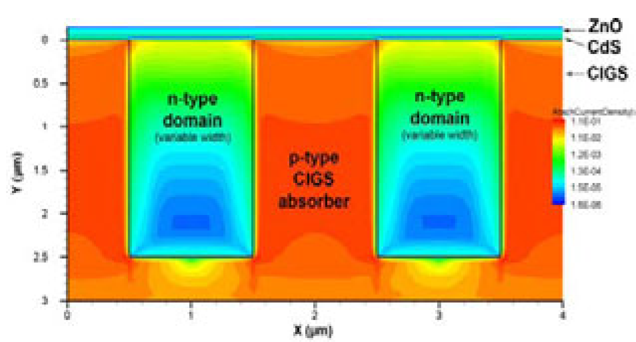


Fig. 9. Hole current density calculated for micron-size n-type domains within a p-type matrix in a CIGS solar cell. Cell is in short circuit.

Relocated Electro-Optical laboratories to the S&TF: The Electro-Optical Characterization Team moved approximately 70% of its laboratory facilities from the Solar Energy Research Facility (SERF) to the S&TF during FY 2006. The laboratories moved included Fourier Transform Infrared (FTIR), Photoconductive Decay (PCD) Lifetime, Deep-Level Transient Spectroscopy (DLTS), VASE, and Electro-Optical Technique Development.

The moves were performed in two phases, with the FTIR, DLTS, and VASE labs moving in late June and the PCD and Electro-Optical labs moving in late July. The lab moves were well planned and efficiently executed, yet still consumed significant portions of staff time prior to, during, and after the moves. Prior to moving, staff were involved in move planning, utilities specification and fit-up in the new labs, and equipment decommissioning and packing. Staff supervised the movers to ensure delicate equipment was safely moved. After moving, staff were responsible for unpacking, set-up, and recommissioning of lab equipment. Finally, the old labs in the SERF had to be decommissioned and made ready for their new occupants. Downtime was as short as one week for some FTIR lab equipment, and as long as several weeks for sophisticated pulsed lasers used for the PCD lifetime measurements. All lab facilities were fully up and running by the completion of FY 2006.

3.4 Surface Analysis Task

Study relationship between moisture barrier deposition fundamentals and ultimate barrier performance characteristics:
Flexible polymer substrates coated with inorganic oxide moisture barriers are a potential replacement for glass backsheets in thin-film PV modules. These coatings may also be suitable for direct application to cells. Silicon oxynitride (SiO_xN_y) deposited by plasma-enhanced chemical vapor deposition (PECVD) on polyethylene terephthalate (PET) represents one potential new backsheet candidate. Studies in FY 2005 using X-ray photoelectron spectroscopy (XPS), showed that plasma pretreatment of PET surfaces prior to deposition induces chain scission of the PET molecular structure, resulting in the formation of low-molecular-weight, polar fragments. These fragments were found to be volatilized or diffused into bulk PET on heating above 75°C and were also found to be water soluble. Non-removal of these fragments led to a weak interfacial layer that delaminated either during the initial peel tests or after damp-heat testing. Work in FY 2006 explored several fundamental deposition parameters and their relationship to the subsequent SiO_xN_y film properties and interfacial stability. The mobility of the fragments at relatively low temperatures implies that if the deposition temperature is high enough, these fragments should be removed during deposition. A new calibration curve for the substrate heater versus platen temperature led to substantially higher deposition temperatures, resulting in films with no observable damaged layers at the PET/SiO_xN_y interface as measured by XPS. In addition, careful mapping of the film composition shows that there is a large difference in thickness over the entire 12-in x 12-in substrate. Film composition was similarly mapped by XPS depth profiling and differences in nitrogen composition were observed for the SiO_xN_y films. These differences provide the opportunity to study the effect of barrier thickness and composition using a combinatorial approach. To facilitate using a combinatorial approach, we designed, built, and implemented a small-area water vapor transport rate (WVTR) cell for the MOCON analyzer. The new design allows us to use a more uniform film area to test the barrier performance, and also to attain a better correlation with the true film thickness and composition.

Better understanding of the deposition system has allowed us to reproducibly fabricate SiO_xN_y barriers with excellent adhesion to the PET, such that, during pull tests, cohesive failure often occurs in the PET rather than at the interface. Initial barrier performance is also excellent. However, peel strength degrades with continued damp-heat testing, indicating that the interface between the PET and barrier still degrades under the 85°C/85% humidity conditions. It should be noted, however, that films have excellent barrier properties prior to adhesion loss during damp-heat testing. Properties of the PET itself are thought to be contributing to SiO_xN_y/PET interface failure. We have shown that PET swells when exposed to moisture, and since the WVTR test requires that the uncoated PET side be in contact with the moisture, it may be that mechanical and chemical changes in the PET are causing the loss of adhesion during damp-heat stress. We are currently testing PET films with barrier coatings on both sides to try and alleviate this problem. In addition, deposition of SiO_xN_y barriers directly on Al/glass mirrors is planned as a parallel study of barrier performance, leading into direct coating of cells. Parts of this work were presented and published in the *4th World Conference on*

Photovoltaic Energy Conversion Proceedings. This work will continue in FY 2007 with parallel studies of barriers deposited directly on Al mirrors.

Design and specify a cart-based Auger electron spectroscopy tool for use in the S&TF:
Extensive planning meetings to define the scope of capabilities for this tool began during the first quarter of the year. During the second quarter, the technical advisory committee developed detailed technical specifications for the tool. The technical specifications were distributed in a statement of work (SOW) through a formal competitive bid process. Nine vendors were identified, and two responded with actual bids for construction of the system. The technical review committee analyzed the bids and was unanimous in its selection of the winning bid, submitted by DCA Instruments. DCA addressed all the points in the NREL SOW and even suggested an improvement to one item. In addition, the bid was within the budgeted amount for this tool. The procurement moved swiftly through NREL's Contracts and Business services, and the purchase request was placed with DCA Instruments on September 28, 2006. The milestone to specify, complete a competitive bid, and place the order for this tool was met. Since the end of the fiscal year, this activity has progressed through refinement of technical drawings to the construction phase. Delivery of the tool is expected at the beginning of the third quarter of FY 2007.

Move Surface Analysis Cluster Tool to the S&TF:
The contents of the Surface Analysis laboratory, including the five major pieces of equipment comprising the cluster tool, were moved from SERF E130 to S&TF 140 in late July. Prior to disassembly and transfer of the equipment, the lab was cleaned and sampled for hazardous materials. All areas sampled were found to be below threshold limits in accordance with good laboratory hygiene practices. Following the physical move to the new laboratory, reassembly of components and restarting of vacuum systems were performed. In addition, various components and subsystems on the cluster tool were serviced. Within four weeks of the move date, the PHI 670 Auger tool, PHI 5600 XPS/UPS, ultrahigh vacuum (UHV) transfer system, and glove box were operational. The UHV deposition system was sent off site for chamber cleaning and is being reassembled. The reassembled cluster tool equipment passed the readiness verification review on September 13, 2006, and the laboratory resumed full operations, completing the FY 2006 milestone.

Study the reaction kinetics of nanoscale Cu_xTe films:
Copper telluride is being explored as a potential back-contact material for tandem thin-film PV devices in, which the top cell is based on a CdTe-CdS junction. Copper telluride has good electrical properties for a back contact to a CdTe-based solar cell. If sufficiently thin, Cu_xTe films can be deposited on CdTe and the optical transmission of the Cu_xTe back contact should be high enough to allow light into the bottom cell of the tandem PV device. Much of the research into Cu_xTe back contacts is currently focused on understanding deposition and processing of this material on CdTe substrates. In addition, CuTe is an ideal prototypical system for learning about fundamental properties of other PV-relevant chalcogenides such as Cu_xSe and Cu_xS, which are relevant to CIGS deposition and processing. Measurements were performed to probe the reaction kinetics of nanometer-scale thin films of Cu_xTe. These measurements were performed in the surface-analysis deposition system using thermal-desorption mass spectrometry (TDMS). Initial measurements revealed that separately deposited ultrathin-film Cu and Te react to form Cu_xTe (with x ~2), and that the Cu_xTe decomposes via the $Cu_xTe = xCu + 1/2Te_2$ reaction at temperatures above about 700 K. This reaction appears to obey first-order kinetics with respect to the amount of Cu_xTe that is present. This is combined with parallel studies of a surface-segregated metastable Cu_xTe phase found on the CdTe (111)-B surface. Preliminary research indicates that this phase may be responsible for ohmic behavior of Cu in CdTe back contacts. Understanding the reaction kinetics is necessary for developing models to predict formation of this phase and subsequent process tolerances required to maintain long-term CdTe/CdS device stability. A manuscript detailing the surface-segregated Cu_xTe phase is in preparation.

Conducted studies of wet-chemical processing of PV material surfaces, leading to better control of deposition processes:
Previously, we have duplicated a chemical bath deposition (CBD) reactor in our cluster tool to study the interaction and chemistry of the CBD CdS process with CIGS surfaces. Using our dedicated setup, we have shown various chemical and electronic changes in the CIGS surface as a result of interaction with the aqueous NH_3 bath. In

addition, we developed a surfactant-assisted method that provides a more uniform CdS deposition and consequently improved CdS/CIGS junction performance. Experiments at the start of FY 2006 looked at an ammonia-free process for CdS deposition. Initial results indicated that CdS produced in this fashion contains smaller amounts of oxygen than the standard ammonia process. Unfortunately, it was not possible to have devices made on this material due to limited resources. For the remainder of the year, we focused on better control of the CBD process. As currently performed, the CBD reaction is a batch process and the resulting films can be subject to significant variations from run to run. We have begun testing a liquid-phase quartz crystal microbalance (LP QCM) sensor for film thickness and endpoint detection of the CBD process. The instrument has revealed interesting and potentially important issues with nucleation of chemical bath-grown CdS films. Problems anticipated with the use of this type of instrument with the NREL CdS process, including excessive noise from stirring, bubble formation on the sensor head, and rapidly changing temperature, were found to be manageable. Using this system, we have demonstrated that a liquid-phase QCM is able to measure deposition rates in the cluster tool CBD reactor, despite the non-ideal conditions typical of the NREL CdS reaction. The sensor has shown that the CdS CBD deposition rate in the standard NREL process is highly nonlinear and that the variability of the rate from run to run is high. The QCM was also used to test if the surfactant-assisted CBD method developed in our lab can be extended to CdTe technology. The QCM was used to prepare CdS films of known thickness on TCO/glass substrates for further processing into CdTe devices by collaborators within NREL (X. Wu) and at the Institute for Energy Conversion (B. McCandless). Although previous work with the CdS/CIGS material system showed significant improvements with the surfactant-assisted method, initial results for CdTe/CdS devices grown on two different Cd_2SnO_4/glass substrates showed a substantial decrease in efficiency. It was not clear at the end of FY 2006 if this difference was attributable to the choice of TCO substrate or a more fundamental difference in the reaction chemistry of CdS and CdTe. We are currently awaiting results from devices grown on commercial TEK15 TCO/glass substrates to help resolve this.

4. Planned FY 2007 Activities

A list of selected FY 2007 planned activities is given below. A more complete list of planned activities and milestones can be found in the Measurements and Characterization FY 2007 Annual Operating Plan. In FY 2007, we will complete the following milestones:

- Provide measurement support in the areas of analytical microscopy, cell and module performance, electro-optical characterization, and surface analysis to at least 70 PV research partners in industry, academia, and NREL.
- Maintain ISO accreditation for primary and secondary cell and module calibrations.
- Develop integrated plan to support SAI TPP awardees that meets their R&D needs within the context of available resources.
- Investigate the atomic structure of the c-Si/a-Si interface, and the thickness and crystallinity of the a-Si layer in Si heterojunction cells, as a function of cell processing conditions.
- Develop luminescence mapping capability for industrial silicon wafers.
- Organize the *17th Workshop on Crystalline Silicon Solar Cell & Modules: Materials and Processes*: identify priority R&D issues for the Si PV industry.
- Improve understanding of CdTe back-contact reaction kinetics by developing a quantitative model for surface-segregation phenomena.
- Investigate materials chemistry of CIGS on flexible substrates, leading to an improved understanding of long-term reliability.
- Complete study of the kinetics of microcrack propagation and improve our understanding of how thermal profiling and mechanical stresses, associated with conventional processing, impact propagation.
- Assess the technical shortcomings of minority-carrier lifetime measurement techniques used to determine material quality of mc-Si; apply improved understanding to facilitate better measurements of material quality for PV industry.
- Develop enhanced cell and module measurement capabilities that improve measurement turnaround time and uncertainty necessary to support the SAI (requires capital equipment funding).

5. FY 2006 Special Recognitions and Awards

- Sally Asher was elected a chair of the Applied Surface Science Division of the AVS and is program committee co-chair for the 54th AVS International Symposium.
- Pete Sheldon was elected a director of the AVS.
- The Cell and Module Performance team received the 2006 NREL Staff Outstanding Team Award.

6. Major FY 2006 Publications

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Solar Resource Characterization

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Dave Renné, 303-384-7408, david_renne@nrel.gov

DOE HQ Technology Manager: Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2006 Budget: $420K

Objectives

- Complete a 15-year update (1991–2000) of the National Solar Radiation Data Base (NSRDB).
- Produce an enhanced 1998–2005 10-km gridded data solar product for the United States.
- Develop methods and plans for a 1991–1997 10-km gridded solar product based on the microstructures of 1-degree NASA solar data grid.
- Implement Task 36 "Solar Resource Knowledge Management" under the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme.

Accomplishments

- Completed a draft 15-year NSRDB and distributed for review. Completed plan for final NSRDB update and began final validation and production.
- Technical results in several topical areas coming out of Task 36 "Solar Resource Knowledge Management."

Future Directions

- Distribute the 15-year NSRDB update.
- Produce a Typical Meteorological Year data set based on the updated NSRDB.
- Finalize plans for producing a 10-km gridded data set for 1991–1998.
- Produce reports through the IEA Task 36 that benchmark and quantify various solar resource assessment approaches developed by different countries and international institutions, including NREL's NSRDB.

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1. Introduction

This project addresses solar resource assessment as outlined in the *DOE Solar Program Multi-Year Technical Plan*. This includes access to data and characterization of the solar resource, as well as the needs of designers, modelers, and resource assessment interests, both in the United States and internationally. This is a multi-year project to update the 1961–1990 National Solar Radiation Data Base (NSRDB) and to implement the IEA "Solar Resource Knowledge Management" Task for benchmarking international solar resource data sets. Work performed in FY 2005 included: (1) recommendations for an NSRDB update and (2) development of an updated plan and Annex and IEA approval of the "Solar Resource Knowledge Management" task.

In 1992, NREL released the 1961–1990 NSRDB, a 30-year, 239-station data set of measured and modeled solar radiation and accompanying meteorological data for the United States. In 2003, NREL investigated the feasibility of producing a 1991–2000 update of the NSRDB and devised a proof-of-concept project to investigate solutions to several obstacles, including the switchover by the National Weather Service (NWS) to the Automated Surface Observing System for routine meteorological observations.

In 1998, NREL hosted the first workshop on satellites for solar resource assessments, bringing together international researchers on the topic. Two follow-up workshops were held, one in 2000 and one in 2003, leading to the development of a concept paper and work plan for an IEA "Solar Resource Knowledge Management" task. In June 2005, this task was approved as Task 36 under the Solar Heating and Cooling Programme, and NREL was selected as the Operating Agent. This task links NREL's domestic NSRDB research activities with the international solar resource assessment work conducted by several agencies around the world.

2. Technical Approach

Two tasks are under way in the Solar Resource Characterization Project: (1) a domestic task focused on updating the NSRDB and (2) an international task that allows the NSRDB to be benchmarked against international solar resource assessment methods. Previous work allowed us to select a solar radiation model (METSTAT). FY 2006 work centered on producing a draft NSRDB for review and moving ahead with final production.

The IEA/SHC Solar Resource Knowledge Management task provides a collaborative mechanism to allow researchers from a number of international research institutions to compare and benchmark various approaches for assessing solar resources, allowing for the new NSRDB to be benchmarked against these other methods. Two task experts meetings (November 2005 and July 2006) have been held, where experts from the participating countries presented research results and future plans on topics directly related to the task. A third task meeting will be held in March 2007, and a mid-term review of technical results will be held in November 2007

Total project funding for FY 2006 was $420K, broken down in the following table:

Task Title	FY 2006 Budget ($K)
IEA Task 36 Solar Resource Knowledge Management	100
NSRDB Update	320

3. Results and Accomplishments

3.1 National Solar Radiation Data Base

The changeover to automated stations by the National Weather Service eliminated the human observed total and opaque sky cover amounts used for inputs to the METSTAT model, which was used for the 1961–1990 NSRDB. To adapt the model to currently available data sets, we derived equivalent sky cover inputs (total and opaque cloud cover) from a combination of Automated Surface Observing System (ASOS) and ASOS supplemental cloud measurements (the latter derived from Geostationary Operational Environmental Satellite [GOES] satellite data). ASOS detects clouds to 12,000 ft (3660 m), whereas the ASOS supplemental cloud measurements provide sky cover estimates for heights above 12,000 ft for a 50 km x 50 km area centered on the ASOS station.

Based on foundation work in FY 2005, we produced a draft NSRDB with all fields and stations for the purpose of review distribution. About 10 participants volunteered to review the data set, which included our design, methods, procedures, and output fields. From this review came validation of the overall design, as well as a few problem reports that were corrected.

The draft NSRDB included about 1400 sites with hourly data fields for the period 1985–2005, allowing some overlap with the original 1961–1990 NSRDB for comparisons. We developed a tiered classification scheme for categorizing the sites based on data completeness and data quality. Class I sites are those with a complete 15-year period of record, with no missing hourly solar radiation and key meteorological data fields. Class II stations are those that have gaps in the data, but hold enough data to be useful for some applications (a minimum of three years). Figure 1 shows a preliminary map of NSRDB sites compared with the 1961–1990 NSRDB.

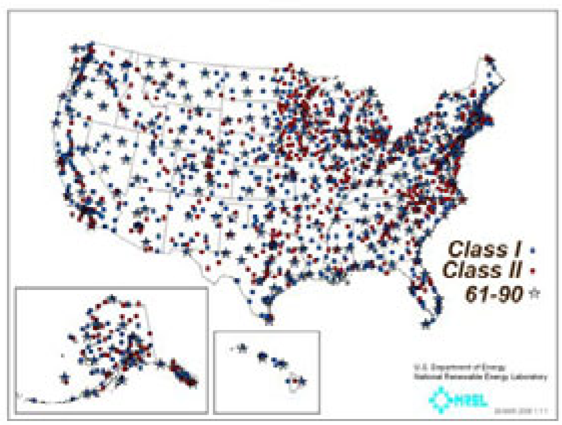

Fig. 1. Preliminary map of NSRDB sites

Validation work on the NSRDB uncovered problems with input cloud cover data due to the changes in weather service observations. Some work was done to enhance the cloud data, as well as to define higher uncertainties for modeled data under certain conditions.

3.2 "Solar Resource Knowledge Management" IEA Task 36

The three subtasks in Task 36 are contributing to achieving the vision of fast and easy access to relevant, qualified, and reliable solar resource information that has been benchmarked to international standards.

Subtask A: Standard qualification for solar resource products. This subtask is focusing on:

- Coherence and benchmarking of models producing surface irradiance values from satellite data. This includes SUNYA, NREL's Climatological Solar Radiation (CSR) model, and NASA Surface Meteorology and Solar Energy (SSE) models, which are also being used for the NSRDB updates
- Accessibility and coherence of ancillary model input data such as atmospheric conditions and land surface parameters
- Sensitivity analyses
- Ground truth validations with high-quality data
- Definition of validation protocols and measures of end-product confidence
- Cross-satellite platform and cross-model comparisons.

Subtask B: Common structure for archiving and accessing resource products. This subtask focuses on:

- Development of worldwide networking between distributed data centers, resulting in a global coverage for high-quality solar resource data
- Development of information and data exchange protocols
- Reliable and fast end-user access
- Preparation of data documentation for specific end-user applications.

The main outcome of Subtask B will be a unique Web entry point that performs a smart network of resources and products. Specifically, Subtask B will build on existing Web services, such as the SoDa or NASA portals, to construct an advanced prototype of the distributed information system. Resources (e.g., a database) will comprise a Web server and will be connected on a voluntary basis to this information system. Providers of such resources will be organizations such as NREL, NASA, and the German Aerospace Center (DLR). The Web service (entry point) will be easy to maintain, transfer, operate, and duplicate (to ensure reliability). This service will be maintained by Task 36 partners, and in some cases may involve possible commercial revenues.

Subtask C: Improved techniques for solar resource characterization and forecasts. This subtask covers R&D work and mainly focuses on:

- Improved Satellite Retrieval Methods for Solar Radiation Products: This activity focuses on key model input parameters and methodologies, such as cloud indices, radiative transfer schemes, aerosol data retrievals, and treatment of snow and other surface albedo artifacts. The activity also addresses ways of improving the spatial resolution of satellite-derived broadband solar resource products.
- Climatological Analysis of Solar Resources: To ascertain future impacts on system performance due to climate variations, this activity includes the analysis of long-term surface and satellite-derived data sets and climate models, specifically addressing natural long-term fluctuations associated within the ocean-atmosphere system, such as the Southern Oscillation/El Nino.
- Forecasting of Solar Radiation: This activity investigates different approaches for developing solar resource forecasts based on global numerical weather predictions and extrapolation of cloud motion vectors.

Preliminary results of comparisons of long-term satellite-derived climatological solar data with high-quality ground stations at two locations in Oregon are shown in Figure 2.

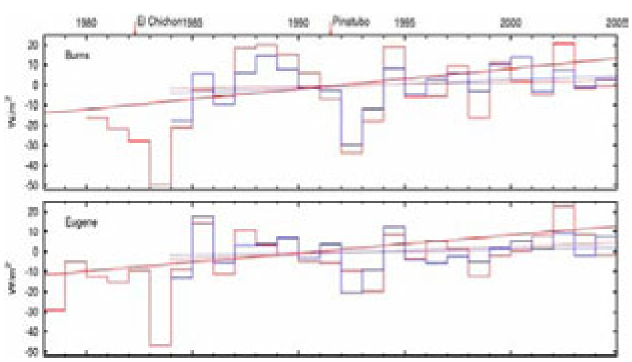

Fig. 2. Comparison of DLR satellite-derived direct normal irradiance estimates with ground measurements collected at Burns and Eugene, Oregon (USA): From Stackhouse, et al., IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Denver, July-August 2006.

4. Planned FY 2007 Activities

At the current level of funding, the planned distribution of the updated 1991–2005 NSRDB will occur in 2007. We plan annual updates of the NSRDB through 2009. In 2011, a 2001–2010 decade update will be produced, funding permitting. Additional products, such as Typical Meteorological Year and Data Manuals, will also be produced.

During 2007, participants in IEA Task 36 will focus on appropriate benchmarking procedures for comparing international solar data sets, and on methodologies for improving satellite-derived estimates, with particular emphasis on high-resolution and long-term data. A technical workshop will be held at the Joint Research Center in Ispra, Italy, in March 2007, and mid-term review with the IEA/SHC Executive Committee will be held at a location to be determined in November 2007.

5. Major FY 2006 Publications

Wilcox, S., M. Anderberg, W. Beckman, A. DeGaetano, R. George, C. Gueymard, W. Marion, D. Myers, R. Perez, M. Plantico, D. Renne, P. Stackhouse, F. Vignola. “Toward Production of a National Solar Radiation Database,” *Proc. Solar 2006, American Solar Energy Society, 2006.*

David S. Renné, Richard Meyer, Hans-Georg Beyer, Lucien Wald, Richard Perez, and Paul Stackhouse, “Solar Resource Knowledge Management: A New Task of the International Energy Agency,” *Proc. Solar 2006, American Solar Energy Society, 2006.*

P.W. Stackhouse, Jr., D. Renné, H. -G. Beyer, L. Wald, R. Meyer, M. Schroedter-Homscheidt, R. Perez, and M. Suri “Towards Designing an Integrated Earth Observation System for the Provision of Solar Energy Resource and Assessment,” *Proc. IGARRS Conference, 2006.*

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6. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2006 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
State University of New York, Albany Richard Perez	Albany, NY perez@asrc.cestm.albany.edu	Produce 10-km gridded data for the United States; Investigate methods of interpolating 1-degree grid to 10-km grid.	30
University of Oregon Solar Monitoring Laboratory Frank Vignola	Eugene, Oregon fev@darkwing.uoregon.edu	Develop procedures for correcting rotating shadowband radiometer data and apply the corrections to NSRDB-measured solar data.	20

Environmental Health and Safety

Performing Organization: Brookhaven National Laboratory (BNL)

Key Technical Contact: Vasilis Fthenakis, 631-344-2830, vmf@bnl.gov

DOE HQ Technology Manager: Alec Bulawka, 202-586-5633, alec.bulawka@ee.doe.gov

FY 2006 Budget: $400K

Objectives

- Assist in preserving the safe and environmentally friendly nature of photovoltaics and in minimizing environmental health and safety (EH&S) risks and associated costs, to ensure the public support and economic viability of PV systems.
- Identify potential EH&S barriers of PV materials, processes, or applications and define strategies to overcome such barriers.
- Maintain the EH&S Research Center as the world's best source on PV EH&S, providing accurate information related to EH&S issues and perceptions.

Accomplishments

- Conducted a comparative study of Greenhouse Gas Emissions during the Life Cycle of PV and nuclear fuel cycles; Energy Policy, in press.
- Conducted a life-cycle analysis (LCA) of the Amonix c-Si PV concentrator system.
- Promoted and established international collaborative life-cycle environmental assessments of PV energy technologies, enhancing the quality and quantity of PV environmental assessments.
- Optimized a Cd/Te ion-exchange separation and filled patent application 11/421,343 for "System and Method for Separating Tellurium from Cadmium Waste," May 31, 2006.
- Advanced the recovery of 99.9%-pure Cd in the CdTe recycling program at a projected cost of 0.1 ¢/W_p.
- Assisted First Solar, United Solar Ovonic, DayStar Technologies, and the University of Toledo with site-specific EH&S issues.
- Co-organized and co-chaired, with General Motors, the three-day Symposium "Life-Cycle Analysis for Green Materials and Process Selection," Materials Research Society (MRS), Boston, Nov. 2005.
- Answered several requests for EH&S information from the public and the industry.

Future Directions

EH&S research at BNL will support the Solar American Initiative (SAI) objectives by:

- Defining low-cost recycling for manufacturing and spent modules
- Assisting the industry in preventing accidents and releases of hazardous materials to the environment, and guiding them toward environmentally friendly material and process options
- Extending EH&S research and LCA to III-V PV concentrators
- Accurately defining the environmental profiles of solar electric and solar thermal technologies as they scale up to meet the SAI challenge
- Answering inquiries from the industry, legislators, and the public about EH&S issues in solar energy cycles.

In addition, research at BNL will identify and characterize EH&S hazards associated with emerging materials, including nano-material forms, for the U.S. Department of Energy, its contractors, and the private sector.

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1. Introduction

The activities of the Environmental, Health and Safety (EH&S) Research Center focus on minimizing potential EH&S impacts associated with current and future photovoltaic energy systems and applications. This objective is accomplished by proactive research, rigorous industry outreach, and technical communications.

The overall goal is to preserve the safe and environmentally friendly nature of PV and minimize EH&S risks and associated costs, to ensure the public support and economic viability of PV systems. Minimization of EH&S risks and costs is paramount for achieving the Solar Program's goal of $0.06/kWhr by 2020, while having the support of the public is a prerequisite for existence and growth to the scale that would support this low cost.

Also, the Center serves as the world's best source on PV EH&S, providing accurate information related to EH&S issues and perceptions. This activity supports the overall communications and outreach objectives of the Solar Program.

2. Technical Approach

The major areas of Brookhaven National Laboratory's activities are Hazard Identification and Characterization, Hazard Management, Industry Outreach, and Information Dissemination. Ongoing efforts are required because the PV industry is undergoing changes in type and quantities of materials, manufacturing processes and scale, and because continuous vigilance is required in safety and loss prevention.

Task 1: Identification and Characterization of EH&S Issues. In FY 2006, we conducted and published: (1) an LCA of the Amonix high-concentrator PV system; (2) an LCA-based comparison of PV with nuclear power systems; (3) a study of energy payback times, greenhouse gases, and external cost of PV; and (4) a comparison on the environmental metrics of grid-connected and ground-based PV systems.

Task 2: Hazard Management. In FY 2006, we advanced the recycling of CdTe PV by accomplishing a recovery of 99.9%-pure cadmium through optimized separations and electrowining, at a projected cost of 0.1¢/W.

Task 3: Industry Outreach and Support to DOE-HQ and NCPV. The industry outreach activities include frequent interactions with EH&S personnel, site visits, guidance with EH&S issues and concerns, and assistance with new facilities.

Task 4: Information Dissemination. Providing accurate and objective information on PV EH&S issues is crucial as the PV industry as installations grow to levels that attract public interest and scrutiny.

Task Title	FY 2006 Budget ($K)
1. Hazard Identification and Characterization	180
2. Hazard Management and Recycling	90
3. Industry Outreach/DOE/NCPV	78
4. Information Dissemination	52

3. Results and Accomplishments

Task 1

- Completed and published LCAs of commercial CdTe PV systems.
- Conducted LCA-based comparisons of greenhouse-gas emissions and risks in the PV and nuclear fuel life cycles.
- Completed and published an LCA of crystalline Si concentrator systems.
- Contributed to several cooperative LCAs with researchers in Europe.

Task 2

- Increased the recovery rate and purity of Cd and Te from actual CdTe manufacturing scrap.
- Conducted a safety analysis of silane storage systems with United Solar Ovonic, and presented it at a conference.

Task 3

- Provided facility-specific assistance to First Solar, United Solar Ovonic, and DayStar Technologies.
- Organized a PV EH&S task workshop for the International Energy Agency (IEA).

Task 4

- Answered several requests for EH&S information from different agencies, business partners, citizen organizations, and the media.
- Organized an MRS symposium on LCA.
- Published and presented extensively.

4. Planned FY 2007 Activities

Task 1: Hazard Identification/Characterization
This task is part of BNL's proactive research to overcome EH&S barriers to support for large-scale implementation of PV. Activities planned for FY 2007 include:

- Life-cycle investigation of CdS alternatives in CIGS PV systems
- Life-cycle investigation of greenhouse gas emissions in crystalline silicon etching operations
- LCA-based study of CIGS PV module manufacturing efficiencies (pending industry data), or LCA-based comparisons of CIGS, CdTe and a-Si PV module manufacturing efficiencies based on energy use, thermodynamics, and kinetics.

Task 2: Hazard Management/Recycling
These activities are pivotal to preserving the safe and environmentally friendly nature of the PV industry as it moves toward large-scale manufacturing. In FY 2007, research at BNL will focus on:

- Improving the purity of Te and Cd, which are recycled from CdTe manufacturing scrap and spent modules
- Scaling up Cd/Te/Cu/Fe separations and Cd and Te recovery processes to study the actual variability in manufacturing scrap composition
- Assisting the industry in developing a recycling infrastructure
- Assisting the industry in implementing recycling options.

Task 3: Industry Outreach/Support to DOE and NCPV

- Start IEA PV EH&S Task 12; serve as the lead organizer and U.S representative to the task.
- Guide the industry and R&D labs on accident prevention and pollution prevention.
- Support DOE and NCPV as needed.

Task 4: Information Dissemination
The results of BNL's research will be disseminated with new publications, e-mail, and the Internet. The PV EH&S Research Center serves as a clearinghouse for EH&S information requested by potential customers, business partners, citizen organizations, and the media. Such inquiries have been increasing as the industry, universities, and national laboratories respond to the challenge of the Solar American Initiative toward cost-effective production of solar electricity by 2020.

BNL staged MRS Symposium R: Life Cycle Analysis for New Energy Conversion and Storage Systems to take place in Nov. 2007. NREL and the EPA will co-organize the event.

5. FY 2006 Special Recognitions, Awards, and Patents

Filed patent #11/421,343, "System and Method for separating Te from Cd Waste."

Vasilis Fthenakis received the U.S. DOE Certificate of Appreciation "*for superior technical, management and communications skills exhibited in photovoltaic environmental research and in effective dissemination of research results,"* March 2006.

6. Major FY 2006 Publications

Fthenakis V.M., Fuhrmann M., Heiser J., Lanzirotti A., Fitts J., and Wang W., "Emissions and Redistribution of Elements in CdTe PV Modules during Fires," *Progress in Photovoltaics: Research and Applications* **13**, 713–723, 2005.

Mason J., Fthenakis V.M., Hansen T., and Kim C., "Energy Pay-Back and Life Cycle CO2 Emissions of the BOS in an Optimized 3.5 MW PV Installation," *Progress in Photovoltaics: Research and Applications* **14**, 179–190, 2006.

Fthenakis V.M and Wang W., "Extraction and Separation of Cd and Te from Cadmium Telluride Photovoltaic Manufacturing Scrap," *Progress in Photovoltaics: Research and Applications* **14** 363–371, 2006.

Fthenakis V.M. and Alsema E., "Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status," *Progress in Photovoltaics Research and Applications* **14** 275–280, 2006.

Fthenakis V.M. and Kim H.C., "Greenhouse Gas Emissions from Solar Electric and Nuclear Power: A Life Cycle Study," *Energy Policy*, in press.

Kim H.C. and Fthenakis V.M, "Amonix High-Concentrator Photovoltaic System: Life Cycle Energy Demand and Greenhouse Gas Emissions," *Proceedings IEEE 4th World Conference on Photovoltaic Energy Conversion,* Hawaii, May 8–12, 2006, 628–631.

Fthenakis V.M., "Quantifying the Life-Cycle Environmental Profile of Photovoltaics and Comparisons with other Electricity-Generation Technologies," *Proceedings IEEE 4th World Conference on Photovoltaic Energy Conversion,* Hawaii, May 8–12, 2006, 2477–2480.

de Wild-Scholten M.J., Alsema E., ter Horst E.W., Bachler M., and Fthenakis V.M., "A Cost and Environmental Impact Comparison of Grid-Connected Rooftop and Ground-Based PV Systems," *Proceedings 21st European Photovoltaic Solar Energy Conference,* Dresden, Germany, 4–8 September 2006, 3167–3172.

Alsema E., de Wild-Scholten M.J. and Fthenakis V.M., "Environmental Impacts of PV Electricity Generation — A Critical Comparison of Energy Supply Options, *Proceedings 21st European Photovoltaic Solar Energy Conference,* Dresden, Germany, 4–8 September 2006, 3201–3207.

Fthenakis V.M., Colli A., Arellano A., Kirchsteiger C., and Ale B., "Evaluation of Photovoltaics in a Comparative Context," *Proceedings 21st European Photovoltaic Solar Energy Conference,* Dresden, Germany, 4–8 September 2006, 3194–3201.

Fthenakis V.M., "CdTe Photovoltaics: Life-cycle Environmental Profile," *European Material Research Society Meeting, Symposium O*, Invited Paper, Nice, France, May 29–June 2, 2006.

Fthenakis V.M., "Photovoltaics Life Cycle Analysis," Invited Plenary Presentation, *Renewable Energy 2006*, Chiba, Japan, October 11, 2006.

Fthenakis V.M., "International Energy Agency Workshop of PV-EH&S," held in conjunction with the *21st European Photovoltaic Solar Energy Conference*, Dresden, Germany, Aug./Sept. 2006.

Fthenakis V.M., Carlisle C., and Chan W., "Silane Safety in Amorphous Silicon and Silicon Nitride Operations," *Proceedings 21st European Photovoltaic Solar Energy Conference,* Dresden, Germany, 4–8 September 2006, 1761–1783.

Fthenakis V.M., Wang W., Meader A., and Squires K., "Recycling of CdTe Photovoltaic Modules: Recovery of Glass, Cadmium and Tellurium," *Proceedings 21st European Photovoltaic Solar Energy Conference,* Dresden, Germany, 4–8 September 2006, 2539–2541.

Wang W. and Fthenakis V.M., "Recovery of Tellurium from Cadmium Telluride Photovoltaic Module Manufacturing Scrap and other Sources," *The Minerals, Metals & Materials Society 135th Annual Meeting & Exhibition,"* San Antonio, Texas, March 12–16, 2006.

Crystalline Silicon Project

Performing Organizations:	National Renewable Energy Laboratory (NREL) DOE Golden Field Office (DOE/GO)
Key Technical Contacts:	David Mooney (Primary Contact, Project Lead) 303-384-6782, david_mooney@nrel.gov Glenn Doyle (DOE/GO), DOE PV Center of Excellence 303-275-4706, glenn.doyle@go.doe.gov Howard Branz (NREL) C-Si PV: Materials and Device R&D, 303-384-6694, howard_branz@nrel.gov Richard Matson (NREL) University C-Si Research Project 303-384-6431, rick_matson@nrel.gov Brent Nelson (NREL) Science & Technology Facility 303-384-6407, brent_nelson@nrel.gov
DOE HQ Technology Manager:	Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov
FY 2006 Budgets:	$4,397K (NREL), $950K (DOE/GO)

Objectives

- Further the fundamental understanding and implementation of performance-enhancing features of low-cost, high-efficiency crystalline silicon (c-Si) solar cells.
- Support the Crystalline Si Center of Excellence for optimizing solar cells through university/industry collaborations on production processes.
- Direct university research addressing fundamental technological concerns to the c-Si PV industry.
- Design and procure a c-Si cluster tool for conducting process integration R&D in the new NREL Science & Technology Facility.
- With the introduction in 2006 of the Solar America Initiative (SAI), c-Si R&D efforts will address, as required, levelized cost of energy targets (in residential, commercial, and utility markets) and manufacturing/installed capacity targets under the SAI. Assessment of selected Technology Pathway Partnerships (TPPs) will be conducted and R&D opportunities that are complementary to TPP goals will be considered.

Accomplishments

- Achieved a record efficiency for p-wafer silicon heterojunction solar cells with a confirmed efficiency of 18.2%. This 1 cm^2 cell has a-Si contacts on both sides and an open-circuit voltage of 0.667 V (NREL Silicon Materials and Devices).
- Synchrotron measurements provided first evidence that transition metals interact within silicon during the precipitation process to form complex silicides, a process subsequently termed "internal eutectic gettering" (University of California, Berkeley).
- Modeling showed that 18%–20%-efficient low-cost cells with screen-printed contacts using 100 to 200 µm-thick c-Si wafers can reduce the levelized cost of electricity to 5–10 ¢/kWh (Georgia Institute of Technology, Rohatgi).
- Solar cell processing equipment to scale up experimental cell areas from 4 cm^2 to 149 cm^2 has been installed at the Georgia Tech.
- A Georgia Tech (Danyluk)/NREL collaboration to implement CAMX software for data collecting, distribution, and processing is active and will benefit researchers as well as the PV industry's manufacturing processes.
- Research in cell processing coupled with development of new processes and controls for manufacturing 4 cm^2 commercial cells has resulted in significant cost reductions in processing cells with efficiencies in the 16%–20% range. Application of these process improvements to larger, thinner wafers continues (DOE Center of Excellence).

- Used the scalable hot-wire chemical vapor deposition (CVD) technique to deposit 11 microns of epitaxial Si at 110 nm/min on a Si wafer at the glass-compatible temperature of 615°C. With quality improvements and a suitable seed layer on glass this technique could be used to develop thin crystal Si layers on inexpensive substrates (NREL Silicon Materials and Devices).
- Project management oversaw the construction of a cluster tool to support silicon research to be delivered to NREL in January 2007.

Future Directions

Note: Following the formation of the SAI, R&D on c-Si will no longer take place within the Crystalline Silicon Project. Instead the efforts will be distributed within the National Center for Photovoltaics (NCPV) in a way that aligns with complementary R&D efforts and the NCPV organizational structure.

- Study and mitigate factors limiting the high-yield manufacturing of cost-effective PV devices by identifying and addressing issues related to c-Si materials, cells, and modules.
- The University Crystalline Silicon Photovoltaic R&D (Center of Excellence) award was recompeted during 2006. Georgia Tech was selected for negotiation of a new award. Completion of the current award scope ended in December 2006.
- The c-Si university c-Si research effort will be (1) winding down in anticipation of its resurrection under the SAI and (2) continuing at a considerably reduced funding level in FY 2007 in the form of a consortium of six universities, NREL, and at least one PV company investigating the mechanisms for defect cluster formation in Si solar cells.
- NREL's Silicon Materials and Devices Group will use our improving heterojunction passivation and contacting technologies in a variety of device configurations once single-crystal efficiencies on both n- a dn p-type wafers are brought near 20%. This technology can be particularly valuable on multicrystalline and thin crystal silicon materials and in interdigitated cell configurations.
- NREL's Silicon Materials and Devices Group will grow epitaxial Si layers and solar cells on a variety of Si seed layers on glass to test the viability of our epitaxy at glass-compatible temperatures.

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1. Introduction

Crystalline silicon solar cells have demonstrated a long and consistent history of continued performance improvements and cost reductions. The consensus in the global c-Si PV community is that this trend will continue with appropriate investment Si PV R&D. Given the abundance of possible solar-grade and purer silicon, the evolving methods for expanding the utility of the anticipated silicon feedstock, and a considerable technological infrastructure to leverage any improvements in the cost and/or performance characteristics of c-Si PV, the global bet (with a ≥90% market share) is placed on c-Si PV for the foreseeable future—at least the next decade. As such, there is a clear case for a very significant increase in U.S. engagement in the global c-Si PV competition in parallel with its existing PV R&D programs.

There were four distinct components within the DOE c-Si solar cell research effort for FY 2006: (1) the NREL in-house (fundamental and exploratory) research effort; (2) the DOE-funded PV Center of Excellence at Georgia Tech; (3) the subcontracted university research effort; and (4) NREL's new Science & Technology Facility (S&TF), where integrated material and device research, as well as cell manufacturing R&D, will be performed by individuals and groups throughout the c-Si research community.

2. Technical Approach

2.1 Silicon Materials and Devices Group at NREL

This group researches options for both near-term and future photovoltaic technology improvements using both wafer and film forms of silicon. Our main project in wafer silicon photovoltaics is the development of silicon heterojunction (SHJ) surface passivation and solar cell devices. The SHJ is fabricated by putting ultrathin hydrogenated amorphous silicon (a-Si:H) passivation layers on c-Si; this is a key step toward fabrication of high-efficiency silicon solar cells at low temperatures (<250ºC). We deposit the a-Si:H layers by hot-wire chemical vapor deposition (HWCVD) to avoid any ion-bombardment damage of the high-quality Si wafers that are employed.

A longer-term, high-risk goal is to develop crystal Si films on glass that can be used to fabricate 15% PV cells. We aim for crystal Si efficiencies at costs per unit area comparable to the thin-film manufacturing cost potential (~\$100/m^2). Development of this wafer equivalent on glass requires excellent Si seed layers on the glass *and* a capability for rapid epitaxial thickening with about 10 microns of Si at glass-compatible temperatures below 700°C. We are using HWCVD for epitaxial deposition because it is a promising candidate capable of high-rate epitaxy and can be scaled for large-area manufacturing.

16th Workshop on Crystalline Silicon Solar Cells and Modules: Materials and Processes. Invaluable to the c-Si community at large, these annual NREL-sponsored workshops are a technical and practical mainstay for the whole community, theoreticians and industrialists alike.

2.2 DOE/GO Center of Excellence
Negotiation of this new award is ongoing, but the key research objectives are to advance the current state of c-Si solar cell technology to make it more competitive with conventional energy through R&D in areas such as: low-cost, high- performance screen-printed metallization; gettering and passivation of defects in low-cost c-Si materials; cost-effective formation of rear contacts with low back surface recombination velocities/high back surface reflectance; and low-cost fabrication of thin c-Si solar cells. The project is designed to enhance fundamental and applied research appropriate for education and advanced degrees, while also performing industry-relevant research.

2.3 University Crystalline Silicon Research Project
This work complements the foregoing R&D by providing applied and exploratory research in c-Si on topics that serve industry's technical concerns. The topics are determined by a consensus among the c-Si PV industry, universities, and NREL staff and management. Current topics include development of improved silicon nitride hydrogenation, methods for handling and processing thin wafers with high yield, neutralization of bad regions in wafers, rear-surface passivation, hybrid heterojunction emitters, and innovative c-Si technologies.

Task Title	FY 2006 Budget ($K)
NREL c-Si Materials and Devices Group	2,470.
University c-Si PV Research Project	500
Initiative in PV Manufacturing	100
DOE/GO Center of Excellence Georgia Tech	950
Process integration (S&TF): c-Si component	580.
Technical coordination	743

3. Results and Accomplishments

3.1 Silicon Materials and Devices Group (NREL)
The group obtained a high of 667 mV on textured p-type float-zone (FZ) c-Si wafers in the double-heterojunction structure (front n/i SHJ emitter and back i/p SHJ contact). This result indicates that both back- and front-surface passivation are excellent. For comparison, replacing the SHJ back contact on a p-type c-Si wafer with an Al back-surface field (BSF) yields a V_{oc} of only 636 mV. Although traditional alloyed BSF contacts have excellent contact-resistance characteristics, HWCVD a-Si:H back contacts are superior for their combined passivation and current-transport capabilities. The 18.2% conversion efficiency we obtain with HWCVD is the best yet reported on p-type crystalline Si.

Other research focused on improvements to crystalline silicon on glass. We found that HWCVD a-Si:H films crystallize about five times faster than plasma-enhanced chemical vapor deposition (PECVD) a-Si:H. Because these rapidly crystallizing HWCVD films were also grown at higher rates, up to 110 Å/s, they might replace PECVD films in thin polycrystalline Si photovoltaics or other devices crystallized from a-Si:H. However, grain sizes may be slightly smaller than films crystallized from PECVD a-Si:H.

3.2 DOE Center of Excellence for Photovoltaic Research, Education, and Collaboration Program
Results included fabricating: (1) a 42-cm^2 Czochralski (CZ) silicon cell of 18.6% efficiency on low-cost materials using conventional furnace processing and photolithography; (2) 4-cm^2 cells with a target efficiency of 17%–20% by implementing an optimized P-diffusion profile in rapid thermal processing and screen-printed Al-doped back surface field with in-situ oxide emitter passivation; (3) 4-cm^2 commercial cells with target efficiency of 16%–19% on commercial substrates by more effective monitoring/control of wafer

temperatures during belt furnace processes and stabilization of the belt furnace before processing to improve uniformity/reproducibility of results in conjunction with Ag paste with a n+ emitter, low-frequency PECVD SiN film, and metallization firing in a belt furnace or rapid thermal processing; (5) a selective emitter and bifacial and intermediate-band solar cells cells on commercial materials with target efficiencies of 17%–20% on FZ and CZ Si using high sheet resistance emitters and surface texturing: 17%-efficient bifacial cells on FZ Si.

3.3 University c-Si Research Project

Beyond the technological mandates for lower cost, higher performing, and more durable solar cells and modules, provisions of the *DOE Solar Program Multi-Year Technical Plan* (MYTP) specifically call for fundamental R&D involving our colleges and universities and, as a corollary, the development of the next generation of solar technologists as a complement to the NREL PV research. This directed, yet fundamental and exploratory, research project covers a spectrum of R&D, ranging from synchrotron studies of atomic-level defects in solar-grade c-Si to collaborative manufacturing research efforts, and from theoretical studies of the role of hydrogen in passivation to characterizing the effect of crucible contaminants, wafer sawing, and device processing on device performance. Some results of these studies include the following.

Texas Tech. Researchers conducted theoretical studies focused on the identification and characterization of electrically active defect centers in Si PV devices as well as on the origin of their electrical activity and the possibility of passivation with hydrogen. At *Lehigh University,* Texas Tech's experimental counterpart, researchers focused on the detection and measurement of H passivation of Si from SiN antireflection AR coatings.

UC Berkeley. This group observed and studied a formerly unknown alloy phase with fluorite-type structure containing Ni, Fe, Cu, and Si, which are found as precipitates in multicrystalline silicon. The analysis of extended X-ray absorption fine-structure microspectroscopy (m-EXAFS) measurements provided first evidence that transition metals interact during precipitation within silicon and form complex silicides. This finding may have far-reaching consequences for both understanding precipitation behavior of transition metals in silicon and for reduction of their detrimental impact on solar cell efficiency.

Georgia Tech (Rohatgi). Researchers developed and applied their PV module manufacturing cost model in conjunction with the Solar Advisor Model from NREL to show that 18%–20%-efficient low-cost cells with screen-printed contacts using 100–200-μm-thick c-Si wafers can reduce the levelized cost of electricity to 5–10 ¢/kWh. By controlling the contact firing process, efficiencies approaching 19% on 4-cm^2 FZ Si cells and exceeding 17% on 149-cm^2 FZ Si cells were achieved. A model to predict the impact of material inhomogeneity on the V_{oc} of mc-Si cells was also developed.

Georgia Tech (Danyluk) and University of South Florida (USF). This group developed a model for handling stresses in c-Si wafers produced by a Bernoulli gripper, measured breakage stresses in 150–200-mm-thick BP wafers, and developed methods to extract residual stresses from 170-micron-thick polycrystalline wafers. USF performed Finite Element Analyses modeling of different vibration modes to assess the sensitivity of the resonance ultrasonic vibration method versus crack length. They also have been working extensively with a number of PV industrialists on the issues of handling thin Si wafers. Such relationships are critical and speak well of the relevance and effectiveness of the project.

Duke University. Performed theoretical studies of the mechanisms of low-temperature precipitate dissolution using optical processing and vacancy injection. Al gettering of metallic precipitates, carried out using optical processing, is able to accomplish the same effect that takes tens of hours under thermal annealing at 700°C. Possible mechanisms involved in optical-processing gettering were proposed and demonstrated via physical modeling and simulations.

California Institute of Technology. Having previously developed processes for the formation of large-grained polycrystalline templates for epitaxial growth and low-temperature Si epitaxy via HWCVD, this year CalTech focused on growing high-quality p/n junctions with poly-Si growth via HWCVD. After evaluating several different growth processes for n/p and p/n junction formation with and without dilution, they were able to obtain best-quality p/n junctions by growth at 250°C without introducing hydrogen for a record open-circuit voltage of 430 mV.

North Carolina State University (NCSU). The co-precipitation dynamics of O and C in multicrystalline sheet silicon were examined experimentally. A model based on the synergetic role of intrinsic point defects on O/C precipitation was proposed by comparing experimental results with numerical modeling.

3.3 Crystalline Silicon PV Research Project Management

This supports the management activities needed for high-quality research within project budgets. Activities include peer reviews, solicitations for proposed research, budget planning, contract negotiation, contract monitoring, reporting of project results through conferences and publications, and partnering with other government, state, and private entities to leverage related research.

3.4 Science and Technology Facility

The silicon cluster at the S&TF was substantially completed in FY 2006. It consists of a central robot in a vacuum chamber with ten ports around the periphery. Eight of the ten ports are being completed with the cluster tool. Of the remaining two, one is for the transport pod interface and one is left open for future expansion—probably an analytical chamber. The eight capabilities substantially complete are a load lock, plasma-etching chamber, sputtering chamber for transparent conducting oxides, PDCVY chamber for depositing silicon nitride passivation layers, two PECVD a-Si:H chambers, and three combinatorial chambers for depositing thin silicon layers by either PECVD or HWCVD (see Fig. 1).

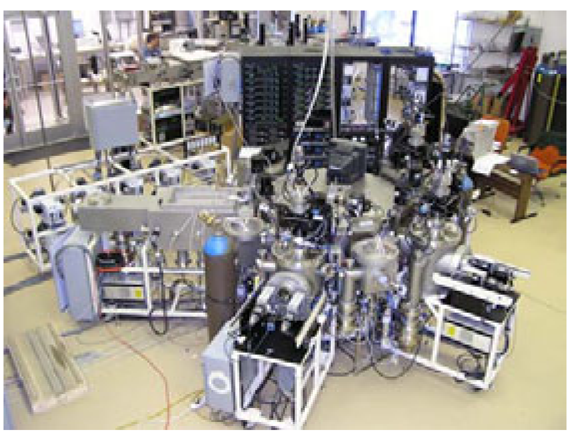

Fig. 1. The silicon cluster tool at the S&TF

4. Planned FY 2007 Activities

In accordance with the formation of the SAI, activities included under the c-Si Project in FY 2006 have been redistributed within the NCPV for FY 2007, thus dissolving the intended 2006 DOE c-Si Project as such. Crystalline silicon R&D will remain a strong, well-coordinated activity in the NCPV, however, as these activities will be included in areas of the NCPV that align with their function and that best complement c-Si activities funded under SAI. Planned activities are to:

- Issue a request for letters of interest for new university c-Si research projects.
- Finalize current research and development on high-efficiency, low-cost c-Si production processes.
- Extend three of the six university projects to the end of FY 2007 (Texas Tech/Lehigh, NCSU, and Georgia Tech/USF). Integrate these into a consortium of other universities (Duke, Washington State University, UC Berkeley) and NREL in-house research groups in a project to characterize and neutralize the performance-crippling defect clusters found in multicrystalline Si.

5. Major FY 2006 Publications

M.-H. Du, H.M. Branz, R.S. Crandall, and S.B. Zhang, “Self-trapping enhanced carrier recombination at light-induced boron-oxygen complexes in silicon” *Phys. Rev. Lett.* **97**, 256602 (2006).

Q. Wang, C. Teplin, P. Stradins, B. To, K.M. Jones, and H.M. Branz, “Significant improvement in silicon chemical vapor deposition epitaxy above the surface dehydrogenation temperature,” *J. Appl. Phys.* **100**, 93520 (2006).

C. Teplin, E. Iwaniczko, B. To, H. Moutinho, P. Stradins, and H.M. Branz, “Breakdown physics of low-temperature silicon epitaxy from silane radicals” submitted to *Phys. Rev. B* **74**, 235428 (2006).

D. Young, D. Williamson, P. Stradins, Y. Xu, L. Gedvilas, H.M. Branz, R. Reedy, A.H. Mahan, and Q. Wang “Rapid solid-phase crystallization of high-rate, hot-wire-chemical-vapor deposited hydrogenated amorphous silicon” *Appl. Phys. Lett.* **89**, 161910 (2006).

Y. Yan, M. Page, T.H. Wang, M.M. Al-Jassim, H.M. Branz, and Q. Wang, "Atomic structure and electronic properties of c-Si/a-Si:H heterointerfaces," *Appl. Phys. Lett.* **88**, 121925 (2006).

G. Yue, B. Yan, G. Ganguly, J. Yang, S. Guha, C.W. Teplin, “Material structure and metastability of hydrogenated nanocrystalline silicon solar cells,” *Appl. Phys. Lett.* 88, 263507 (2006).

C.W. Teplin, D.S. Ginley, H.M. Branz, "A new approach to thin crystal silicon films on glass: Biaxially textured silicon on foreign template layers," *J. Non-Cryst. Solids* **352**, 984-988 (2006).

T.H. Wang, E. Iwaniczko, M.R. Page, D.H. Levi, Y. Yan, H.M. Branz, and Q. Wang, "Effect of emitter deposition temperature on surface passivation in hot-wire chemical vapor deposited silicon heterojunction solar cells," *Thin Solid Films* **501**, 284-287 (2006).

A. Carvalho, R. Jones, M. Sanati, S.K. Estreicher, J.Coutinho, and P.R. Briddon, "First-principles investigation of a metastable boron-oxygen interstitial pair in Si," *Phys. Rev. B* **73**, 245210 (2006).

Residual Stresses in Polycrystalline Sheet Silicon and Their Relation to Electron-Hole Lifetime." He, S., Danyluk, S., Tarasov, I., and Ostapenko, S., Appl. Phys. Lett., 89 (11), 2006, p. 111909.

A. Belyaev, O. Polupan, W. Dallas, S. Ostapenko, D. Hess, and J. Wohlgemuth, "Crack Detection and Analyses Using Resonance Ultrasonic Vibrations in Full-Size Crystalline Silicon Wafers," *Appl. Phys. Lett.* 88, 111907-3 (2006).

X. Brun and S.N. Melkote, "Experiments and Modeling of Silicon Wafer Handling Using a Bernoulli Gripper," *Proceedings of the International Symposium on Flexible Automation*, July 10-12, 2006, Osaka, Japan.

M. Sanati and S.K. Estreicher. "Oxygen-Boron Complexes in Si," *Physica B* **133**, 376-377 (2006).

A. Carvalho, R. Jones, M. Sanati, S.K. Estreicher, J.Coutinho, and P.R. Briddon, "First-principles investigation of a metastable boron-oxygen interstitial pair in Si," *Phys. Rev. B* **73**, 245210 (2006).

D. West and S.K. Estreicher. "First-principles calculations of vibrational lifetimes and decay channels," Phys. Rev. Lett. **96**, 115504 (2006).

6. University and Industry Partners

These organizations partnered in the project's research activities during FY 2006 (no cost share).

University c-Si PV Research Project

University/Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
Caltech Harry Atwater	Pasadena, CA haa@caltech.edu	Si Passivation and CVD of Si Nitride	37.5
UC Berkeley Eicke Weber	Berkeley, CA weber@gsonet.org	Efficiency Improvement of Si Solar Cells	101.4
Georgia Tech Ajeet Rohatgi	Atlanta, GA ajeet.rohatgi@ee.gatech.edu	Fundamental R&D for Improved Crystalline Solar Cells	101.2
Texas Tech Stefan Estreicher	Lubbock, TX Stefan.estreicher@ttu.edu	Hydrogen Passivation of Si Solar Cells	97.8
NCSU George Rozgonyi	Raleigh, NC rozgonyi@ncsu.edu	Improved Efficiency and Yield R&D	71.2
Georgia Tech Steven Danyluk	Atlanta, GA steven.danyluk@ma.gatech.edu	Birefringence of Stresses in Thin Si Sheet	100.8
Georgia Tech Steven Danyluk	Atlanta, GA steven.danyluk@ma.gatech.edu	Initiative in Photovoltaic Manufacturing	100.0

DOE Center of Excellence in Crystalline Silicon Project

University/Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
Georgia Tech Ajeet Rohatgi	Atlanta, GA ajeet.rohatgi@ee.gatech.edu	University Photovoltaic Research, Education, and Collaboration Program	950

Electronic Materials and Devices

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: John Benner, 303-384-6496, john_benner@nrel.gov

DOE HQ Technology Manager: Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2006 Budget: $8,048K

Objectives

- Apply combinatorial methods to identify optimum material and demonstrate conductivity >6200 S/cm in an In-Ti-O system.
- Initiate deposition and processing of CIGS using inkjet-written precursor layers.
- Complete specification and engineering design of copper indium gallium diselenide (CIGS) platform for the Science and Technology Facility (S&TF).
- Demonstrate 17%-efficient thin (<1 micron) CIGS solar cell.
- Demonstrate 40%-efficient PV conversion.

Accomplishments

- New combinatorial capabilities for Raman, work function, deposition, and elemental analysis.
- Applications for six patents on the direct printing of precursors for copper indium diselenide (CIS) solar cell absorbers and metallization for Si solar cell contacts.
- Developed state-of-the-art infrastructure for organic photovoltaics (OPV). Obtained a 4.2%-efficient bulk heterojunction cell and >3% inverted OPV solar cells using ZnO anodes.
- 19.52%-efficient CIGS/CdZnS solar cells.
- 17.1%-efficient, 1-µm, thin CIGS solar cell and 15.02%-efficient thin CdTe cells.
- $Cd_{1-x}Mg_xTe/CdS$ solar cells for tandem cell applications
- Lowered series resistance of inverted three-junction cells for 40% performance under concentration.
- Demonstrated GaInNAs 1-eV cells with good depletion widths for use in four-junction cells
- Achieved record efficiency in lattice-mismatched GaAsP on silicon for low-cost multijunction cells.

Future Directions

- Transfer Si ink technology and develop 10% CIS solar cell from solution precursors.
- Develop improved polymers for OPV and address interface issues to achieve a 6% solar cell.
- Install and operate polycrystalline thin-film cluster tool in the S&TF.
- Achieve >40% efficiency concentrator solar cell.
- Initiate partnerships with awardees in the Solar America Initiative (SAI).

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1. Introduction

The Electronic Materials and Devices Project carries out research in semiconductor materials, device properties, and fabrication processes to improve the efficiency, stability, and cost of photovoltaic solar energy conversion. This research can be characterized in three forms. First, we apply our capabilities to assist industry and the National Research Teams in addressing current problems. Second, we explore specific techniques and processes to develop and transfer technology improvements that industry will soon need. Finally, we seek to create new technologies and lead the development of the knowledge base and tools for the future of PV. Through these activities, the project supports both flat-plate and concentrator PV technologies at the cell and module level, in all of the application targets and time frames identified in the *DOE Solar Program Multi-Year Technical Plan*.

Our base of operations in the United States presents several unique opportunities for our PV community. First, our industry leads the world in the development of thin-film technologies. This is the fastest growing segment of the PV market and is widely perceived to hold significant production cost advantages. Second, the U.S. solar resources are well suited to the use of concentrator system technologies for large-scale power generation. Finally, the relatively low cost of electric power in the United States will drive PV production to a lower cost-point than is needed in most of the rest of the world. This requires new processes that enable production methods that avoid vacuum processing (which is costly), minimize mechanical stress (to reduce breakage and increase yield), or dramatically increase throughput. Exploration and development of technologies to exploit these three opportunities compose the three primary tasks of the Electronic Materials and Devices (EM&D) Project.

2. Technical Approach

The project is composed of three primary research tasks and management. The management task coordinates project planning and operations within the PV Subprogram and interactions with projects of related interests from other agencies and private sources. Funds are also consolidated in this task for planned major costs for equipment upgrades and unanticipated major repairs. The research tasks and areas of investigation follow.

2.1 Process and Advanced Concepts

- Develop combinatorial materials science deposition, diagnostics, and data analysis tools: application to transparent conducting oxide (TCO) materials.
- Inkjet processing of electronic materials: application to metallization and semiconductor materials.
- Organic and nanocomposite solar cells
- In-situ diagnostics for thin-film growth and new analytical diagnostics
- Cooperative Research and Development Agreements (Heliovolt, Evergreen Solar).

2.2 Thin-Film Polycrystalline Compounds

- Examination of device performance in progressively thinner absorber layers.
- TCOs for thin-film solar cells
- Develop simplified and improved processes for CdTe and CIS manufacture.
- Thin-film intrinsic device stability
- Wide-bandgap absorbers for polycrystalline thin-film tandem solar cells.

2.3 Concentrator Crystalline Cells

- Inverted growth of a lattice-mismatched cell for separation from the substrate
- Dilute nitrides for four-junction GaInP/GaAs/GaInAsN/Ge or similar cell
- GaAsP cells on silicon.

Task Title	FY 2006 Budget ($K)
Processes and Advanced Concepts	2,379
Thin-Film Polycrystalline Compounds	3,195
Concentrator Crystalline Cells	2,214
EM&D Technical Coordination	260

3. Results and Accomplishments

3.1 Process and Advanced Concepts

The Process and Advanced Concepts Team works with other groups at NREL to explore new processing approaches, such as combinatorial science, ink-based electronic materials deposition, and hybrid nanostructures for solar energy conversion. In addition, we facilitate an integrated approach between staff and engineers to develop new tools and to install tools in National Center for Photovoltaics (NCPV) laboratories.

Combinatorial materials science offers a powerful approach to understanding the science and technology of multicomponent systems. Often information can be acquired 20 to 50 times faster than when using conventional approaches. To implement this, we are developing a suite of deposition, analysis and database, and mining tools to be broadly applicable to NCPV activities.

The basic scientific approach can be viewed as consisting of three basic areas: (1) deposition of libraries, (2) analysis of libraries, and (3) mining of data.

Deposition of Libraries. We have developed a number of deposition capabilities for producing libraries, including two sputter systems, which produce compositionally graded samples, and a multihead inkjet printing system, which can deposit samples with either continuously graded or discrete local compositions. The tools so far developed have shown a versatile capability for depositing optoelectronic materials, and our focus has been on TCO materials. These capabilities have let us rapidly develop state-of-the-art materials, attracting the interest of companies such as First Solar, HP, Gentex, Evergreen Solar, and Heliovolt.

Analysis of Libraries. A major focus in the program has been the development of analytical tools specific to combinatorial research and to coordinate this effort with NREL's Measurements and Characterization Division to ensure that eventually most tools will be able to handle combinatorial libraries. We have continued to develop tools to facilitate the analysis of key optoelectronic properties, as well as to correlate those to compositional, structural parameters as a function of process conditions. This year, we have worked on developing an improved conductivity mapping tool, an in-house micro-Raman tool, a work-function mapping tool, and new composition mapping tools.

Mining of Data. This consists of two separate areas. First is the development of information archiving and display for the vast amounts of data being acquired. We have been successful in developing databases and data-handling approaches that make data taking and initial analysis quite facile. We have also initiated a project with the NREL Scientific Computing Center to investigate data base structures and input-output approaches compatible with the combinatorial methodology and tools. This potentially will provide a generic database approach for the NCPV. The second area is in the development of smart software tools to analyze multidimensional phase space so as to extract key data and trends. This is more complex, and we are prototyping initial tools to better understand what is most suitable to electronic materials needs.

We now have increasingly sophisticated tools for analyzing the combinatorial data to extract key electronic properties. For TCOs, we have developed tools to aid in the display and analysis of optical data. In Fig. 1, we use color intensity to show an optical reflectivity map from 0.3–25 µm for a combinatorial TCO library. From the plasma wavelength (λ_p), which is determined by simultaneous fitting of the reflection and transmission data to the Drude (free-carrier) model and overlaid in black, one can determine the electrical carrier concentration.

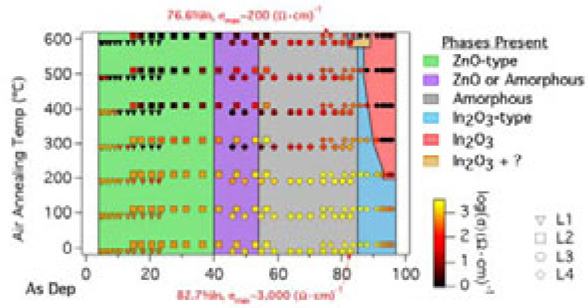

Fig. 1. Air annealing of IZO libraries from RT to 600°C showing a remarkable stability of the amorphous phase and the formation of a new phase at the amorphous/InO phase boundary.

A second major area of investigation is development of new technologies for very low-cost processing. This includes investigation of solution-based precursors for atmospheric processing, inkjet delivery of those precursors, highly processible organic solar cells, and new processes to make solar-grade silicon from thin-film precursors. A key current focus is to develop inkjet-printable precursors for solar cell materials, including materials for noncontact deposition of contacts for Si solar cells and precursors to CIS-based solar cell absorbers. We are also initiating efforts to direct-print organic materials for OPV devices. This approach has a number of inherent advantages, including that it is very materials efficient and allows direct patterning, writing on 3D and flexible surfaces, and the use of multiple sources to write complex compositions or layers. In the area of contacts for solar cells, we have developed a new set of metals and a new reaction layer that is Pb free and burns through SiN_x antireflection layers as low as 600ºC.

A key activity area this year has been the initial development of solution-based binary and ternary precursors to CIS materials. In theory, combining solution precursors with rapid thermal processing techniques might offer a new route for manufacture of CIS-based solar cells. We have developed a set of initial precursors (five disclosures) and the process to phase-pure CIS as shown in Fig. 2.

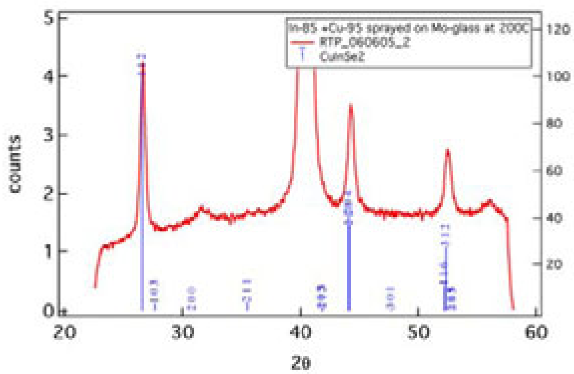

Fig. 2. X-ray diffraction illustrates the formation of phase-pure CIS from solution-based precursors sprayed at 175-180°C combined with rapid thermal processing for 5 min. at 500°C in argon. This work has led to a close developmental effort with Helivolt looking at the potential for using solution-based precursors combined with FASST® processing.

In the OPV area, we have developed a world-class processing capability allowing for the very controlled processing of organic-inorganic composite structures. Using these tools, we have already obtained a 4.2% bulk heterojunction organic solar cell and believe this will enable us to rapidly move forward exploring new inorganic, organic, and interfacial device structures. We are also combining this task with the two previously discussed ones to use inkjet printing as a combinatorial tool to rapidly explore organic device configurations and process conditions.

Along the lines of developing new process methodologies for low-cost, high-efficiency solar cells, we have been investigating the methodology of the nucleation of amorphous Si when it crystallizes to crystalline silicon. Work has been done by in-situ transmission electron microscopy and X-ray diffraction analysis, combined with other analytical approaches; an initial paper has been accepted and a model has been proposed and is being validated. Figure 3 shows some of the differences observed in the behavior of high- and low-hydrogen hot-wire material and of plasma-enhanced chemical vapor deposition (PECVD) materials under similar annealing conditions.

Finally, the engineering team has been exceptionally busy in keeping up the design, bid, and installation of equipment in the new S&TF. System development has been delayed due to limited resources. This will continue as both a priority and challenge next year.

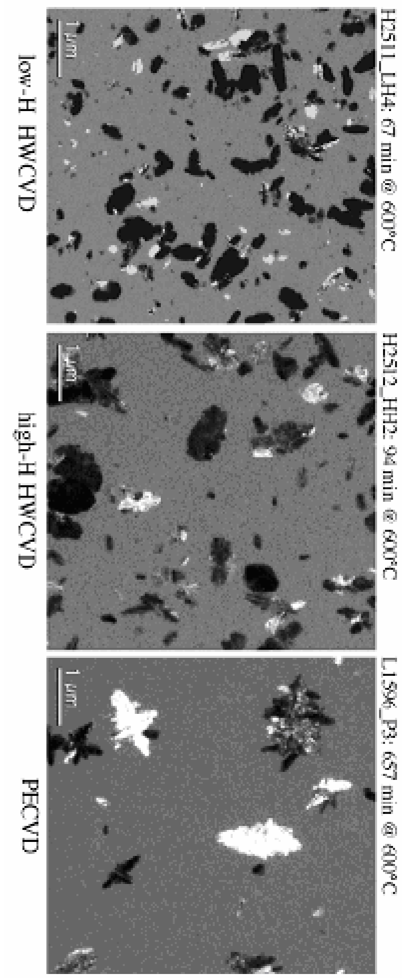

Fig. 3. Scanning electron microscopy images of silicon films crystallized by annealing. Amorphous films were grown by hot-wire chemical vapor deposition with both low and high hydrogen content and by PECVD.

3.2 Thin-Film Polycrystalline Compounds

The Polycrystalline Thin Film Team currently has within its technology process portfolio the ability to fabricate the world's highest efficiency CIGS and CdTe solar cell devices. These processes were developed with emphasis necessarily placed first on efficiency, as this defines the potential product and must precede manufacturing concerns in cost and reliability. Recent and planned infrastructure improvements will make it possible for us to address these shortcomings in the future. New tools planned for the S&TF (e.g., vapor transport, flexible layer interchange modules) will provide us with increased processing latitude necessary to develop thinner and improved device structures necessary to meet SAI module performance goals by 2015.

The project leads the development of thin-film CdTe, CIGS, and related materials for use in high-performance and stable single-junction solar cells. The objectives are to support near-term manufacturing, build the knowledge and technology base for future manufacturing improvements, and sustain innovation that supports progress toward the future and the long-term Solar Program goal of 15%-efficient commercial modules. Over the past decade, we have steadily improved the quality of the layers in the CdTe device and achieved a world-record efficiency of 16.5%. Our work in CIGS set the world record in 2006 at 19.52%. Our polycrystalline tandem solar cells of semi-transparent CdTe on top of CIS set the record at 15.3%.

High-efficiency (19.52% confirmed) CIGS-based solar cells have been fabricated by using a single-layer, NREL-developed, chemical-bath-deposited (CBD) CdZnS buffer layer. The CdZnS buffer layer allows higher-energy photons to reach the junction in order to increase the short-circuit current above that obtained for the CdS layer, which was confirmed by comparing the absolute external quantum efficiencies for both CIGS/CdS and CIGS/CdZnS devices. It was clearly evident from the absolute external quantum efficiencies that we gained significant current between 300 and 500 nm, when a CdZnS buffer layer was used. We also did not use an i-ZnO layer for the CdZnS buffer layer, which makes it commercially favorable technique. The CBD CdZnS thin film was obtained from a solution containing $CdSO_4$, $ZnSO_4$, thiourea, ammonia, water, and iso-propanol. The compositional ratio of Cd:Zn = 80:20, as analyzed by inductively coupled plasma (ICP) analysis.

The devices were measured by the Cell Performance Characterization Group at NREL. The cell parameters, in order of open-circuit voltage (V_{oc}, current density, fill factor (FF), and efficiency (η) are 0.7052 V, 35.515 mA/cm^2, 77.90%, and 19.52%, respectively. At present, we are optimizing the processing condition to obtain even higher current and fill factor of about 80%, which will produce >20% devices.

Our group has been the world leader in fabricating the most efficient CIGS thin-film solar cells (>19% since 2002). The ability to produce very high efficiency solar cells is one of the yardsticks by which a technology will be judged. Other criteria might include material cost, ease of fabrication, and throughput. For high-volume production of PV, all of the above factors might become important. The price of indium has risen sharply in recent months, and this can have an adverse impact on the prospects of our CIS industries. One solution is to reduce the thickness of the absorber without compromising high efficiency. Presently, our absorbers are 2.5–2.75-μm thick, and reducing the thickness to 0.5 μm would be desirable. However, severe losses are encountered because of incomplete generation and enhanced recombination. Figure 4 displays this challenge as shown in the optical properties of a thin CIGS cell.

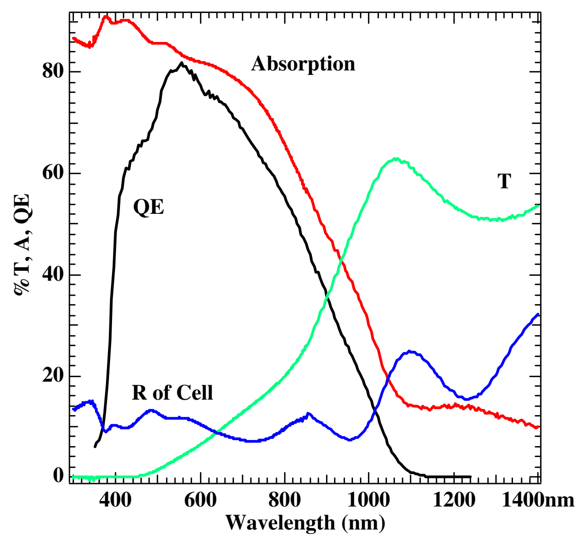

Fig. 4. Reflection, absorption, transmission, and quantum efficiency of a CIGS solar cell at 0.4-μm thickness.

We have modified our three-stage process to deposit thinner CIGS layers. For 1-μm-thick absorbers, we have fabricated several solar cells with efficiencies ≥17%. The parameters of the best solar cell are as follows: V_{oc}=0.678 V; J_{sc}=31.93 mA/cm^2; FF=79.2%, and η=17.15%. This is an impressive result for a solar cell that is less than half the thickness of our standard cells. This achievement meets the FY 2006 milestone of demonstrating a 1-μm-thin, 17%-efficient CIGS solar cell (Kannan Ramanathan).

Much of the past NREL development of CdS/CdTe high-efficiency devices focused on using relatively thick CdTe (~8 μm) layers. It has been argued, however, that manufacturing cost and material availability concerns, particularly for Te, require much thinner CdTe devices. About 2-μm-thick CdTe cells with efficiencies of 13%–14% by sputtering and electrodeposition have been demonstrated. However, these two techniques have very low deposition rates. Deposition of ~2-μm-thick CdTe film by sputtering requires more than 1 hour. CdTe cells that are 12%–13%-efficient with a 2–4-μm-thick CdTe layer have been prepared by close-spaced sublimation (CSS) and vapor transport deposition with high deposition rates. However, the efficiencies of CdTe cells prepared by these two techniques need to be improved further. Recent work by our group toward reducing CdTe film thickness reported that relatively high performance could be maintained in CdTe devices with a much reduced CdTe film thickness (3.5 μm).

The NREL Polycrystalline Device Team has developed the techniques to prepare high-efficiency thin CdTe solar cells by CSS as follows: (1) use of modified device structure, CTO/ZTO/nano-CdS/poly-CdTe, developed at NREL; (2) systematic study of the effects of CdTe deposition conditions on film thickness, grain size, and pinhole density of CdTe film; and (3) optimization of postdeposition $CdCl_2$ treatment and back contact. As a result, we have achieved a 3.5-μm-thick CdTe cell with an NREL-confirmed total-area efficiency of 15.02% (V_{oc}=829.2 mV, J_{sc}=24.13 mA/cm^2, FF=75.06%). The deposition time of the CdTe film in this cell was 1 minute.

To better understand the impact that reduced film thickness might have on device stability, we recently modified our baseline CdTe process to provide a process window for making devices in the 11%–12% range with thickness values of 2–3 μm. These devices will subsequently be used for accelerated stress studies. Thinner CdTe devices appear to show considerably more sensitivity to precontact etches. The best performance at 1.9 μm (V_{OC}=0.811, J_{SC}=21.9, FF=63.7, η=11.3%) was obtained without a precontact etch. Slightly higher performance (V_{OC}=0.826, J_{SC}=22.5, FF=64.6, η=12.0%) at 2.3 μm did, however, require a slight Br:MeOH etch. Film adhesion was also observed to significantly improve with reduced CdTe film thickness. No film delamination was observed during processing, even with excessively long vapor $CdCl_2$ treatments.

We have developed solar cells based on $Cd_{1-x}Mg_xTe$ (CMT) alloy films for use as a top cell in two-junction tandem solar cells. Previously we had reported efficiencies in the range of 5% to 6 % for the devices using the CMT alloy films. CMT solar cells were fabricated using polycrystalline $Cd_{1-x}Mg_xTe$ films prepared by co-evaporation of CdTe and Mg, a method developed at NREL. The postdeposition chloride treatment was carried out in the ambient of $CdCl_2$ and $MgCl_2$ vapor mixture instead of $CdCl_2$ vapor alone. We also have varied the partial pressure of oxygen in the ambient. Overpressure of Mg and minimized oxygen levels both contributed to preventing the loss of Mg from the $Cd_{1-x}Mg_xTe$ alloy. Even though we have deposited $Cd_{1-x}Mg_xTe$ alloy films in a wide range of bandgaps, 1.5 to 2.3 eV, the work reported here concentrates on the bandgap range of 1.5 to 1.7 eV for two-junction tandem solar cell applications. The first sets of devices fabricated using the modified postdeposition treatment have shown considerable improvement in device performance.

The devices were measured by the Cell Performance Characterization Group at NREL as summarized in the following table.

Alloy	E_g (eV)	V_{oc} (volt)	J_{sc} (mA/cm^2)	FF	Eff.
$Cd_{0.93}Mg_{0.07}Te$	1.60	0.796	19.51	51.78	8.04
$Cd_{0.92}Mg_{0.08}Te$	1.62	0.845	16.38	52.36	7.25
CdTe	1.49	0.779	21.09	56.89	9.35

These initial results with modified postdeposition processing demonstrate the potential for high device performance of polycrystalline $Cd_{1-x}Mg_xTe$ films fabricated by the NREL-developed technique and exceed the milestone for this project for the current fiscal year. We are working on optimization of the device processing and detailed characterization of these devices and expect further improvement in device performance.

3.3 Concentrator Crystalline Cells

We have embarked on a new approach for ultrahigh-efficiency concentrator tandem solar cells based on inverted III-V heteroepitaxial structures that combine both lattice-matched and lattice-mismatched component subcells in a monolithic structure. In an ideal tandem solar cell, the top solar cell produces most of the total power. Each cell underneath contributes progressively less, but all serve to boost the total efficiency. Thus, the design of a process to produce the tandem cell must ensure that the top cell is of the very best quality. In conventional designs, where the cell is grown on a substrate from the bottom cell to the top, all current designs to develop a bottom cell at the optimum bandgap of 1 eV degrade the crystalline structure of the top cell. In the new inverted cell, the lattice-matched GaInP and GaAs cells are grown upside down on the GaAs wafer, as shown on the left panel of Fig. 5.

A transparent grade changes the lattice constant, in preparation for growth of the GaInAs (1 eV) bottom cell. After growth, the sample is attached to a convenient handle, the original substrate is removed, and the grids are applied (right). These ultrathin devices have many systems-level advantages and a realistic potential to exceed 40%-efficient terrestrial concentrator conversion. In initial work, we have already demonstrated a record efficiency of 37.9% for concentrator tandem cells using our new approach.

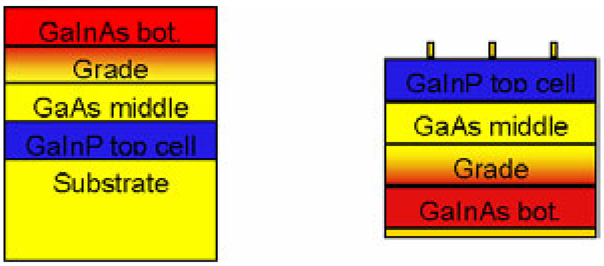

Fig. 5. Inverted growth and handle-mounted thin-film, high-efficiency solar cell

The achievement of a 40%-efficient cell this year relies on our ability to identify and mitigate all series resistance sources in the multijunction solar cells. We recently installed and adapted a new flash simulator that already has helped identify and remove one source of series resistance.

Our record cell achieved 37.9% efficiency at about 10 suns of concentration. We estimated that a similar cell operating at about 300 suns should achieve about 40% efficiency and, therefore, set a 40% milestone for this year. Unfortunately, the repair of a system failure necessitated redesigning the cell recipe from scratch.

After the redesign was completed, we found that the internal series resistance of the cell was too high to allow efficient operation at 300 suns. However, measurement of the series resistance is difficult: some cells have shown low series resistance in forward bias and higher resistance when tested under concentrated sunlight. To quantify the series resistance quickly, we needed a flash simulator that we could access on a daily basis. Fortunately, members of measurements team (Keith Emery and James Kiehl) were willing to donate the flash simulator they had obtained under a project with a Russian group. We moved the simulator to the Solar Energy Research Facility (SERF) and worked through numerous issues with reliable operation of the system.

The system is now demonstrating its utility, allowing us to quantify the series resistance in our cells. We found that the series resistance in the GaInP top cell is probably coming from a Zn-doped AlGaInP layer. The phosphine cylinder we are currently using is almost gone, and it is known that the impurities are concentrated at the end of the life of the cylinder. We were already using a purifier, but found that the addition of a second purifier on the phosphine line reduced the series resistance of the GaInP cell, presumably because of a cleaner Zn-doped AlGaInP layer, which is known to be especially sensitive to oxygen contamination. Although the triple-junction cell was quickly implemented in FY 2005, the structure has about 50 layers, each of which has the potential to introduce series resistance. Identification and elimination of each series resistance will take time, but will progress much more quickly now that the flash simulator can be used as a reliable tool.

Our second primary area of investigation continues the development of 1.0-eV material for the fourth junction of a high-performance GaInP, GaAs/1-eV material/Ge solar cell. Theoretically, GaInNAs has the potential to contribute to a 40%-efficient four-junction solar cell. The use of molecular beam epitaxy (MBE) growth has been shown to dramatically improve the photocurrent from the GaInNAs junctions, relative to organometalic chemical vapor deposition (OMCVD). This is probably because of lower carbon and hydrogen concentrations. We have achieved depletion widths in excess of 1.5 μm for bandgaps in the 1.05–1.10-eV range.

One strategy for increasing the photocurrent for GaInNAs cells is using a *p-i-n* structure with a wide depletion width. The use of MBE growth results in background carrier concentrations that are dramatically lower than those obtained by OMCVD. We believe that this may be related to the lower carbon and hydrogen contamination for the MBE material. Recent results show that the background carrier concentration, and hence depletion width, depend greatly on the ion content of the rf-plasma source used for nitrogen. The use of biased plates at the nitrogen source aperture to deflect ions away from the growing film dramatically reduces the carrier concentration. As a result, wide-depletion-width samples have been grown, even at the high nitrogen concentrations necessary to achieve low bandgaps.

Multijunction solar cells employing III-V top junctions with a silicon bottom junction are very attractive based on the potential for very high efficiency, coupled with relatively low substrate cost. A 1.7-eV top junction on an active silicon junction has theoretical efficiencies of 34% at 1 sun AM0 and 44% under 500 suns concentration AM1.5G. Increasing the number of junctions has the potential for even greater efficiencies. AlGaAs and GaAsP have long been prime candidates for top junctions on silicon-based multijunction solar cells. Organometallic vapor phase epitaxy (OMVPE) is a commonly used technique that can be employed to fabricate such devices. Unfortunately, many challenges to high-quality epitaxial growth of these III-V materials on Si exist. The most significant is the lattice mismatch and thermal expansion mismatch between silicon and most III-V materials. Other important challenges include silicon surface cleanliness, antiphase domain (APD) formation, and interdiffusion.

Excellent-quality $GaAs_{0.8}P_{0.2}$ single-junction solar cells grown on GaAs substrates have been demonstrated using thick compositionally graded buffer layers. These mismatched solar cells had threading dislocation densities lower than 106 cm^{-2} with efficiencies as high as 17.8%, but the growth of such cells on Si has proven much more challenging. A tandem $GaAs_{0.7}P_{0.3}$/Si solar cell using thermal cycle annealing (TCA) has been demonstrated with two-terminal AM0 efficiencies of 9.2%. We explore the use of compositionally graded buffer layers to grow $GaAs_{0.7}P_{0.3}$ solar cells on Si substrates. In our approach, we grade to a composition that is in compression at the growth temperature such that, on cooling, the strain will be relieved. This is shown in Fig. 6.

The strain state and composition of these cells was determined from (224) grazing incidence reflection X-ray diffraction reciprocal space maps (RSM). The actual P composition in the $GaAs_{0.7}P_{0.3}$ was adjusted from 25% to 31% to vary the bandgap from 1.7 to 1.8 eV. The passivating $Ga_{0.6}In_{0.4}P$ layers were carefully lattice matched to the $GaAs_{0.7}P_{0.3}$ junction material using this information. The thermal expansion mismatch of III-V grown on Si tends to stress the layer toward tension on cooling. The fact that the X-ray data show very little strain at room temperature indicates that the layers were grown with significant residual compressive strain at growth temperature. When III-V layers are grown to be stress free on Si at growth temperature, large tensile stress on cooling can result in cracking of the grown film, which these cells did not exhibit.

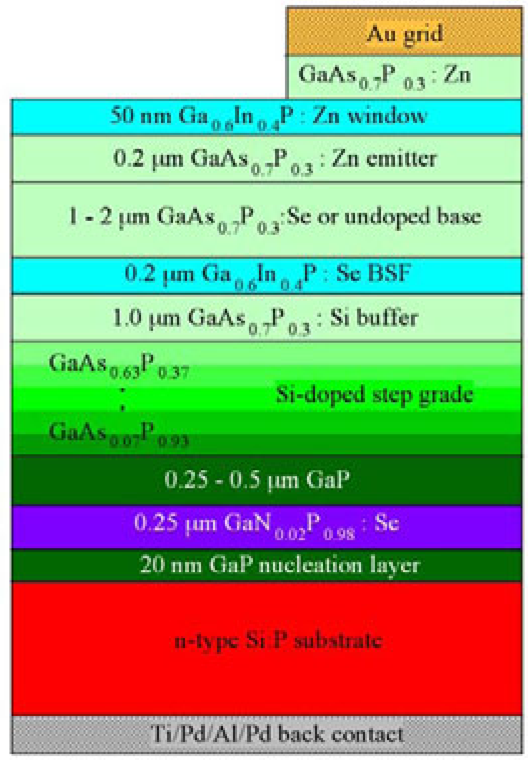

Fig. 6. Schematic of a GaAsP-on-Si solar cell

We have demonstrated lattice-mismatched *p-on-n* $GaAs_{0.7}P_{0.3}$ cells on silicon using a compositional step-graded buffer. The performance of our devices, with efficiencies of about 10%, rivals or surpasses previous reports of AlGaAs and GaAsP solar cells grown on Si using thermal cycle annealing. The internal quantum efficiency (QE) of some $GaAs_{0.7}P_{0.3}$ solar cells exceeded 80%. The wide depletion regions in cells with undoped bases help to achieve the highest QEs. Intentional Se doping in the base of MG228 show that the QE remains relatively high, even for narrower depletion widths. However, further reduction in threading dislocation density will be needed to realize the predicted efficiencies of this potentially low-cost structure.

4. Planned FY 2007 Activities

During FY 2007, much of our attention will be on relocating facilities and building new tools in the new S&TF. This is an important milestone for the PV Subprogram, requiring significant attention during the first half of the year. Despite this interruption, this project will also complete several other accomplishments, including:

- Install, debug, and operate the silicon cluster tool, the first major tool installed in the Process

Development and Integration Laboratory (PDIL) at the S&TF.

- Demonstrate inkjet printing on whole cells with ohmic contracts processed by rapid thermal processing.
- Validate readiness of the CIGS cluster tool by performing acceptance tests at NREL.
- Evaluate inverted triple-junction solar cell under 300 suns illumination

5. FY 2006 Special Recognitions, Awards, and Patents

Numerous project staff have been chosen by their peers to lead professional organization activities as general chair, program chair, session organizer, session chair, tutorial instructor, and similar honors. Two of the more notable of these recognitions are:

- Dr. David Ginley served as General Chair of the Fall 2005 Materials Research Society Meeting. Subsequently he was selected to be Secretary of the Society.
- Dr. Timothy Coutts served as Program Chair of the 4^{th} World Conference on Photovoltaic Energy Conversion. He has been selected to be General Chair of the 33^{rd} IEEE Photovoltaics Specialists Conference.

The project also leads the entire lab in generation of new intellectual property, filing 12 patents, which is more than a third of all of the records of invention from NREL in FY 2006. During the year, four of the inventions reported in earlier years were granted patents. Titles of these, and the first listed inventor, include:

- *Method for Producing High Carrier Concentration P-Type Transparent Conducting Oxides,* X. Li
- *Stacked Switchable Element and Diode Combination with a Low Breakdown Switchable Element,* Q. Wang
- *High Resolution Metal Deposition by Ink Jet Printing of Organometallic Silver Compounds from Aqueous and Organic Solvents under Mild Reducing Conditions at Low Temperature in Air,* D. Ginley.

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High-Performance Photovoltaics

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Martha Symko-Davies, 303-384-6528, martha_symko_davies@nrel.gov

DOE HQ Technology Manager: Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2006 Budget: $5,143K

Objectives

The High-Performance Photovoltaics (HiPerf PV) Project aims to explore the ultimate performance limits of PV technologies, approximately doubling their sunlight-to-electricity conversion efficiencies during its course. This work includes developing:

- Thin-film tandem cells and modules toward 25% and 20% efficiencies.
- Precommercial multijunction concentrator modules able to convert more than one-third of the sun's energy to electricity.
- High-risk/high-payoff third-generation PV technologies, primarily high-efficiency and exciton-based solar cells, aimed at substantially surpassing the performance of existing solar cell technologies.
- Scientific and technical research opportunities for minority undergraduate and graduate students in solar energy technologies via the Minority University Research Associates Project.

Accomplishments

- The Institute of Energy Conversion (IEC) demonstrated an 11.9% CIGSS (1.5eV) top cell material of the polycrystalline thin-film tandem.
- Boeing Spectrolab demonstrated a 40.7%-efficient GaInP/GaInAs/Ge cell that was verified by NREL at 236 suns.
- Researchers investigated the design of shallower acceptors in ZnO and proposed new concepts to overcome p-type doping difficulty in wide-gap semiconductors such as ZnO, which is an important transparent conducting oxide (TCO) for solar cells. By manipulating the wavefunction character of the defect states, they can design defect complexes that can significantly lower the acceptor transition energy levels, thus providing a new opportunity to make p-type ZnO.
- The University of Delaware has provided a model for defect formation during the growth of the III-nitrides during both molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD), allowing further improvements in material and solar cells.

Future Directions

The project will merge into University and Exploratory Research to address key R&D issues in support of the goals of the Solar America Initiative. These include:

- Demonstrating a 41% III-V multijunction solar cell incorporated into a high-concentration module.
- Designing approaches for fabricating solar cells with >50% efficiency, in quantity, in 5 years.

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1. Introduction

The HiPerf PV Project aims to explore the ultimate performance of PV technologies, approximately doubling their sunlight-to-electricity conversion efficiencies during its course. The project is expected to enable progress of high-efficiency technologies toward commercial prototype products. This begins with the investigations of a wide range of complex issues and provides initial modeling and baseline experiments of several advanced concepts.

Categories within the HiPerf PV Project are: (1) subcontracted research in polycrystalline thin-film tandems; (2) subcontracted research in III-V multijunction concentrators; (3) subcontracted Future Generation research; (4) high-efficiency novel concepts conducted by NREL's in-house Energy Sciences Division, and (5) the Minority University Research Associates (MURA) task.

Near-term milestones for the R&D tasks under the project follow and are listed in the *DOE Solar Program Multi-Year Technical Plan* (MYTP). Throughout the project's term, there will be opportunities to reach established program goals by both disruptive technology advances and/or multiple incremental improvements.

This development of R&D will lead the pathway toward new record cell efficiencies and commercial prototype products. For concentrating photovoltaics (CPV), gaining a position in the marketplace could portend the emergence of CPV systems in the next 2–5 years at installed system costs of $3 per watt.

2. Technical Approach

The project consists of three phases for the polycrystalline thin-film tandems and III-V multijunction concentrators, which focus on a specific approach to solving the challenges associated with high efficiencies. The first phase is critical as it provides a means to accelerate toward the most promising paths for implementation, followed by commercial prototype products.

The HiPerf PV Project funds in-house and university teams developing high-risk innovative concepts (such as organic solar cells and novel solar conversion processes) with the potential for ultra-high efficiency (>50%) and very low cost. These tasks are well leveraged by related science supported by DOE's Office of Science, Basic Energy Sciences.

The MURA task provides scientific and technical research opportunities for minority undergraduate students to work on various solar energy technology projects.

Task Title	FY 2006 Budget ($K)
High-Performance PV Management	1,123
Thin-Film Polycrystalline Tandems	790
III-V Multijunction Concentrators	870
Future Generation Project	508
MURA	335
High-Efficiency Concepts	1,520

3. Results and Accomplishments

All results reflect an MYTP milestone and will be discussed after the milestone is stated.

3.1 High-Performance PV Management

- Assessed research on exploring pathways to high-efficiency PV MYTP: Task 1 of Section 4.1.2

The subcontracts under the Polycrystalline Thin-Film Tandems and the III-V Multijunction Concentrators are ending for the most part in FY2007. The Future Generation and MURA subcontracts are targeted to end in FY 2008.

3.2 Thin-Film Polycrystalline Tandems

Oregon State has identified several new materials of interest as window and absorber materials for PV applications, and progress has been made in developing processes for thin-film deposition. With bandgaps >2 eV, the materials Cu3TaQ4 (Q = S, Se) are two inexpensive candidates as *p*-type window materials. A pulsed laser deposition (PLD) process has been developed for deposition of the sulfide, and initial characterization of electrical and optical properties has been completed. Progress in deposition of films of the potential absorber materials Fe_2MS_4 (M = Si, Ge) has also been made via electron-beam deposition and annealing in sulfur atmospheres. Notably, control of carrier concentration has been demonstrated by doping of the M site, providing additional impetus to develop this sulfide system. Wide-bandgap BuCuTeF films have continued to be of interest as transparent back contacts for CIGS and CdTe cells, and incorporation of BCTF films in CIGS structures has been investigated.

Improved efficiency has been demonstrated by IEC for the $Cu(InGa)(SeS)_2$ absorber layer. This process uses a bilayer evaporation process, which results in through-film S and Se compositional gradients. The resulting devices have higher fill factors, up to 78%, than previous $Cu(InGa)(SeS)_2$ cells. This is attributed to improved current collection. The best cell had V_{OC} = 0.77V, J_{SC} = 20.6 mA/cm^2, FF = 75.2%, and efficiency = 11.9%. The complete cell structure for each is: glass/Mo/$Cu(InGa)(SeS)_2$/ZnO/ITO/Ni-Al grid / MgF_2. This $Cu(InGa)(SeS)_2$ absorber layer had average composition over the top ~1 µm, as measured by energy dispersive x-ray spectroscopy, of 23.9% Cu, 11.8 % In, 13.9% Ga, 28.5% Se, and 22.2% S. This composition indicates a bandgap energy (Eg) of 1.61 eV. However, because of the compositional gradient in the film, the bandgap is not uniform through the film thickness. Therefore, a more relevant measure of Eg is obtained from the long wavelength edge of the quantum efficiency (QE) by comparison with a $CuInS_2$ device, which has a known bandgap of 1.53 eV and a steep edge in the QE. In this case, the $Cu(InGa)(SeS)_2$ cell has the same bandgap of 1.53 eV.

3.3 III-V Multijunction Concentrators

- Demonstrated a 40.7%-efficient III-V multijunction cell under concentration. MYTP: Task 1 of Section 4.1.2

Boeing Spectrolab achieved a new world record efficiency of 40.7% for a three-junction terrestrial concentrator cell. This is the highest NREL-confirmed efficiency ever measured for any PV device. A large experimental matrix of three-junction GaInP/GaInAs/Ge terrestrial concentrator cells was carried out, using metamorphic and lattice-matched configurations, optimization of current ratio, and a variety of high-efficiency semiconductor device structures, cell sizes, grid patterns, and fabrication processes. A metamorphic Ga0.44In0.56P/Ga0.92In0.08As/Ge three-junction solar cell from these experiments reached a record 40.7% efficiency at 240 suns. This metamorphic device is the first solar cell to reach over 40% in efficiency, and has the highest solar conversion efficiency for any type of photovoltaic cell developed to date. Spectrolab also demonstrated first-prototype four-junction cells with initial efficiencies at >35%.

Amonix developed an improved optical system specifically fitted for the existing Amonix Fresnel lens that was designed to provide a concentrated sunlight distribution pattern for the back-contact silicon solar cell. The optical paths of the new system were designed for better tracking tolerance, which yields more energy production per installed kilowatt. Amonix has designed and fabricated a single-plate multijunction module (>28% efficiency), which is being field-tested. Since this field-tested module installation, another module has been built and tested at the factory using the improved optics and the latest Spectrolab cells. Initial readings have shown an efficiency of nearly 30% at equilibrium temperature.

The University of Delaware efforts are directed toward the InGaN material system. This offers the potential for increased solar cell efficiencies, most immediately through the realization of high-bandgap solar cells (>2.4 eV), which are required for ultra-high efficiency tandems. This 2.4 V open-circuit voltage was in fact achieved using $In_{0.05}Ga_{0.95}N$ with a bandgap of 3.3 eV. The increased voltage was achieved by improving the phase separation in the InGaN MOCVD-grown material. Although phase separation increases at high In compositions, methods to suppress this phenomenon have been identified by controlling the growth process. Further, models for defect formation during the growth of the III-nitrides during both MBE and MOCVD have been developed, allowing further improvements in material and solar cells.

The California Institute of Technology is focused on a “Four Junction Solar Cell with 40% Target Efficiency by Wafer Bonding and Layer Transfer.” Integration of dissimilar materials to form multijunction solar cells requires a method to accommodate the large lattice mismatch between the constituent layers, and this method should maintain high crystalline quality in the active layers and enable an ohmic electrical contact at the interface. Direct wafer bonding of III-V compound semiconductors lattice-matched to InP and GaAs can enable formation of highly lattice-mismatched interfaces with high electronic quality. They demonstrated the first multijunction solar cell with an interface formed by direct wafer bonding. The cell is a two-junction GaAs/InGaAs/InP cell with a direct covalently bonded interface between the GaAs subcell and InGaAs/InP subcell. The open-circuit voltage of the direct bonded two-junction cell is equal to the sum of the open-circuit voltages of the constituent, indicating a bonded two-junction cell with high electronic quality.

3.4 Future Generation

The provisions of the MYTP (Sect. 4.1.1) specifically call for fundamental R&D involving our colleges and universities and, as a corollary, the development of the next generation of solar technologists. The following accomplishments support this activity.

The University of Delaware developed a new model that includes internal optical absorption and recombination within a finite intermediate band (as opposed to the infinitesimally narrow band typically assumed). In addition to showing that such transitions are required to realize physically consistent efficiency results, the results demonstrate that the efficiency is a slowly varying function of the intermediate band width. The ability to implement a solar cell with multiple bands depends critically on realizing a material that has a band structure as close to ideal as possible, but also one in which the absorption coefficients match those from detailed balance calculations. To model the absorption coefficients, the group developed a model of the density of states for a quantum dot solar cell, using a piecewise continuous parabolic density of states while assuming that all transitions are direct. Calculations showed that by introducing asymmetry into the oscillator strengths, absorption coefficients can be designed that show very little overlap, and together they cover the range of high solar irradiance so as to lead to solar cells with high efficiencies.

Northwestern University attacked two major bottlenecks in TCO electrode growth for photovoltaic cells: (1) enhancing the mobility/conductivity of TCO films grown on amorphous glass substrates and (2) optimizing TCO surface properties for maximum electrode performance. It was shown that:

- MOCVD-derived MgO template layers, which grow spontaneously with high degrees of texture on glass, can be used to template MOCVD CdO films with higher crystallinity and mobility than is normally possible on simple glass substrates.
- Highly conductive In-doped CdO electrode films grown by MOCVD can be enhanced in work function and corrosion resistance by coating with thin layers of ion-beam-assisted deposition (IBAD)-derived ITO films. Films with one-third the sheet resistance of commercial ITO are produced that contain only 15% of the In of commercial ITO films

3.5 Novel High-Efficiency Concepts

The High-Efficiency Concepts effort was recompeted to target emerging state-of-the-art, high-efficiency concepts. This group listed in the following table is from NREL's Energy Sciences Division and works directly with NCPV scientists.

Researchers have developed a comprehensive theoretical understanding of these basic materials properties in the TCOs In_2O_3 and ZnO, and predict their variation with process parameters during crystal growth. The theoretical tools developed are prerequisite for the design of new PV materials.

Researchers determined that photoelectrons in TiO_2 recombine with oxidized redox species in the electrolyte via surface states rather than from the conduction band, etc. (Zhu, et al., *J. Phys Chem. B.,* in press). In addition, researchers discovered that the charge-collection efficiency and light-harvesting efficiency are markedly enhanced in sensitized oriented nanotube arrays.

Researchers have investigated the influence of a number of chemical treatments on the optical properties of PbSe and PbS quantum dot (QD) films and on the behavior of PV devices made with QD arrays. In addition, they have begun fabricating and characterizing PV devices in which a thin absorber layer of PbS QDs is deposited on a planar conducting oxide surface. The device operates in similar fashion to a Gratzel-type cell where photoexcited electrons in the QDs are injected into the oxide, and the QDs are subsequently reduced by an ionic species in an electrolyte after charge injection. The advantages of this device configuration versus a device with a QD-sensitized porous oxide are the ability to better control the interface between the QDs and oxide surface, a simpler fabrication process, and a geometry that is easier to model. Ideally, we would like to make devices with just a monolayer of QDs to allow the most efficient charge transfer.

Researchers investigated the design of shallower acceptors in ZnO. They proposed new concepts to overcome p-type doping difficulty in wide-gap semiconductors such as ZnO, which is an important TCO for solar cells. They show that by manipulating the wavefunction character of the defect states, they can designed defect complexes that can significantly lower the acceptor transition energy levels, thus providing a new opportunity to make p-type ZnO.

Researchers investigated light-induced recombination centers in p-type CZ Si. They identified the microscopic mechanism for the generation of non-radiative recombination centers in boron-doped, oxygen-rich p-type CZ silicon. Boron forms a complex with O_2 dimer, and under illumination, the complex reconfigures between bistable configurations, causing non-radiative recombination, thereby reducing solar cell efficiency.

Researchers studied monolithic ultra-thin lattice-mismatched solar cells with optimal bandgaps: The underlying concepts are part of an invention (NREL IR #05-17 by Wanlass/Mascarenhas). This effort enhances the possibility of designing very high efficiency monolithic multi-bandgap tandem solar cells. Tandem designs involving lattice-mismatched materials typically suffer from epilayer bowing problems. Conventional cell designs are based on non-optimal bandgaps. They researched approaches directed at helping circumvent these limitations.

NREL High-Efficiency Concepts Group

Principal Investigator	Title/Research Activity
Arthur Frank	Dye Cell Research
Arthur Nozik	Quantum Dots
Angelo Mascarenhas	Solid State Spectroscopy
Su-Huai Wei	Computational Materials Science
Alex Zunger	Solid State Theory

3.6 The MURA Program

This includes eight minority-serving universities (six Historically Black Colleges and Universities and two Hispanic-serving universities). Accomplishments in 2006 include development of a software tool, Tonatiuh, for the design and analysis of solar concentrating systems. Tonatiuh is well under way to being released in 2007. When finished, Tonatiuh will become a very valuable tool for assisting solar researchers in the design and analysis of solar concentrating systems (University of Texas at Brownsville). At Fisk University, semiconductor QDs have been fabricated using both pulsed electron-beam deposition (PED) and PLD techniques via direct ablation of device-quality target materials. ZnO nanowires have been grown routinely via a vapor-liquid-solid process at Fisk. Their sizes, density, and growth direction with respect to the substrate can be controlled through the growth conditions. And, direct deposition of QDs on ZnO nanowires by PED has been achieved. A comparison of the photo-induced current response of cells consisting of ZnO nanowires sensitized by QDs synthesized using wet chemistry methods and from direct deposition showed enhanced charge transport.

The Renewable Energy Academic Partnership (REAP) Review Meeting was held August 7, 2006, in conjunction with the 16th Crystalline Silicon Workshop in Denver, CO. Presentations generated interesting discussions, which demonstrated great enthusiasm by participants toward the individual projects. The DOE NREL MURA Program continues to receive worldwide recognition for its unique efforts.

4. Planned FY 2007 Activities

The planned activities directly support the MYTP under Task 1, sections 4.1.1.5 and 4.1.2.5.

The subcontracted R&D in this area will be ending during FY 2007 and into FY 2008. The HiPerf PV Project will merge into the University and Exploratory Research Program.

- Finalize subcontracts under "Exploring and Accelerating Pathways towards High Performance PV: Phase I-B" through FYs 2006/2007.
- Demonstrate a 41%-efficient III-V multijunction cell under concentration.
- Continue modeling of the enhanced performance of quantum-dot-based solar cells to see how far one can push the multiple-exciton-generation effect in various PV cell configurations to maximize cell efficiency.
- Target 10% efficiency for organic solar cells.
- Continue R&D of ultra-high efficiency solar cells targeting >50% efficiency.
- MURA: Ensure progress on projects currently under way and invite additional universities to participate in the REAP Conference through partnerships with other similar programs.

5. Major FY 2006 Publications

M. Symko-Davies and R. McConnell, “Progress in High Performance PV: Future Generation PV," *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006).

R. McConnell and M. Symko-Davies, “Multijunction PV for High Performance Concentrators, *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006).

M. Symko-Davies, R. McConnell, K. Tanabe, A.F. Morral, H.A. Atwater, "Direct-bonded GaAs/InGaAs tandem solar cell," *Appl. Phys. Lett.* **89**, 102106 (2006).

M.J. Griggs, D.C. Law, R.R. King, A.C. Ackerman, J.M. Zahler, H.A. Atwater, "Design Approaches and Materials Processes for Ultrahigh Efficiency Lattice Multi-junction Solar Cells," *Proceedings of 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006).

O. Jani, C. Honsberg, Y. Huang, J.O. Song, I. Ferguson, G. Namkoong, E. Trybus, A. Doolittle, S. Kurtz, “Design, Growth, Fabrication and Characterization of High-Band Gap InGaN/GaN

Solar Cells," *Proceedings of 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006)

B. Fluegel, S. Francoeur, and A. Mascarenhas, "Spin-Orbit Bowing in $GaAs_{1-x}Bi_x$," *Phys. Rev. Lett.* **97**, 067205 (2006).

J. Li, S.-H. Wei, S.-S. Li, Jian-Bai Xia, "Design of shallow acceptors in ZnO: First-principles band-structure calculations," *Phys. Rev. B* **74**, (Rapid Communication), 081201(R) (2006).
Y. Yan, M. M. Al-Jassim, and S.-H. Wei, Doping of ZnO by group-Ib elements," *Appl. Phys. Lett.* **89**, 181912 (2006).

T. J. Coutts, X. Li, T. M. Barnes, B. M. Keyes, C. L. Perkins, S. E. Asher, S. B. Zhang, S.-H. Wei, and S. Limpijumnong, "Synthesis and characterization of nitrogen-doped ZnO films grown by MOCVD," (Book Chapter) in *ZnO Bulk, Thin-Films, and Nanostructures--Processing, Properties and Applications*, edited by C. Jagadish and S.J. Pearton, (Elsevier Science, New York, 2006), p. 43.

M.-H. Du, H. M. Branz, R. S. Crandall, and S.B. Zhang, *Phys. Rev. Lett.* **97**, 256602 (2006).

S. Lany and A. Zunger, "Dopability, intrinsic conductivity, and non-stoichiometry of transparent conducting oxides," *Phys. Rev. Lett.* (In Press).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2006 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
Georgia Institute of Technology Ajeet Rohatgi	Atlanta, GA Ajeet.Rohatgi@ece.gatec.edu	Thin-Film Si Bottom Cells for Tandem Device Structures	60
University of Delaware Bill Shafarman	Newark, DE wns@udel.edu	High-Performance PV Polycrystalline Thin-Film Tandem Cells	209
University of Toledo Alvin Compaan	Toledo, OH adc@physics.utoledo.edu	Sputtered II-VI Alloys and Structures for Tandem PV	217
University of Oregon David Cohen	Eugene, OR dcohen@darkwing.uoregon.com	Identifying the Electronic Properties Relevant to Improving the Performance of High Band-Gap Copper-Based I-III-VI_2 Chalcopyrite Thin Film PV Devices	139
Oregon State University Douglas Keszler	Corvallis, OR Douglas.keszler@orst.edu	Novel Materials Development for Polycrystalline Thin-Film Solar Cells	165
Spectrolab, Inc. Raed Sherif	Sylmar, CA rsherif@spectrolab.com	Ultra-High-Efficiency Multijunction Cell and Receiver Module	223
Amonix, Inc. Vahan Garbushian	Torrence, CA drvahan@earthlink.net	Design and Demonstration of a Greater than 33% Efficiency High-Concentration Module Using 40% III-V Multijunction Devices	232
California Institute of Technology Harry Atwater	Pasadena, CA haa@daedalus.caltech.edu	Four-Junction Solar Cell with 40% Target Efficiency Fabricated by Wafer Bonding and Layer Transfer	174
JX Crystals Lew Fraas	Issaquah, WA lfraas@jxcrystals.com	Toward 40% Efficient Mechanically Stacked III-V Terrestrial Concentrator Cells	33

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
University of Delaware Christiana Honsberg	Newark, DE honsberg@ece.gatech.edu	Novel High Efficiency PV Devices Based on the III-N Material System	145
Ohio State University Steve Ringel	Colombus, OH ringel@ee.eng.ohiostate.edu	Optimized III-V Multijunction Concentrator Solar Cells on Patterned Si and Ge Substrates	35
Underwriters Lab/ Arizona State University Liang Ji	Phoenix, AZ Liang.ji@us.ul.com	Development of IEC Design Qualification Standard for Concentrator PV Modules	15
Princeton University Steve Forrest	Princeton, NJ forrest@ee.princeton.edu	Approaching 10% Efficient Cells Using Tandem Organic PV Cell with Enhanced Optical Coating	80
University of Colorado-Boulder Josef Michl	Boulder, CO michlj@colorado.edu	Ultra-High Efficiency Excitonic Solar Cells	148
Northwestern University Tom Mason	Evanston, IL tmason@northwestern.edu	Interface and Electrodes for Next-Generation Organic Solar Cells	115
University of Delaware Christiana Honsberg	Newark, DE honsberg@ee.udel.edu	Theoretical and Experimental Investigation of Approaches to >50%-Efficient Solar Cells	165
Southern University and A&M College Rambabu Bobba	Baton Rouge, LA Rambabu@grant.phys.subr.edu	Student research projects related to energy conversion and storage devices	38
University of Texas, El Paso Gregory Lush	El Paso, TX glush@gerdau.com	Investigation, fabrication, characterization, and modeling of solar cells	42
Fisk University Richard Mu	Nashville, TN rmu@fisk.edu	Development of Si quantum dots for advanced solar cells with maximum efficiency	47
Howard University J.M. Momoh	Washington, DC jmomoh@msn.com	Developing automation/strategies to improve power management and distribution of renewable energy resources	42
N. Carolina Central University Joe Dutta	Durham, NC jmd@nccu.edu	Fabricating and characterizing bulk and non-phase PV materials for student research	42
University of Texas, Brownsville M. Blanco	Brownsville, TX mjblanco@utb.edu	Student/faculty teams for designing and developing computer-simulation tools for design of solar concentrating systems.	35
N. Carolina A&T State University G. Shahbazzi	Greensville, NC ash@ncat.edu	Modeling performance of a grid-connected PV system in a residential area	34
Central State University Clark Fuller	Wilberforce, OH cfuller@prodigy.net	Renewable energy technology and technology transfer in developing countries	51 4*

* Funded with prior year (FY 2005) funds.

Advanced Materials and Devices

The Advanced Materials and Devices effort carries out research in semiconductor material properties, device mechanisms, and fabrication processes to improve the efficiency, stability, and cost of photovoltaic energy conversion. The effort focuses on thin-film materials and modules (which hold promise for major reductions in PV costs), module manufacturing methods, and module reliability.

The Thin-Film PV Partnership has formed strong research teams to focus R&D on promising thin-film candidates, such as amorphous silicon, cadmium telluride, copper indium diselenide, and thin silicon. These research teams comprise laboratory, industry, and university researchers who work to solve generic issues as well as industry-specific problems.

The overall objective of the PV Module Reliability Project is to work with industry to develop PV modules that have 30-year service lifetimes. This project also provides critical performance and reliability testing and benchmarking of modules to validate the progress and accomplishments of the Solar Program's investments in PV module technology R&D. The Inverter and BOS Development Project is directed toward improving inverters and balance of systems (BOS) through the High-Reliability Inverter Initiative.

In PV Manufacturing R&D, strong partnerships with the U.S. PV industry have been formed with the goal of retaining and enhancing the industry's leadership in the development and manufacture of PV modules. Many problems in manufacturing R&D exist whose solutions are critical to further reducing the cost of PV.

Achievements in Advanced Materials and Devices for FY 2006 include the following.

Thin Film PV Partnership

- Two Technology Partners expanded manufacturing facilities in the United States (First Solar 85 MWp and Uni-Solar 60 MWp).
- Production of thin films in the United States grew from 12 MWp in 2003 to an estimated >70 MWp in 2006.

PV Module Reliability R&D

- Upgraded and maintained accelerated module testing capabilities essential to industry partners and progressed toward becoming an accredited Certified Testing Body Testing Laboratory.
- Reported results of high-voltage stress testing (module leakage currents using the High Voltage StressTestbed) for potential high-voltage applications by industry.

Inverter and BOS Development

- Completed Phase II of the High-Reliability Inverter Initiative (HRII) with hardware beta deliverables by GE and Xantrex.
- Assessed HRII beta inverter and controller prototypes for conformity to utility interconnection requirements, performance objectives, and manufacturing objectives.

PV Manufacturing R&D

- Completed the development (achieve manufacturing-line-ready status) of at least three in-line diagnostic processes initiated in FY 2002 awards from "In-Line Diagnostic, Intelligent Processing (IDIP) Solicitation" with at least five of the U.S. PV industry partnerships involved in the IDIP solicitation having reported a minimum of 22 in-line diagnostic processes that have been implemented on U.S. PV production lines.
- Conducted a stage-gate evaluation of project participants to assess and determine the needs for additional manufacturing R&D and select areas for elimination or support.

Thin Film PV Partnership

Performing Organizations:	National Renewable Energy Laboratory (NREL) DOE Golden Field Office (DOE/GO)
Key Technical Contact:	Harin S. Ullal, 303-384-6486, harin_ullal@nrel.gov
DOE HQ Technology Manager:	Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov
FY 2006 Budget:	$7,500K (NREL)

Objectives

- Support the Solar America Initiative Technology Partnership Pathway Funding Opportunity Announcement to achieve levelized electricity cost by 2015.
- Support the near-term transition to first-time manufacturing and commercial introduction of reliable thin-film amorphous silicon (a-Si), copper indium diselenide (CIS), cadmium telluride (CdTe), and film silicon modules.
- Build a technology base on which these advanced PV technologies can be successful in improving manufacturing and continue to progress in terms of performance, reliability, and reduced cost for products meant to compete in the PV marketplace.
- Sustain innovation to support progress toward ambitious long-term PV cost and performance goals (e.g., 15% modules at under $50/m^2$ and capable of lasting 30 years) appropriate for cost-competitive PV electricity.

Accomplishments

- Met two important OMB/DOE/EERE/SETP Joule milestones.
- Two Technology Partners expanded manufacturing facilities in the United States (First Solar 85 MWp and Uni-Solar 60 MWp).
- Production of thin films in the United States grew from 12 MWp in 2003 to an estimated >70 MWp in 2006.

Future Directions

- Continue to address key issues supporting the transition to successful first-time manufacturing or major production expansion in each thin film.
- Significantly reduce CIS and CdTe layer thicknesses in cells and support transfer of this to future manufacturing technologies.
- Direct thin-film CdTe solar cell research toward higher open-circuit voltage.
- Investigate nanocrystalline bottom cells for thin-film silicon multijunction solar cells.

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1. Introduction

Thin-film PV technologies are regarded as having good potential to meet ambitious cost and performance goals consistent with the Solar America Initiative Technology Partnership Pathway to achieve long-term goals for levelized cost of energy by 2015. The Thin Film PV Partnership Program is designed to accelerate progress toward those goals. It includes subcontracted R&D in CIS, CdTe, amorphous silicon, and new thin films such as film silicon. The Partnership works closely with NREL's in-house research, facilitating collaborative activities through the Partnership's National Research Teams. Three National R&D Teams work in material-specific areas—a-Si/thin-film c-Si, CdTe, and CIGS)—and there are crosscutting teams in Thin Film Module Reliability and environmental health and safety (EH&S), the latter with Brookhaven National Laboratory. The National Teams are made up of leading researchers from academia, U.S. industry, and NREL and other national laboratories (e.g., Pacific Northwest National Laboratory) who work together to define and carry out shared activities and common goals.

2. Technical Approach

The Partnership had 22 subcontracts during FY 2006 (see Section 6). Eight subcontracts ended in 2005. The subcontract areas were broken down as shown in Table 1.

Table 1. Thin Film PV Partnership Funding

Task Title	FY 2006 Budget ($K)
Project Management and Team Coordination	971
Thin Film Center of Excellence	971
Amorphous and Thin Film Silicon	972
CIS Devices	1090
CdTe Devices	1090
Module Testing and Analysis	1040

Three groups were major Technology Partner subcontracts: Global Solar in CIS; First Solar in CdTe; and United Solar Ovonic (Uni-Solar) in a-Si. Shell Solar terminated their CIS research and technology development and have redirected their activities elsewhere. The rest were R&D Partners, which were either small businesses making progress toward pilot production or universities supporting the Partnership objectives.

3. Results and Accomplishments

The Thin Film PV Partnership supported the transition to successful first-time manufacturing of key thin-film technologies during the fiscal year. This is our most important activity in the short term, because it will help establish thin films in the marketplace, improve their chances of future growth and success, and help define the transition of technologies that have been successfully developed by DOE funding to the private sector. This evolution has been more than two decades in the making and is not yet accomplished. However, with the substantial growth in CY 2006 to more than 70 MW (from only 12 MW in the United States in 2003), thin films are in this important transition. Based on surveys of the Partnership's Technology Partners, it is expected that this may again double in CY 2007 to about 140 MW of annual U.S. production. If so, this will indicate the arrival of these key, potentially lower-cost technology options—and even the resumption of U.S. leadership in the PV marketplace (because thin films may take a leading role, going forward).

Table 2 summarizes the worldwide production capacity of thin-film PV modules. It is estimated that by the year 2010, worldwide thin-film PV production capacity will be over 1700 MW, with U.S. production capacity estimated at ~1 GW, for about 56% of the world market share.

Table 2. Estimated Worldwide Production Capacity of Thin Film PV Modules by 2010

	Group	Material	Present (MW)	Additional (MW)	Total (MW)	Totals	Grand Total
USA	First Solar	CdTe	85	–	85	967	1727
	Uni-Solar	a-Si	60	240	300		
	MiaSole	CIS	5	50	55		
	Global Solar	CIS	3	60	63		
	EPV	a-Si	2	8	10		
	Daystar Technologies	CIS	1	10	11		
	Power Film	a-Si	1	10	11		
	Ascent Solar	CIS	–	2	2		
	Nanosolar	CIS	–	430	430		
JAPAN	Kaneka	a-Si	20	35	55	182	
	Showa Shell	CIS	–	20	20		
	Sharp	a-Si	15	–	15		
	Fuji	a-Si	–	15	15		
	MH1	a-Si	10	30	40		
	Kanto Sanyo	a-Si	7	–	7		
	Honda	CIS	3	27	30		
EUROPE	First Solar	CdTe	–	100	100	453	
	CSG Solar	Thin-Si	10	10	20		
	Wurth Solar	CIS	3	15	18		
	Antec Solar	CdTe	10	–	10		
	Schott Solar	a-Si	3	27	30		
	ICP Solar Tech	a-Si	3	–	3		
	Solar Cells	a-Si	1	–	1		
	Free Energy	a-Si	1	–	1		
	Solar Plus	a-Si	–	5	5		
	Sulfur Cells	CIS	5	–	5		
	Aleo Solar	CIS	–	30	30		
	Ersol	a-Si	–	40	40		
	AMI	a-Si	–	160	160		
	Johanna Solar Tech	CIS	–	30	30		
ASIA	First Solar	CdTe	–	100	100	125	
	Bangkok Solar	a-Si	5	–	5		
	Sinonar	a-Si	3	–	3		
	T. J. Solar Cell	a-Si	2	–	2		
	Soltech	a-Si	15	–	15		

The following summarizes highlights from FY 2006.

3.1 First Solar 85-MWp Factory Expansion
First Solar completed an aggressive expansion in 2006 with an installed manufacturing capacity of 85 MW and expected sales of about 50 MW in 2006. Also, worldwide production capacity of First Solar is expected to be 185 MW with projected sales of over 100 MW in 2007, making it one of the top ten PV companies in the world, and the number one thin-film PV company in the world.

Fig. 1. First Solar's 1400-kW thin-film CdTe solar field deployed in Germany.

Substantial progress has been made in terms of: (1) the new 85-MWp coater, which is now fabricating the majority of products; (2) reducing maintenance costs by substantially enhancing materials utilization rates; and (3) automating and improving most aspects of production. First Solar plans to move to a cost structure that would allow the installation of $3/Wp ground-mounted PV systems in the not-too-distant future. First Solar also has expansion plans in Asia. An announcement is expected sometime in CY 2007. First Solar's initial public offering (IPO) raised more than $400 million in 2006, the largest amount ever for a thin-film PV company.

The DOE Solar Program and NREL, the National Center for Photovoltaics (NCPV), and the Thin Film PV Partnership have supported the research and development of this very promising thin PV technology at First Solar for the past several years. First Solar uses a very rapid vapor transport deposition technique to deposit the semiconductor films in less than one minute, which gives it a significant advantage over its competitors. The deposition process won a prestigious R&D 100 Award in 2003, which was shared by NREL. "These accomplishments strengthen the position of U.S. manufacturers as leaders in the next generation of thin-film solar technologies and accelerate our nation's drive to make solar electricity competitive with conventional electricity," said David Garman, Under Secretary, U.S. Department of Energy.

3.2 Uni-Solar 60-MWp Factory Expansion
The Uni-Solar a-Si factory is working at full capacity of about 2 MWp/month. Due to the silicon shortage, module prices have been rising, and profitability is increasing. Recently, Uni-Solar built a second 30-MWp plant in Michigan, bringing its total manufacturing capacity to 60 MW. In describing the competitiveness of Uni-Solar technology, company President Subhendu Guha made the case that their peel-and-stick roofing material is directly competitive with all other rooftop PV approaches (including c-Si and CdTe) because of the ease of installation (e.g., reduced balance of system costs) and superior aesthetics and durability (see Fig. 3). He mentioned two major "wins" over such competition for large commercial rooftop projects, one for 1 MW on the GM building and another for 750 kW in California.

Fig. 2. The Uni-Solar a-Si factory produces peel-and-stick thin-film PV roofing material.

Of interest, First Solar and Uni-Solar have different, but complementary, focus markets: Uni-Solar on commercial roofs and First Solar for large, ground-mounted systems. In both markets, they are quite competitive compared to crystalline silicon technology.

3.3 Global Solar to Expand Capacity to 60 MW by 2008
Global Solar has announced expansion plans of 60 MW of thin-film CIGS modules in 2008. All the necessary equipment for the manufacture of the thin-film CIGS modules have been ordered and are expected to be delivered by late 2007. Some of the new encapsulation/packaging of the CIGS modules have shown exceptional stability, especially in the damp-heat tests. Tests are also

being conducted at the Tucson Electric Power in Springerville, AZ.

Global Solar Energy (GSE) fabricated a 10.2%-efficient, 88.9-W thin-film CIGS power module, the highest-wattage CIGS module in the world. ITN Energy Systems (ITN/ES), Littleton, CO, developed the intelligent processing system for improved processing conditions and yields for cell and module fabrication that helped produce this module. The module parameters are as follows: I_{sc} = 4.07 Amp, V_{oc} = 36 V, FF = 0.606, area = 8709 cm^2. Stainless steel (ss) web lengths of 1000 feet were used for the roll-to-roll processing of the devices. The typical cell structure is ITO/CdS/CIGS/Mo/ss. CIGS is deposited by physical vapor deposition, CdS by a modified chemical-bath deposition process, and ITO and Mo by sputtering. More process optimization should improve the module performance in the near future. NREL and GSE shared an R&D 100 Award in 2004 for development of the GSE CIGS technology.

3.4 National Research Teams

There are three active national research teams—one each in a-Si, CIGS, and CdTe. Each team holds an annual meeting. The team members consist of scientists, engineers, managers, professors, and students representing academia, the Air Force, the thin-film PV industry, and the national laboratories (NREL and Pacific Northwest National Laboratory [PNNL]). At these meetings, industry representatives report on the progress and future plans of their respective groups. For example, in 2006, Uni-Solar presented data on its 30-MW plant in Auburn, MI, with plans to expand to 60 MW in 2006 and 180 MW in 2008. First Solar presented its expansion plans to 85 MW in 2006 and another 100-MW plant in Germany in 2007, for a cumulative worldwide production capacity of 185 MW by 2007. Global Solar presented plans to expand its production capacity to 60 MW in Tucson, AZ, in 2008.

The commercial success of Uni-Solar is a driving force behind the a-Si Team's activities. An open question is whether Uni-Solar will switch its manufacturing operations from triple-junction amorphous silicon to a-Si:H/nc-Si:H multijunctions. Uni-Solar, which also conducts extensive in-house research on nc-Si Solar cells, currently believes that nc-Si remains an attractive option for future manufacturing if cell performance can be further improved. But company personnel consider the performance of a-Si/nc-Si multijunctions to be only equivalent, not superior, to a-Si:H/a-SiGe:H multijunctions. Providing fundamental researchers with such feedback from industry is very important. Many researchers in Japan and Europe assume *a priori* that the performance of nc-Si:H cells is superior to a-SiGe:H cells. There is also renewed interest in producing a-Si:H single or multijunctions (or a-Si:H/nc-Si:H) on glass superstrates, but current resources within the team are somewhat limited for effectively supporting such activities (e.g., at EPV or at Applied Materials).

The CIGS Team focuses on developing thin absorber layers of about 1.0 micron, or even thinner to about 0.5 micron, for future module fabrication. Thus far, NREL scientists have fabricated total-area efficiency of 17.1% for a thin-film CIGS solar cell using an absorber thickness of about 1.0 micron. Modeling should provide some answers, especially lower J_{sc} for the thin absorber cells. Additional presentations were made by Air Force Research Laboratory personnel on their thin-film PV activities, namely, a-Si and CIGS; and NREL, with 19.5% CIGS solar cells using CdZnS buffer layers, device physics of CIGS solar cells, and nanodomains of CIGS absorbers. IEC presented an overview of its thin absorber research that has been performed by researchers worldwide.

In the area of CdTe, the Device Physics Subteam described measurements and analysis that elucidated device physics specific to thin-film polycrystalline CdTe PV devices. The Stability Subteam identified several modes of changed device performance that have been observed to varying degrees in a wide variety of CdTe PV devices subjected to conditions of elevated temperature, electrical bias, illumination, or environmental stress—conditions that are intended to accelerate the type of degradation that could occur in the field. The Materials Chemistry Subteam addressed issues relating to the impact of Cu, O_2, Cl, and other impurities on CdTe PV device performance; another focus is on developing thin CdTe absorber layers of about 1.0 micron for fabrication of solar cells. Total-area, solar cell efficiency of 14% has been achieved for thin-film CdTe devices by researchers at the University of Toledo.

3.5 University Technical Highlights

The University Center of Excellence (Institute of Energy Conversion, IEC, University of Delaware) continues to provide both valuable insights and services to the fabrication of thin-film solar cells.

Recently, IEC implemented vapor-transport deposition of CdTe solar cells and has fabricated and analyzed 450 of the solar cells fabricated. A significant effort of this work has been to characterize the role of impurities (in the CdTe absorber and during "contacting") on cell performance.

Regarding $CuInGaSe_2$ (CIGS) solar cells, IEC, at the urging of NREL, has put significant effort into working on the reaction kinetics of selenization and sulfurization reactions. This now includes $CuInS_2$ solar cells and compares their characteristics to similar-bandgap $CuInGaSe_2$ cells. While historically IEC has also developed much know-how and understanding related to co-evaporated CIGS solar cells, it had been expressed by the community that there was not enough fundamental support for those companies practicing CIGS formation by selenization (sulfurization) of metallic precursors. One key aspect of the scheme of producing CIGS by this method is to shorten the selenization (sulfurization) reaction times. Understanding the reaction kinetics is critical toward accomplishing a processing time reduction.

In the area of Si film solar cells, IEC recently used its deposition capabilities to produce heterojunction "HIT" solar cells. A cell with a new heterojunction wrap-through emitter design was fabricated and delivered to NREL, where it was measured as 11.8% efficient. IEC had previously worked on Al-induced recrystallized Si film layers as the absorber layer for solar cells. While carried out with much talent at IEC, this work (not unlike similar work performed by other institutions outside the United States) has not yet resulted in cells with a competitive performance advantage over existing cells.

IEC maintains the capability to produce state-of-the art, or near state-of-the-art, solar cells in all thin-film PV technologies using a variety of deposition approaches, which continues to enable start-up companies to complete solar cells with the companies' own materials.

Solar cell making continued at the University of Toledo (a-Si [Deng and Collins] and CdTe [Compaan, Karpov, and Collins]); FSEC (CIGSS cells [Dhere]); and in-house at NREL and IEC. Device making by university groups requires a significant long-term investment for enabling such cell fabrication, but also confers four major benefits: (1) commercial spin-off opportunities are created (e.g., Midwest Optoelectronics from Toledo); (2) improved understanding of solar cell physics can be obtained, because the university cell makers will usually reveal more detail than industrial groups about their cell fabrication; (3) specialized cells for specialized measurements can be fabricated that resemble regular cells; (4) options for changes in processing can be explored before industry has to invest in expensive modifications of pilot or production equipment. Beneficiaries of this were the University of Nevada (Heske, chemical composition and energy-bandgap measurements of solar cells), Syracuse University (Schiff, time-of-flight measurements, project ended 9/30/06), the University of Oregon (Cohen, defect spectroscopes), and PNNL (Olsen, encapsulation research). Each of these groups at times required special cell structures to carry out their specialized experiments. Aside from NREL in-house work, the work at PNNL is the only effort dealing with cell/module packaging and encapsulation issues. This is an important area, as many current industrial start-ups make preparations for producing a flexible CIGS product on foil substrates. Low-cost, flexible transparent packaging schemes for CIS have to provide better protection than for a-Si (nc-Si) cells, as CIGS cells are apparently more moisture sensitive. The University of Utah (Taylor, now at Colorado School of Mines) provides valuable insights into light-induced degradation mechanisms (i.e., Staebler-Wronski effect) in a-Si:H alloys and nc-Si:H. At the University of South Florida, Tampa, FL, researchers are investigating the doping of the CdTe absoprber film with P. They are also studying the effect of a new TiO_2 buffer layer and a $TiSe_2$ back contact by sputtering. Colorado State University (CSU) is expanding its activities to make 1-sq. ft. prototype CdTe submodules using its in-line system based on the close-spaced sublimation process. CSU has already made 12%–13%-efficient thin-film CdTe solar cells. These cells are also being investigated for their stability under light and bias conditions. Device analysis on both CdTe and CIGS solar cells is performed at CSU and the feedback is given to the NREL university and industry groups. Colorado School of Mines has done studies of basic electronic properties of CdTe-based solar cells, such as deep electronic states using admittance spectroscopy techniques.

3.6 Completion of Two Critical OMB/DOE/EERE Joule Milestones

Two OMB/DOE/EERE/SETP Joule milestones were completed within the Partnership. One is related to achieving a higher efficiency thin-film module of 11.2% by the end of the fiscal year. This milestone was achieved by Shell Solar Industries (a Technology Partner) for selenized CIGS thin-film modules. The other Joule milestone concerned the testing the various thin-film modules made by U.S. industry for reliability. The modules are being tested at the Florida Solar Energy Center and Texas A&M University.

3.7 Flow of Venture Capital to Thin-Film Industry Accelerates in FY 2006

We note the acceleration of private and venture capital funding to thin-film start-ups, most of which were spun off or supported by NREL in-house and Thin Film Partnership research and National R&D Teams. We also note the budget pressures resulting from this evolution.

The success of PV in the marketplace has generated a wave of private funding interest for start-ups of all kinds in PV, and in particular for those involved with CIGS. Announcements of major investments have come from: Wurth Solar (55M euro), Miasole ($32M), Nanosolar ($75M), Ascent Solar ($16M – IPO), and Heliovolt ($8M). Wurth Solar is a German company that bases its technology on multisource evaporation, harkening back to the original CIGS work at Boeing and within NREL (all DOE supported). Wurth had about 1–2 MWp of CIGS production capacity and makes the most efficient thin-film products in the world (about 11% total area efficiency). They have now increased their manufacturing capacity to 15 MW per year, perhaps the largest CIGS production capacity in the world to date.

The other three are U.S. start-ups that are precommercial; in fact, they are pre-prototype module development. Their ideas are based on reducing the capital cost and raising the throughput of CIGS versus existing approaches. Together with NREL support, they are making decent, but not outstanding, cells (8%–12%). NREL support has been mostly from consultation or Cooperative Research and Development Agreements with in-house CIGS experts and the NREL Measurements and Characterization Group; and work with the NREL National Research CIS Team. We have started a new subcontract with one (Nanosolar) to do work in high-throughput selenization of flexible-based CIGS films, a known bottleneck in selenization approaches. Overall budget shortfalls in the Thin Film Partnership are preventing us from seeking out additional subcontracts with promising new start-ups, such as Miasole, Ascent Solar, Solo Power, Solyandra and Heliovolt, and another start-up, Daystar ($9M from a public offering in 2004). Thus we are seeking other forms of collaboration and support. To illustrate the relationships involved: Daystar's founder, John Tuttle, is an ex-NREL CIS scientist; Heliovolt's founder Billy Stanbery, was funded by the Partnership at Boeing and later at the University of Florida; Nanosolar's Vice President of Engineering Chris Eberspacher was funded by the Partnership at Unisun and ARCO Solar; and Miasole received direct NREL in-house support via Rommel Noufi and his CIGS team. Bulent Basol, cofounder of Solo Power, was supported while at ISET to develop low-cost, thin-film CIGS solar cells. Joe Armstrong, chief technical officer of Ascent Solar, was funded at Martin Marietta and ITN Energy Systems, while Prem Nath, currently senior vice president of manufacturing at Ascent Solar, was funded at Uni-Solar for product development and module reliability. Ken Zweibel, former manager of the Thin Film Partnership, is now chairman and president of yet another start-up, Primestar Solar, which is working on thin-film CdTe PV technology.

The advent of substantial private funding for CIGS and CdTe PV start-ups is a major change in the development path of thin films. Prior to this, venture money was almost nonexistent, which prevented this channel of development. The change is very favorable for thin-film PV in general, and CIGS in particular, and allows us to leverage the exceptional in-house NREL CIGS and CdTe expertise and characterization capabilities as a major method of supporting outside activities (complementing support via the Partnership subcontracts).

However, we also foresee the possibility of some new difficulties. Start-ups are notoriously hurried to develop technology, which leaves them vulnerable to pitfalls (e.g., in manufacturing and reliability). None of these start-ups have the resources to test their new products in any depth. Thus we foresee a period when we may need to support them with our own testing capabilities, if only to avoid potential black eyes from first-time manufacturing and field failures. We also foresee the potential for these companies to seek local political support, which may in turn lead to undesirable pressure to create new earmarks. This is unfortunate collateral damage from our own budget shortfalls.

3.8 Thin Film Partnership Management

The Partnership had several management accomplishments of note during the fiscal year, as discussed below.

Web Site. We continue to update the Partnership Web site to make it much more accessible. We are now:

- Including descriptive text with each entry.
- Making the whole site searchable by keywords and authors, which is a very powerful tool.
- Adding a “most recent” list of the last ten items posted for those who want to see what's new.
- Adding a “Features” link to the home page, for newsworthy items such as the recent capacity announcements.

With the new excitement in thin-film PV, we expect the site to be used more frequently. It now averages more than a thousand hits per day (www.nrel.gov/ncpv/thin_film).

PV Materials FAQ. We added a FAQ to the NREL site that examines the question, posed as “The Terawatt Challenge” by Hoffert and Lewis: Are materials a constraint preventing PV from meeting climate change problems? The answer is that PV can meet climate change problems, with the example examined being 75 TWp by mid-century. Of commodity materials, glass would be the largest growth, but is not materials limited. Of the specialty semiconductor and contact materials, silver (for grids), indium, and tellurium are constrained and selenium is marginally constrained. However, the FAQ outlines a strategy for making thinner cells, recycling waste and end-of-life modules, and refining more byproduct from existing ores to allow the CIS and CdTe technologies to make the needed amounts. The silicon-based technologies are unconstrained and could also meet the TW challenge. These findings are part of the effort to refine our understanding of future PV issues in relation to big picture issues such as climate change.

Energy Payback FAQ Revision. We completed a revision of the Energy Payback FAQ for the NREL Web site. The changes involved:

- Adding a well-documented payback period for the balance of systems at Tucson Electric) as an example of how ground-mounted systems have about the same energy payback as roof-mounted ones.
- Offering further evidence that including the wafer payback cost does not radically hurt c-Si payback.
- Adding some verbiage to help people understand how energy input is properly paid back in the form of PV electricity.

The FAQs are at (www.nrel.gov/ncpv/faq.html).

Tracking Annual Metrics. Each year, we track cell efficiencies, best prototype module efficiencies, and commercial module efficiencies for thin-film PV (see Tables 3 and 4). Updated versions are posted on our Web site and can be found via the search page. Table 5 summarizes the thin-film PV companies in the United States. There are 12 a-Si/thin Si companies, 6 CdTe companies, and 12 CIGS companies shown in the table. Another four U.S. CIGS PV companies are to be announced in 2007. Worldwide, the estimate for CIGS PV companies is about 33.

Table 3. Best Large-Area, Thin Film Modules
(standard conditions, aperture area)

Company	Device	Size (cm^2)	Efficiency	Power/Watts	Date
Mitsubishi Heavy*	Glass/a-Si	15625	6.4% (stabilized)	100	7/05
Global Solar Energy	CdS/CIGS/SS	8709	10.2%	88.9	5/05
Wurth Solar	CdS/CIGS/glass	6500	13%	84.6	6/04
United Solar	a-Si/a-SiGe/a-SiGe/SS	9276	7.6% (stabilized)	70.8	9/97
First Solar	Glass/CdS/CdTe	6624	10.2%	67	2/04
Shell Solar GMBH	CIS-alloy/CdS/glass	4938	13.1%	64.8	6/04
Sharp*	Glass/a-Si/nano-Si	4770	11% (stabilized)	52.5	7/05
Antec Solar*	Glass/CdS/CdTe	6633	7.3%	52.3	6/04
Kaneka	Glass/a-Si	8100	6.3% (stabilized)	51	7/04
Shell Solar Industries	CdS/CIS-alloy	3644	12.9%	46.8	5/05
Showa Shell*	$Zn(O,S,OH)_x$/CIGS/Glass	3459	13.4% (4 1-ft^2 modules laminated together)	46.45	8/02
EPV	Glass/a-Si/a-Si	7432	5.7% (stabilized)	42.3	10/02
United Solar	a-Si triple/SS	4519	7.9% (stabilized)	35.7	6/97

*Indicates reported by company, but not independently measured (to our knowledge)

Table 4. Commercial Thin Film Modules, Data Taken from Web sites
(total-area efficiencies)

Rated Module Efficiency (%)	Description	Rated Output (Wp)	Estimated Price ($/Wp)	Temperature coefficient*
11.0	**Würth Solar** WS31050/80 (CIS)	80	Above $3	-0.36 %/ºC
9.4	**First Solar** FS65 (CdTe)	67.5	Below $3	-0.25 %/ºC
6.9	**Antec-Solar** ATF50 (CdTe)	50	Below $3	-0.18%/ºC
6.3	**Kaneka** GEA/GSA (single-junction a-Si)	60	Below $3	-0.2%/ºC
6.4	**Mitsubishi** Heavy MA100 (single-junction a-Si, VHF deposition)	100	Below $3	-0.2 %/ºC
6.3	**Uni-Solar** US-64 (triple-junction amorphous silicon)	64	$3.10–$3.40	-0.21%/ºC
5.3	**RWE Schott** ASI-F32/12 (same bandgap a-Si tandem)	32.2	Varies	-0.2%/ºC

Compiled by Bolko von Roedern; 9/2006
*Temperature coefficients will vary slightly depending on local spectral content.
Disclaimer: Listing could be outdated or incomplete (missing manufacturers and/or some "best" product); prices are estimates for large quantities.

Table 5. Thin Film PV Companies – USA

a-Si	CdTe	CIS
Uni-Solar – MI	First Solar – OH	Global Solar – AZ
Applied Materials – CA	Primestar Solar – CO	Miasole – CA
Power Films – IA	AVA Tech – CO	Energy PV – NJ
Energy PV – NJ	Solar Fields – OH	Ascent Solar – CO
V Systems – CO	Canrom – NY	ISET – CA
XsunX – CO	Ascentool – CA	ITN/ES – CO
Gen3 Solar – CA		Daystar – NY
Innovalight – CA		Nanosolar – CA
Nano PV – NJ		Heliovolt – TX
Solexant – CA		Solo Power – CA
Proto Flex – CO		Solyndra – CA
New Solar Ventures – NM		RESI – NJ

4. Planned FY 2007 Activities

In FY 2007, the Thin Film PV Partnership will continue to address key issues supporting the successful first-time manufacturing or explosive manufacturing growth of each thin film. These will be especially critical in FY 2007, which is expected to be a key year in thin-film growth, with U.S. production rising from about 12 MW in CY 2003 to over 70 MW in CY 2006, and perhaps doubling again in CY 2007 to about 140 MW. Any setbacks in manufacturing yield or outdoor reliability could lead to multi-year setbacks or even technology abandonment in extreme cases.

5. Major FY 2006 Publications

We have published several subcontract reports and also have posted them on the Partnership Web site.

B. von Roedern, H.S. Ullal, and K. Zweibel, “Polycrystalline thin Film Photovotaic: From the Laboratory to Solar Fields," *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006).

B. von Roedern, “Thin Film PV Module Review," *Refocus Magazine*, July/August 2006, p 34.

H.S. Ullal; “Thin Film Solar Electric Technologies”, *Solar Power 2006*, San Jose, CA; October 2006.

6. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2006.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)	Cost Share ($K)
Colorado State University Jim Sites	Ft. Collins, CO sites@lamar.colostate.edu	Characterization & analysis of CIS and CdTe devices	170	0
Colorado State University W.S. Sampath	Ft. Collins, CO sampath@engr.colostate.edu	Development of a robust in-line manufacturing approach for CdTe, and stability assurance	309	0
Energy Photovoltaics Alan Delahoy	Lawrenceville, NJ a.delahoy@epv.net	Advanced CIGS photovoltaic technology	320	96
First Solar, LLC Peter Meyers	Perrysburg, OH pmeyers@firstsolar.com	Expanding the Limits of CdTe PV Performance	143	7.5
First Solar, LLC Roger Green	Perrysburg, OH rgreen@firstsolar.com	Research leading to high-throughput processing of thin-film CdTe PV technology	655	655
Florida Solar Energy Center Neelkanth Dhere	Cocoa, FL dhere@fsec.ucf.edu	CIGSS solar cells by selenization and sulfurization	166	10

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)	Cost Share ($K)
Florida Solar Energy Center Neelkanth Dhere	Cocoa, FL dhere@fsec.ucf.edu	Module reliability testing in hot and humid climate	111	0
Global Solar Energy	Tucson, AZ swiedman@globalsolar.com	Cost and reliability improvements for CIGS based on flexible substrates	440	440
International Solar Electric Technologies Vijay Kapur	Inglewood, CA vkkapur@isetinc.com	Lab to large-scale transition for non-vacuum thin-film CIGS solar cells	180	18
NanoSolar Chris Eberspacher	Palo Alto, CA chris@nanosolar.com	High-productivity annealing for thin-film CIS PV	91	4.5
Pacific Northwest National Laboratory Larry Olsen	Richland, WA Larry.Olsen@pnl.gov	Barrier coatings for thin-film cell protection	120	0
Shell Solar Industries Dale Tarrant	Camarillo, CA Dale.tarrant@shellsolar.com	Process R&D for CIS-based thin-film PV	555	555
Syracuse University Eric Schiff	Syracuse, NY easchiff@syr.edu	Transport, interfaces, and modeling in a-Si:H-based solar cells	0	0
Texas A&M University Mike Davis	College Station, TX mdavis@esl.tamu.edu	Outdoor monitoring and high-voltage bias testing of thin-film PV modules in hot and humid climate	45	0
U. of Delaware, Institute of Energy Conversion Robert Birkmire	Newark, DE rwb@strauss.udel.edu	Thin Film Center of Excellence	1190	0
United Solar Ovonic Subhendu Guha	Auburn Hills, MI sguha@uni-solar.com	High-efficiency amorphous and nanocrystalline-based solar cells and modules	510	510
University of Nevada Clemens Heske	Las Vegas, NV heske@unlv.nevada.edu	Characterization of the electronic and chemical structure at the thin film solar cell interfaces	100	0
University of Oregon Dave Cohen	Eugene, OR dcohen@oregon.uoregon.edu	Innovative characterization of amorphous and thin-film silicon for improved module performance	119	0
University of South Florida Chris Ferekides	Tampa, FL ferekide@eng.usf.edu	High-efficiency CdTe cells by CSS	120	8
University of Toledo Al Compaan	Toledo, OH ADC@physics.utoledo.edu	Fabrication & physics of CdTe devices by sputtering	303	91
University of Toledo Xunming Deng	Toledo, OH dengx@physics.utoledo.edu	Fabrication and characterization of advanced triple-junction amorphous-silicon-based solar cells	332	96
University of Utah Craig Taylor	Salt Lake City, UT craig@physics.utah.edu	Innovative characterization of amorphous and thin-film silicon for improved module performance	121	0

PV Module Reliability R&D

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)

Key Technical Contacts: Carol Riordan (NREL Primary Contact), 303-384-6780, carol_riordan@nrel.gov
Carl Osterwald (Exploratory Reliability & Performance R&D), 303-384-6764, carl_osterwald@nrel.gov
Tom McMahon (Module Packaging Research and Reliability), 303-384-6762, tom_mcmahon@nrel.gov
David King (SNL Primary Contact, Module Reliability Characterization), 505-844-8220, dlking@sandia.gov

DOE HQ Technology Manager: Jeffrey Mazer 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2006 Budgets: $2,869K (NREL), $0 (SNL)

Objectives

The key FY 2006 objectives of this Module Reliability R&D Project were to:

- Quickly isolate, scientifically understand, and help industry mitigate module failure and/or degradation mechanisms.
- Gather and analyze outdoor, long-term exposure data for candidate modules.
- Use selected indoor and outdoor accelerated exposure testing to discover and/or replicate observed outdoor failures and performance degradation.
- Develop new and improved module packaging designs that result in improved service lifetimes and reduced annual performance degradation.
- Assist industry with developing new consensus standards and codes for module performance and/or qualification testing.
- Characterize and provide models for PV module performance and reliability.

Accomplishments

- Upgraded and maintained accelerated module testing capabilities essential to industry partners and progressed toward becoming an accredited Certified Testing Body Testing Laboratory.
- Reported results of high-voltage stress testing (module leakage currents using the High Voltage StressTestbed) for potential high-voltage applications by industry.
- Reported on adhesive and cohesive strength of the layers within thin-film module structures of the principal technologies.
- Collaborated with numerous industry partners to develop new encapsulants, provide adhesion and water vapor transmission values, water ingress modeling, and infrared imaging for cracked cells and shunt problems; filed record of invention.

Future Directions

- The current version (pre-appropriations) of the FY 2007 Annual Operating Plan specifies continuing R&D to characterize indoor and outdoor performance and reliability of precommercial and commercial PV modules with the objective of identifying, analyzing, understanding and ameliorating module degradation and failure mechanisms for a range of technologies and operating conditions (temperature, humidity, irradiance) in the quest for long (e.g., 30-year) PV system lifetimes and low (e.g., 0.5%–1%/year) degradation rates that allow the PV industry to reach DOE cost goals for solar electricity.
- Assuming the launch of the Solar America Initiative, these module performance and reliability R&D agreements will play a major part in the test and evaluation of deliverables from the Technology Pathway Partnerships, including application and development of test and evaluation protocols for module performance and energy modeling.

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1. Introduction

One of the top research priorities identified by the PV industry year after year is module performance and reliability, as an essential ingredient for product credibility and consumer confidence. In addition, the relatively recent application of the Systems-Driven Approach used to identify Technical Improvement Opportunities (using the Solar Advisor Model) for program planning has shown that a total system lifetime of 30 years and electrical output that stays within acceptable levels (e.g., no more than 0.5 to 1% annual degradation rates) are critical in order to produce the expected total kWhr of electricity over the system's 30-year lifetime to meet the DOE cost goals. PV modules are the most important system component when cost, performance, and reliability are considered. The modules make up 55% to 65% of the total system price/costs and directly determine the overall system conversion efficiency. Thus, this project addressing module reliability, packaging, performance and characterization R&D—a joint effort of NREL and SNL—continues to be an essential element of the DOE Photovoltaics Subprogram.

2. Technical Approach

The technical approach in this project consists of short- and long-term outdoor module performance testing and characterization, selected outdoor stress testing (e.g., high-voltage environments), accelerated indoor environmental (e.g., temperature, humidity) stress testing, performance analyses/characterization/modeling, failure/ degradation analyses, and module packaging R&D (e.g., moisture ingress analysis and amelioration) to help mitigate failures/degradation and/or reduce module costs and improve performance. To conduct such testing, analyses, and module packaging investigations, NREL and SNL develop and apply advanced measurement techniques, diagnostic methods, and instrumentation. A key aspect of the overall approach is close interactions and collaborations with PV module manufacturers. The intent is to optimize the time and funding required when advancing module technologies from the prototype to the commercial production stage, with respect to meeting acceptable performance, reliability, and cost requirements.

In FY 2006, the work was accomplished under these agreements:

Agreement Title	FY 2006 Budget ($K)
Exploratory Reliability & Performance R&D (NREL)	1,456
Module Packaging Research & Reliability (NREL)	1,413
Module Reliability Characterization (SNL)	0*

*Initial FY 2006 spend plan and agreement planning were for a $500K budget at SNL; however budget reduction resulted in the SNL module reliability effort being minimized and consolidated with complementary activities in the System Test & Evaluation Project. Capabilities were maintained in anticipation of an expanded effort in FY 2007 in support of the Solar America Initiative.

3. Results and Accomplishments

Results and accomplishments for the major activities are as follows.

Exploratory Reliability and Performance R&D (Osterwald/NREL)

- Upgraded and maintained accelerated module testing capabilities (e.g., environmental chamber upgrades, new hail gun) essential to industry partners, and made progress toward becoming an accredited Certified Testing Body Testing Laboratory (quality system development) in a Cooperative Research and Development Agreement (CRADA) with Underwriters Laboratories (9/306).
- Reported analysis of outdoor module performance for module technologies under test in the Performance and Energy Ratings Testbed (PERT) showing effective efficiency and energy production compared to nameplate. (Oral presentation/paper 4th *World Conference on Photovoltaic Energy Conversion* 5/06); PERT system upgrades initiated.)
- Reported results of high-voltage stress testing (module leakage currents using the High Voltage Stress Testbed) for potential high-voltage applications by industry (Oral Presentation/paper at *4th World Conference on Photovoltaic Energy Conversion* (5/06); tests continue (9/06).
- Reported comparisons of module degradation /failure for 2.5x irradiance exposure versus 1x exposure using the Outdoor Accelerated Test System to assess accelerated exposure

capability (initial report 3/06); tests suspended due to resources for equipment repair (9/30).

- Continued support of the Thin-Film Partnership thin-film modules hot & humid outdoor exposure testing experiment (and other subcontracted module research) (comprehensive review and analysis of all data submitted by Florida Solar Energy Center completed, 9/30/06; Texas A&M has not been submitting data as required under their subcontract; ongoing).

Feedback from the DOE Solar Program Peer Review of this area of R&D included statements such as: "[This R&D is] critical to the achievement of DOE goals… [and] the development of sustainable PV markets… highly valuable to the U.S. PV industry… relevant to the DOE objectives by providing a combination of laboratory and field testing of PV modules," and "by solving reliability problems, module life cycle costs are reduced, and thus the DOE goal of lowering system cost is supported." The DOE-conducted peer review scored this R&D across the board as 4.0 on a 4.0-point scale.

Module Packaging Research & Reliability R&D (McMahon/NREL)

- Reported on adhesive and cohesive strength of the layers within thin-film module structures of the principal technologies; many thin-film structures measured. (Oral presentation/paper at *4th World Conference on Photovoltaic Energy Conversion* 5/06; published in *Solar Energy Materials and Solar Cells* (2006).
- With NREL Measurements and Characterization staff, researched and reported on properties of barrier coatings; reported on micro- and macro-conformality 9/06). Completed report on efficacy of plasma-enhanced chemical vapor deposition oxide/nitride/carbide thin-film moisture barriers deposited on mirrors, PET (polyethylene terephthalate), and thin-film cells (12/05); analysis led to future experimental design.
- Laminated and performed accelerated testing of CdTe-based cells and CIGS mini-modules using a variety of encapsulants/processing cycles to determine factors affecting device performance; reported R&D results to internal and external thin-film collaborators (e.g,. Thin-film Partnership National Team meetings) (9/06).
- Collaborated with numerous industry partners to develop new encapsulants, provide adhesion and water vapor transmission values, water ingress modeling, and infrared imaging for cracked cells and shunt problems; record of invention filed; specific industry collaboration being formalized in CRADA; Oral presentation/paper at the *DOE Solar Technologies Program Review*, 11/05.
- Co-chaired DOE's Accelerated Testing Workshop (2/06), giving one of the nine presentations; assisting with final report being prepared by DOE (9/06); very strong industry interest in continued R&D and future workshops.

In the DOE Solar Program Peer Review, the Module Packaging Research and Reliability R&D received an average score of 3.8 on a 4.0-point scale with comments such as, "The relevance of the research is thought to be excellent and critical to meeting DOE goals and objectives as well as reducing the cost of these systems. The approach is seen as excellent and uses a well thought out plan that is highly focused on an area of the technology that is key to the future success of the U.S. PV Program."

4. Planned FY 2007 Activities

FY 2007 planned activities are given in the draft (pre-appropriations) FY 2007 Annual Operating Plan, which is organized differently from previous years.

Module Reliability and Performance R&D will be performed under the Technology Evaluation Activity, PV System Testing and Evaluation Project, with Agreements on "Module and Array Testing" and "Module Failure Analysis" emphasizing accelerated stress testing, module performance testing and analysis, manufacturer support, performance and energy modeling, development of field protocols, array reliability, and application of testing and analytic capabilities to diagnose module failure mechanisms. This same agreement also includes related tasks on inverter, balance of systems, and systems testing and evaluation.

Module Packaging and Reliability R&D will be performed under the Applied Research Activity, Electronic Materials and Devices Project, in the "Cell and Module Stability and Reliability" agreement. Proposed work under this agreement includes providing measures of water vapor transmission, adhesion, and mechanical properties for new and existing packaging materials for a range of temperatures and humidity, before and after stress; modeling moisture ingress for various module structures; R&D on thin-film moisture barriers; assembly of failure diagnostic information on modules from different test sites and identification of dominant failure mechanisms; and R&D on intrinsic device stability for fabrication processes, such as reduced film thickness.

5. FY 2006 Special Recognitions, Awards, and Patents

Record of invention filed: *EPDM-Based Advanced Packaging Materials for Photovoltaic Modules.*

6. Major FY 2006 Publications

C.R. Osterwald, J. Adelstein, J.A. del Cueto, B. Kroposki, D. Trudell, and T. Moriarty, "Comparison of Degradation Rates of Individual Modules Held at Maximum Power," *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006), pp. 2085–2088.

J.A. Del Cueto and B.R. Sekulic, "An Unlikely Combination of Experiments with a Novel High-Voltage CIGS Photovoltaic Array," *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006), pp. 2054-2057.

C.R. Osterwald, J. Adelstein, J.A. del Cueto, W. Sekulic, D. Trudell, P. McNutt, R. Hansen, S. Rummel, A. Anderberg and T. Moriarty, "Resistive Loading of Photovoltaic Modules and Arrays for Long-Term Exposure Testing," *Prog. Photovolt: Res. Appl.* 2006, **14**:567–575.

G.J. Jorgensen, J. Del Cueto, S. Glick, M.D. Kempe, J. Pankow, F.J. Pern, K.M. Terwilliger, T.J. McMahon, "Moisture Transport, Adhesion, and Corrosion Protection of PV Module Packaging Materials," *Solar Energy Materials & Solar Cells*, **90** (2006), 2739–2775.

T. McMahon and G. Jorgensen, "Adhesion And Thin-Film Module Reliability," *Proceedings of 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006).

M.Kempe et al., "EVA Potential Problems for Photovoltaic Packaging," *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006).

M. Kempe, "Modeling of rates of moisture ingress into photovoltaic modules," *Sol. Energy Mat. and Sol. Cells,* **90** (2006) 2720.

F.J. Pern and G.J. Jorgensen, "Development of Damp-heat Resistant Self-primed EVA and Non-EVA Encapsulant Formulations at NREL," Solar Energy Technologies Program Review, Denver, CO, Nov. 2005.

7. University and Industry Partners

There were no subcontracts in this project in FY 2006. Both NREL and SNL researchers interact extensively with industry and university collaborators to test and characterize module performance and reliability, as well as examine failure and degradation mechanisms and perform R&D on module packaging (e.g., backsheet and encapsulant formulation/testing) and reliability. Collaborators and contacts include, but are not limited to companies, universities, and institutes such as: SunPower, GE, United Solar Ovonic, Shell, BP Solar, PowerLight, Miasolé, SolFocus, Texas A&M, FSEC, AKT, Planar Systems, Madico, Deerfield Urethane, DuPont, PPG, Dow Chemical and Dow Corning, BRP, Pilkington Glass, Saint Gobain, Applied Films, Fraunhofer Institute, InnoSense LLC, First Solar, SRS Building Energy, SBM Solar, and Advent Solar.

Inverter and BOS Development

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contact: Ward Bower, 505-844-5206, wibower@sandia.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2006 Budget: $380K

Objectives

Improve inverters and balance of systems (BOS) through the High-Reliability Inverter Initiative (HRII) for PV, to include:

- Mean time between failure (MTBF) of >10 years
- Inverter efficiency >94%
- Inverter cost less than $0.90/watt
- Meet Underwriters Laboratories (UL) 1741 certification requirements.
- Meet FCC Part 15, Class B for electromagnetic emanations requirements.
- Meet National Electrical Code (NEC®) requirements.
- Design for high-volume (>10,000/yr) production.
- Provide modularity and expandability to function with other distributed energy resources.
- Improve inverter and BOS designs that allow full-system integration while maintaining flexibility.
- Influence codes, standards, and certifications through development, validation, and verification.
- Establish the groundwork for high-tech R&D with 20-year MTBF inverter/system-integrated inverter and BOS goals.

Accomplishments

- Completed Phase II of the HRII with hardware beta deliverables by GE and Xantrex.
- Continued the HRII Phase III with GE and Xantrex.
- Assessed HRII beta inverter and controller prototypes for conformity to utility interconnection requirements, performance objectives, and manufacturing objectives.
- Conducted updated verification and validation of prototypes, through laboratory evaluations, environmental testing, and performance measurements.
- Completed development of an innovative high-reliability micro-inverter topology eliminating short-life components.

Future Directions

- Fold the results of the work completed for the “High-tech Inverter Initiative” into the Solar America Initiative (SAI) Funding Opportunity Announcement (FOA) for Technology Pathway Partnerships (TPPs).
- Conduct cooperative work with SAI TPP recipients as needed to help meet the goals of the SAI.
- Conduct high-tech studies for inverters, BOS, systems strategies, and energy management to help assess needs for future generations of inverters, BOS and complete systems.
- Conduct studies on inverter and BOS developments and formulate strategies to facilitate building-integrated and vertically integrated systems.

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1. Introduction

Inverters for PV systems are much more than just the power electronics to convert the DC power from PV arrays to load-compatible AC power. They are actually the power conversion devices surrounded by, and integrated into, total system controls. Given the number of functions the inverter must perform today, much improved reliability, higher performance, and lower costs are essential. Higher-quality inverters, even at constant costs, can reduce the levelized cost of energy (LCOE) of installed PV systems, as indicated in DOE prediction models (such as the PV Systems Analysis Model) being developed within the Solar Energy Technologies Program. The expected outcome is consistent with the SAI and is critical to achieving its $.06/kWh energy production goal for installed PV systems. Further, given that today's "value to the consumer" of installing a PV system is often dependent on rebates and incentives, and not just the value of the energy produced, an out-of-warranty failure of a multifunction inverter can often mean that the system will never work again (end of life). Inverters and their associated control circuits and functions are still, in many respects, in their infancy in terms of design, system integration, communications, performance, and especially reliability. The lifetimes of the inverter (controller of the system) must be improved to better match the lifetimes of PV modules (typically 30 years) and other BOS components.

Today's technical barriers associated with inverters involve matching the MTBF of PV modules, while maintaining low costs and high performance. These barriers are nearly unprecedented in terrestrial applications of power electronics because most electronic products are designed with relatively shorter MTBF. One longer-lived power electronics comparison is a variable-speed drive for industrial motors. The motor load has well-characterized impedances and characteristics. Higher-quality, industrial-grade components are used, and cost is not as important as it is for PV applications. Higher costs are acceptable because of the value added and the major loss of revenue when failures occur.

Many electronic devices sold today are designed with a MTBF of just a few years. That is not acceptable for the inverter (controller) used in PV applications. Another important difference with PV systems is that the inverter/system is classified in the *NEC* as an "energy source." That classification, along with the many unique characteristics of PV power systems, prompted a special section in the *NEC* for PV installations. Inverters with short lifetimes may be repaired or replaced, but both options represent costs that may negate most of the revenue received for power generation. Replacement of an inverter in a 15-year-old system will likely also require costs associated with redesign of the BOS and a reinspection to meet existing code. It will not be like changing a light bulb. The High-Reliability Inverter Initiative took a first step toward higher reliability at no increase in unit cost, namely the improvement of MTBF to more than 10 years. This advance had a significant positive impact on calculated LCOE of PV systems.

The objectives of the Inverter and Balance-of-Systems Project were to focus on power electronics and BOS hardware, to support engineering advancements through characterization feedback of newly developed power electronics and BOS hardware, and to begin establishing the suitability for incorporation of new inverters and BOS into completely integrated systems. The work was closely tied to objectives derived from the DOE Systems-Driven Approach Workshop, the DOE Workshop on a Systems-Driven Approach to Inverter Research and Development, and the DOE High-Tech Inverter Workshop, and will also tie to the Solar America Initiative Technology Pathway Partnership work. Each of the inverter-related workshops resulted in consensus prioritization that guided the High-Reliability Inverter Initiative and later the drafting of a High-Tech Inverter, Balance-of-System, and Systems R&D: A 5-Year Strategy that was folded into the SAI FOA for the TPPs. The workshop reports are still applicable to the future work for improving inverters and controllers.

Many project objectives have transformed into direct aids to the development of certification, codes, and standards for PV inverters, BOS, and systems applications through SNL validations, verification, and modeling. One important related standard change was related to the test procedures needed to list a transformerless inverter.

Some of the inverter- and BOS-related activities in this project are also applicable to other renewable energy technologies such as fuel cells. One Inverter and BOS Project goal was to strive to involve U.S. PV inverter manufacturers and key charge-controller manufacturers to examine key products to determine impacts on both BOS and PV applications. The Inverter and BOS Project strived to improve system reliability and efficiency, and improve LCOE through improved utilization of power electronics and storage and the development of selected BOS (sometimes non-power electronics) components. The BOS Project further sought to develop fully integrated, consumer-friendly PV systems through the development of vertically integrated designs that are suitable for high-volume manufacturing.

2. Technical Approach

The technical approach for this work followed a process by which technology development efforts were driven by well-defined and well-documented requirements based on analyses of present and potential markets, technology trade-off studies, and R&D reviews. All technical targets for R&D for the components and systems that are funded through the Solar Energy Technologies Program are derived from a common market perspective and national energy goals, and the resultant technologies are tested and validated in the context of established criteria for each market. Coordination with industry and potential users of the technology is a key to ensuring that products meet the market needs.

Task Title	FY 2006 Budget ($K)
High-Reliability Inverter Initiative	380
Inverter Development and Manufacturing R&D	0

3. Results and Accomplishments

General Electric conducted in-house testing and Xantrex delivered Phase III prototypes of high-reliability inverters to SNL's Distributed Energy Technologies Laboratory (DETL). Xantrex delivered the advanced alpha prototype to SNL in FY 2006 for additional evaluations. Benchmark evaluations and validations were completed at the DETL, and SNL engineers recommended further improvements.

GE completed beta prototype testing, but abandoned the design in favor of a new lower-cost redesign to be funded entirely by GE. GE's plans to vertically integrate its PV module manufacturing capabilities and the new inverter development into its existing new-construction housing market has been delayed pending development of a lower-cost inverter based on many of the lessons learned in this project.

Xantrex expects to use the fundamental high-reliability design as a basis for its next-generation family of products and has extensive and critically timed commercialization plans for the products developed out of this program. Xantrex used the HRII inverter and charge controller in its XW battery-based integrated system and continues to improve its beta prototype prior to full production. Figure 1 shows the Xantrex XW Battery-based Integrated System. Both General Electric and Xantrex are currently finalizing work for Phase III of the High-Reliability Inverter Initiative.

Fig. 1. The Xantrex XW Battery-based Integrated Power System

Advancements shown in Fig. 2 for the micro-inverter development provided proof of concept for an innovative circuit using no electrolytic capacitors. The calculated MTBF was over 250,000 hours, the performance was better than expected, and the distribution of heat was as calculated. The cost of the inverter was estimated at less than $.30/W in 10,000 quantities. One important characteristic of the innovative topology is the elimination of AC ripple on the PV array through high-speed, feed-forward control. The ripple was measured at about 60% rated operating level and was 0.3% of average DC current. The low ripple will improve maximum-power-point tracking effectiveness. The innovative topology appears to be applicable to higher-power inverters and could significantly impact future designs.

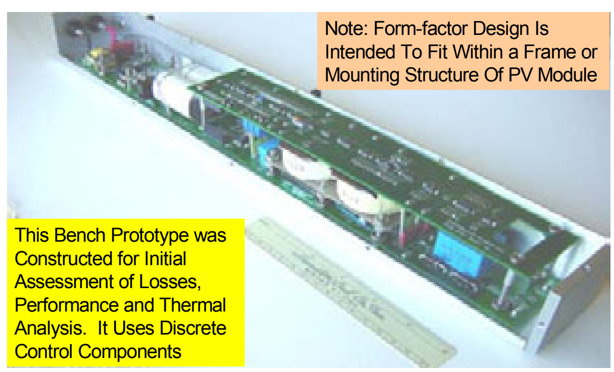

Fig. 2. Micro-inverter thermal analysis prototype

Summary of FY 2006 Results

Milestone or Deliverable	Due Date	Results
Complete Phase II prototype evaluations to establish and verify inverter performance.	2/1/06	Completed on time.
Complete high-reliability commercialized inverter designs and verifications of performance and design.	9/30/06	Work continuing after SNL evaluations.
Initiate contracts for "High-tech Inverter, BOS & Systems R&D Strategies."	9/30/06	Folded into SDA TPPs.
Send RFP for high-tech R&D.	9/30/06	Folded into SAI TPPs.
Review and select winning proposals to initiate high-tech R&D strategies.	9/30/06	Folded into SAI TPPs.
Conduct High-tech Inverter to Systems Link Workshop	9/28/06	Cancelled
Complete Final Reports on High-reliability prototypes, evaluations & verifications	9/30/06	Delayed to include final beta data.
Deliver commercial quality high-reliability (>10 year) inverters to SNL.	9/30/06	Delays due to funding until 6/07.

4. Planned FY 2007 Activities

The planned "High-Tech Inverter, Balance-of-System, and Systems R&D" was folded in the SAI TPP program for FY 2007 and beyond. Proposals and cooperative agreements are expected to include R&D to develop improved inverters and BOS with at least a 20-year MTBF, and then fully integrate those components into optimized system designs. The resulting cooperative agreements are expected to optimize the performance of PV systems through factory-assembled and vertically designed and integrated systems.

SNL's micro-inverter development was completed with demonstration of a prototype that showed feasibility with the inverter mechanical form factor, cost projections, and thermal issues related to mounting the inverter within the frame of a PV module.

5. Major FY 2006 Publications

Bower, W., West, R., Dickerson, A., "Innovative PV Micro-inverter Topology Eliminates Electrolytic Capacitors for Longer Lifetime," Proceedings of the 4th World Conference on Photovoltaic Energy Conversion (WCPEC), Waikoloa, HI, May 2006.

Whitaker, C., Newmiller, J., Bower, W., "Inverter Performance Certification: Results from the Sandia Test Protocol," *4th WCPEC*, Waikoloa, HI, May 2006.

Hudson, R., Edmunds, M., "Development of a High Reliability Inverter," *Proceedings of the DOE 2005 Solar Program Review,* Denver, CO, Nov 2005.

Smolenski, J., "GE High Reliability Photovoltaic Inverter Program," Proceedings of the DOE 2005 Solar Program Review, Denver, CO, Nov 2005.

Bower, W., "Overview of Sandia's High-reliability Inverter Initiative," Proceedings of the *DOE 2005 Solar Program Review*, Denver, CO, Nov 2005.

Bower, W., West, R., Dickerson, A., "Development of an Innovative Micro-inverter Topology," *Proceedings of the DOE 2005 Solar Program Review,* Denver, CO, Nov 2005.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2006 (no cost share).

Organization/Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
General Electric Joseph Smolenski	Niskayuna, NY smolenski@crd.ge.com	Conduct Phase III of the HRII.	210
Xantrex Technologies Ray Hudson	Livermore, CA Ray.Hudson@xantrex.com	Conduct Phase III of the HRII.	100
Xantrex Technologies Rick West	Livermore, CA Rick.West@xantrex.com	Develop/show feasibility of a novel micro-inverter.	12

PV Manufacturing R&D

Performing Organizations: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Richard Mitchell, 303-384-6479, richard_mitchell@nrel.gov

DOE HQ Technology Manager: Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov

FY 2006 Budget: $4,944K (NREL)

Objectives

- Improving PV manufacturing processes and products for terrestrial applications
- Accelerating PV manufacturing cost reductions
- Increasing commercial product performance and reliability
- Laying the foundation for significantly increased production capacity
- Achieving these goals in an environmentally safe manner.

Accomplishments

- As part of the annual DOE Solar Program Review, conducted an evaluation of manufacturing progress in crystalline silicon technologies by U.S. industry participants in the PV Manufacturing R&D project. (1st Q JOULE milestone)
- Completed reviews and required redirections for remaining “In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up” subcontracts.
- Completed reviews, required redirections, and renewals for “Large-Scale Module and Component Yield, Durability, and Reliability (YDR)” subcontracts.
- Analyzed 2005 U.S. PV Industry Cost/Capacity data on progress to produce capacity-weighted, industry average results and reported on progress at the 2006 4th IEEE World Conference on Photovoltaic Electric Conversion.
- Verified, using standard laboratory measurements, a conversion efficiency of 14.0% for a U.S.-made commercial crystalline silicon PV module. (4th Quarter JOULE milestone)
- Completed the development (achieve manufacturing-line-ready status) of at least three in-line diagnostic processes initiated in FY 2002 awards from "In-Line Diagnostic, Intelligent Processing (IDIP) Solicitation" with at least five of the U.S. PV industry partnerships involved in the IDIP solicitation having reported a minimum of 22 in-line diagnostic processes that have been implemented on U.S. PV production lines.
- As part of the annual DOE Solar Program Review, conducted a stage-gate evaluation of U.S. industry participants in the PV Manufacturing R&D Project to assess and determine the needs for additional manufacturing R&D and select areas for elimination or support.
- *Spire* – Completed design and detailed drawings of a new large-area solar simulator capable of handling utility-scale modules up to 1.37 m x 2.00 m.
- *RWE Schott Solar* – Designed, demonstrated and certified a new lower-cost rafter-jack module mounting system for the residential retrofit PV market.
- *Specialized Technology Resources* – Completed environmental testing of prototype modules for the development of improved thin-film encapsulants.
- *BP Solar* – Completed process equipment specifications for sawing, demounting, and handling 100-micron wafers cut on 29- micron centers.
- *Energy Conversion Devices* – Completed testing of on-line PV capacitive diagnostic system to stabilize and optimize a-Si deposition.
- *Energy Conversion Devices* – Transferred the Online Diagnostic Hardware and Display/Analysis Programs to the United Solar Ovonic Manufacturing Team to be used as a production tool with standard operating procedures.
- *Shell Solar* – Demonstrated prototype 10%-thinner cutting wire with no yield change at wafering.
- *Dow Corning* – Demonstrated integrated-cell package technology, including the cell, adhesive, and encapsulant components developed in this subcontract.

- *SunPower* – Completed reliability testing and evaluation of improved modules and test coupons.
- *Xantrex Technology* – Completed low-power electronics and control design, which meets the 25%-reduction cost goal for related inverter subassemblies.
- *BP Solar* – Completed statistical analysis of the causes of wafer/cell breakage on production line.
- *Schott Solar* – Completed fabrication of prototype for building-integrated PV laminate for commercial applications.
- *Shingleton Design* – Demonstrated improvements to control and drive systems for one-axis trackers with goal of reducing installation and commissioning costs by 40% over the course of the subcontract
- *BP Solar* – Established thermal model and began to analyze the dynamics of the production line casting process.
- *First Solar* – Completed development of improved back-electrode design and implementation of improved wet spray activation process.
- *PowerLight* – Completed initial production run with improved PowerGuard tile design as developed under Phase I.
- *Evergreen Solar* – Demonstrated 15%-efficient cells in production.

Future Directions

- Complete stage-gate review of individual progress versus milestones and required redirection for YDR subcontracts.
- Conduct end-of-year measurements to meet the FY 2007 EERE Efficiency Joule Milestone for U.S.-made, commercial crystalline silicon PV modules of 14.5% conversion efficiency.
- Achieve the Solar Program's JOULE Milestone on module efficiency and manufacturing cost
- Analyze U.S. PV Industry Cost/Capacity data on progress to produce capacity-weighted, industry average results
- Complete a DOE Solar Program Internal Review of the SolarWorld, BP Solar, SCHOTT Solar, Dow Corning, GE Energy, SunPower, Evergreen Solar, and First Solar subcontracts under the "Large-Scale Module and Component Yield, Durability, and Reliability" solicitation.
- Evaluate the scope of subcontracted research under "Large-Scale Module and Component Yield, Durability, and Reliability" solicitation with identification of Technology Pathway Partnership awards
- Complete reviews and required redirection for remaining subcontracts under the "Large-Scale Module and Component Yield, Durability, and Reliability" solicitation.

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1. Introduction

The PV Manufacturing R&D (PVMR&D) Project assists the U.S. PV industry through a cost-shared manufacturing R&D partnership with the U.S. DOE and members of the U.S. PV industry. Subcontracted research focuses on U.S. industry improvement of processes and products, resulting in: (1) a substantial reduction of associated manufacturing costs; (2) providing a technology foundation that supports significant manufacturing scale-up (500 MW total U.S. capacity); and (3) positioning the industry to meet rapidly emerging large-scale deployment opportunities. This focus directly supports the DOE Solar Program under "Advanced Materials and Devices." Each subcontractor enhances existing manufacturing technologies through cost-shared development efforts geared toward achieving the overriding PVMR&D goals. Work areas include: improvement of module manufacturing processes to increase module reliability; system and system-component packaging, system integration, manufacturing, and assembly; product manufacturing flexibility; and balance-of-systems (BOS) development, including storage and quality control.

2. Technical Approach

The PVMR&D Project is a government/industry partnership through cost-shared, subcontracted research on PV manufacturing technologies. The approach for the FY 2006 work effort was divided into three areas: (1) Project Management and Support; (2) research subcontracts under the FY 2001 competitive solicitation for "In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up" (IDIP); and (3) research subcontracts under the FY 2003 competitive solicitation for "Large-Scale Module and Component Yield, Durability, and Reliability (YDR)."

2.1 PV Manufacturing R&D Management

The Project Management and Support subtask addresses: (1) management of the PVMR&D project; (2) management of subcontracts awarded under the IDIP and YDR procurements; (3) coordination of NREL in-house activities in support of the PVMR&D industrial partners; and (4) evaluation of current trends in the PV manufacturing industry through collection of data for cost/capacity and recapture of R&D funding.

Table 1. PVMR&D Project Tasks and Budget

Task Title	FY 2006 Budget ($K)
PV Manufacturing R&D Technical Coordination	1,670
In-Line Diagnostics and Intelligent Processing	382
Module Yield, Durability, and Reliability	2,892

2.2 In-Line Diagnostics and Intelligent Processing

The IDIP subtask consists of the FY 2006 cost-shared PV manufacturing R&D subcontracts listed in Tables 2 and 3, awarded under the FY 2001 IDIP competitive solicitation. This solicitation was directed at: improvement of module manufacturing processes; system and system component packaging, system integration, manufacturing and assembly; product manufacturing flexibility; and balance-of-system development. These subcontracts emphasize new and improved in-line diagnostics and monitoring with real-time feedback for optimal process control and increased yield in the fabrication of PV modules, systems, and other system components.

Table 2. FY 2006 IDIP Subcontractors Module Manufacturing

Subcontractor	Title of Subcontract
BP Solar	Large-Scale PV Manufacturing Using Ultra-Thin Polycrystalline Silicon Solar Cells
Energy Conversion Devices, Inc.	Implementation of a Comprehensive On-Line Closed-Loop Diagnostic System for Roll-to-Roll Amorphous Silicon Solar Cell Production
Spire Corporation	Development of Automated Production Line Processes for Solar Brightfield Modules

Table 3. FY 2006 IDIP Subcontractors, System Components

Subcontractor	Title of Subcontract
RWE Schott Solar, Inc.	Plug and Play Components for Building-Integrated PV Systems
Specialized Technology Resources, Inc.	Development of New Low-Cost, High-Performance, PV Module Encapsulant/Packaging Materials

2.3 Yield, Durability, and Reliability

The FY 2006 YDR subtask comprises the cost-shared PVMR&D subcontracts in Table 4 resulting from a FY 2003 competitive solicitation. The focus is improving module manufacturing processes to increase module reliability, system and system-component packaging, system integration, manufacturing and assembly; product manufacturing flexibility; and BOS development, including storage and quality control. It emphasizes enhancing reliability of the module, system components, and complete system.

Table 4. FY 2005 YDR Subcontractors

Subcontractor	Title of Subcontract
Dow Corning Corporation	High Performance Packaging Solutions for Low Cost, Reliable PV Modules
Evergreen Solar	Low-Cost Manufacturing of High-Efficiency, High-Reliability String Ribbon Si PV Modules
GE Energy	Solar Cell Design for Manufacturability
PowerLight Corporation	Accelerating PV Cost Effectiveness Through Systems Design, Engineering, and Quality Assurance
SolarWorld	Manufacturing Improvements in CZ Silicon Module Production
SunPower	Automated Manufacturing of High Efficiency Modules
Xantrex	Advanced, High Reliability, System Integrated 500-kW Photovoltaic Inverter Development
First Solar	Implementation of Reliable Manufacturing of Higher Efficiency Module
Shingleton	One-Axis Trackers – Improved Reliability, Durability, Performance, and Cost Reduction
BP Solar	Development of Large High-Voltage PV Modules with Improved Reliability and Lower Cost
SCHOTT Solar	Subcontracts under “PV Module And Component Yield, Durability, And Reliability” solicitation

3. Results and Accomplishments

3.1 PV Manufacturing R&D Management

To measure progress toward contributing to the Solar Program, the PVMR&D Project completed its FY 2006 milestone to "Analyze U.S. PV Industry Cost/Capacity/Recapture data and produce capacity-weighted, industry average results." This milestone provides input to DOE and NREL decision makers on the growth of the U.S. PV Industry. Both historical and projected values for manufacturing cost and capacity were compiled in collaboration with PV industry partners. An evaluation of the FY 2005 data, completed in May of 2006, indicates progress toward achieving the Solar Program's cost goals, as well as demonstrating cost savings directly related to project participation.

Figure 1 shows the progress in combined crystalline-Si/thin films/concentrator module manufacturing production cost versus capacity from 1992 to 2005, as well as the projections to 2010. From 1992 to 2005, the average module manufacturing cost decreased 54% to $2.73/Wp (in 2005 dollars), an average 5.7%/year decrease, while the production capacity increased 18.5-fold to 251 MW, an average 25%/year increase. These numbers represent a slight slowdown in cost decrease and capacity increase reported previously for the 1992–2003 data set. This change is attributable to a recent temporary shortage in silicon feedstock as discussed further below.

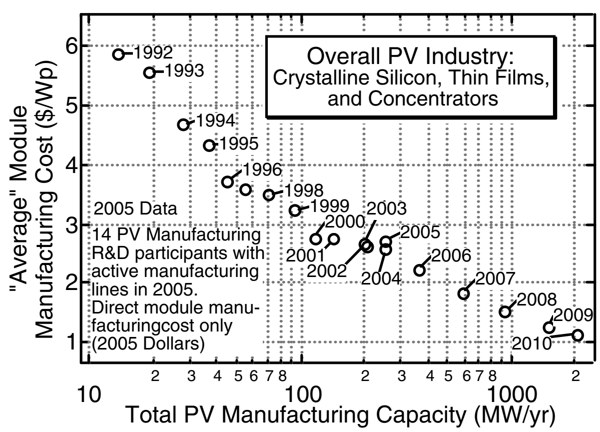

Fig. 1. U.S. PV module manufacturing cost versus capacity

Figure 2 shows the production levels and manufacturing plant utilization (production/capacity) over the same time period, for both thin-film and silicon modules. Also shown is the fraction of production silicon versus thin films. The manufacturing plant utilization for Si modules has to date been quite stable from year to year, while thin-film manufacturing plant utilization has fluctuated much more. There was a pause in the growth of Si production in 2003–2005, attributable to a silicon feedstock shortage. This growth pause is projected to continue into 2006, but a return to normal growth is anticipated in 2007.

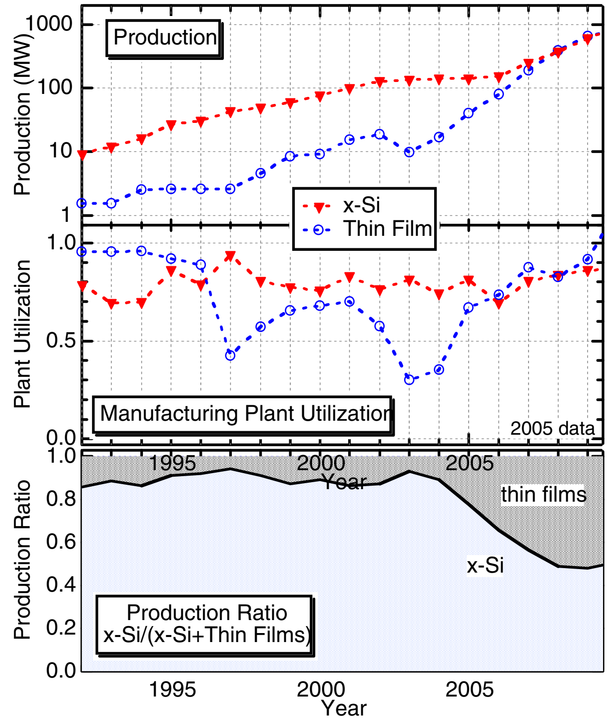

Fig. 2. Manufacturing production levels, plant utilization (production/capacity), and production ratio for crystalline silicon and thin-film PV.

The relationship between production level and cost is shown in Fig. 3 in the form of "experience curves." In this analysis, the dependence of cost on *cumulative production* (i.e. "experience") is considered. It is often observed empirically that cost decreases according to an inverse exponent of the cumulative production. The value of the exponent determines the "progress ratio," the fraction by which the cost falls for each doubling in cumulative production. Figure 3 shows that during the 1992–2003 period, silicon module production cost followed a fairly stable learning curve with an 87% progress ratio. In 2004–2005 the cost actually rose, attributable to the silicon feedstock shortage as previously noted. This rise in cost is projected to be only a temporary anomaly, and the overall trend of costs falling with a roughly 87% progress ratio is forecast to continue through

2010. For thin-film production, the data are less well described by a learning curve due to an anomalous rise in costs in 2001–2003 related to redesigns of the modules during that time period. The fit to a learning curve is shown in Fig. 3 as the dashed line, with a progress ratio of 81% from 1992 to 2010.

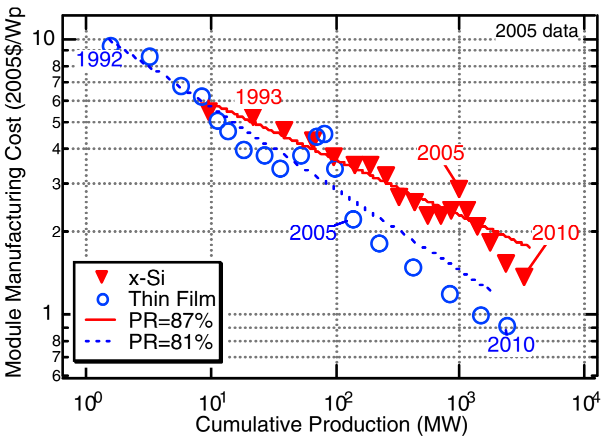

Fig. 3. Experience curve plot of module cost vs. cumulative production for x-Si and thin-film modules. The solid line represents a progress ratio=87% fit to the 1992–2003 x-Si data.

3.2 In-Line Diagnostics and Intelligent Processing

Under this subtask, the PVMR&D milestone to "complete reviews and required redirection for remaining subcontracts" focused on guiding the IDIP project to a successful conclusion. This milestone was completed in December 2005.

Other significant achievements under this subtask were accomplished by individual subcontractors, and are described in the following.

Specialized Technology Resources, Inc.

"Development of New Low-Cost, High-Performance PV Module Encapsulant/ Packaging Material"

- Cost reduction opportunities for the manufacturing of the faster-curing encapsulant were identified and initiated. A tension management system/winder, part of the cost reduction solution, has been fabricated and cleared for production utilization.
- A new flame-retardant (FR) technology has been developed with PN Solutions to maintain the electrical insulation properties of the encapsulant. A promising FR formulation was manufactured, with samples submitted for module qualification and flammability testing.

Energy Conversion Devices, Inc.

"Implementation of a Comprehensive On-Line Closed-Loop Diagnostic System for Roll-to-Roll Amorphous Silicon Solar Cell Production"

- Designed an improved second-generation component cell PV capacitive diagnostic tool in which: all but one of a dozen electrical vacuum feedthroughs have been eliminated; all water temperature stabilization systems have been removed from the vacuum; the system can be quickly and easily removed; the electronics have been professionally packaged and software and data acquisition hardware updated to the latest versions.
- Designed an improved second-generation component cell spectrometer.
- Designed an improved reflection spectrometer system including: increased signal-to-noise from optics changes; incorporation of an infrared spectrometer to provide absolute thickness measurements; and implementing a 2-D spectrometer array to measure, online, the complete longitudinal and transverse deposition profile of each cathode.

Schott Solar, Inc.

"Plug and Play Components for Building-Integrated PV Systems"

- Developed a dark I-V test station prototype to test the ASE-300 module performance and ultimately become an in-process inspection tool.
- Developed a new design for free-standing mounting system bracket, allowing module to be completely free to rotate to shallower angles in response to wind forces and preventing it from over-rotation; this design has been evaluated/validated rigorously, including wind tunnel testing on scale-model array design.

Spire Corporation

"Development of Automated Production Line Processes for Solar Brightfield Modules"

- Design engineering was completed and fabrication is under way on a 2-m x 4-m solar simulator for module performance testing. This single long-pulse system has recently achieved commercial success, as Spire has sold several long-pulse simulators to PV module manufacturers and a test laboratory.
- Initiated development of high-throughput low-stress processes for automated cell string assembly from cells as thin as 150 to 200 µm.
- Developed a strategy for implementing a computer integrated manufacturing system for module line supervisory control and data acquisition.

3.3 Yield, Durability and Reliability

The "Large-Scale Module and Component Yield, Durability, and Reliability" letter of interest issued in FY 2003 focused on addressing the needs of two categories. Category A, PV System and Component Technology, largely addresses non-module aspects of PV systems component manufacturing processes. Category B, PV Module Manufacturing Technology, primarily addresses aspects of module manufacturing processes. During FY 2005, 11 of the 17 responses to the YDR solicitation that were ranked in the competitive range were selected for funding. These projects represented a wide spectrum of the value chain in the PV industry, ranging from BOS work to PV module manufacturing. Significant achievements under this subtask by the individual subcontractors are described below.

PowerLight Corporation

"Accelerating PV Cost Effectiveness Through Systems Design, Engineering, and Quality Assurance"

- Implemented improvements to data-logger capabilities to allow increased communication with data collector and inverter systems.
- Developed and implemented improvements in the RFT10 sloped roof product to reduce cost. These included elimination of foam insulation, where little value is achieved, and the incorporation of more universal parts in the construction process.
- Improved reliability and reduced permitting delays through analysis and high wind effects and the modeling of system stability during seismic events.

GE Energy, LLC

"Solar Cell Design for Manufacturability"

- Produced molded wafers with thickness as low as 400 µm.
- Specified, purchased, and installed a new pilot line for cell processing.
- Produced first metal wrap-through prototypes.
- Improved SiNx process to achieve a 30% increase in diffusion length.
- Produced an 11.8%-efficient solar cell.

Evergreen Solar, Inc.

"Low-Cost Manufacturing of High-Efficiency, High-Reliability String Ribbon Si PV Modules"

- Began pilot operation of the in-situ ribbon cutting process.
- Developed and implemented improved contacting processes, resulting in cell efficiencies as high as 15% on 190-µm ribbons.
- Demonstrated a successful process for forming a frameless module all in one lamination step.

SolarWorld Industries America

"Manufacturing Improvements in CZ Silicon Module Production"

- Accomplished a gain in silicon utilization through reductions in wire saw (140 to 120 µm) and wafer thickness (280 to 240 µm).
- Improved cell processing resulting in 16.6% cell efficiencies.
- Implemented decay-free glass that cut the light-induced degradation in half at the module level.

SunPower Corporation

"Automated Manufacturing of High Efficiency Modules"

- Improved understanding of wafer breakage and automated wafer handling techniques.
- Continued development of Pb-free soldering.
- Developed new interconnects for cell-cell stringing that reduced forces on solder joints by >50%.
- Investigated and implemented antireflection glass, resulting in an efficiency gain of 2%.

BP Solar

"Development of Large High-Voltage PV Modules with Improved Reliability and Lower Cost"

- Employed thermal modeling to guide improvements in casting run time (14%), energy consumption (18%), sizing cycle time (15%), carrier lifetime, and number of defects (50%).
- Began evaluation of the impact of brick surface roughness on yield.
- Developed improvements in module production through the implementation of anti-reflection glass (2.4% more power), evaluation of polymer frames to eliminate shorting, and improved module termination to improve reliability.

Dow Corning Corporation

"High Performance Packaging Solutions for Low-Cost, Reliable PV Modules"

- Continued development through analysis and down-selection of new cell adhesive layers.
- Developed improved encapsulation formulation with the potential for faster processing speed and the potential to eliminate traditional laminator processing.

First Solar
"Solar Cell Design for Manufacturability"

- Demonstrated the ability to fabricate CdTe modules using a modified transparent conducting oxide and buffer layer with a demonstrated potential for >0.5% efficiency point improvement.
- Improved vapor transport deposition distributors for CdS, resulting in a 35% reduction in CdS thickness variation.
- Improved the sputtered interfacial layers and wet spray activation process, resulting in >0.3% efficiency improvement over the baseline process.

Xantrex Technology
"Advanced, High Reliability, System Integrated 500-kW Photovoltaic Inverter Development"

- Generated a detailed Functional Specification document to guide the development and evaluation of an improved inverter.
- Improved the high-power electronics and packaging design, resulting in cost reduction and reliability enhancements greater than the 25% targets.
- Improved the low-power electronics and control design, resulting in a cost savings of 52%.
- Improved the design of system-integrated features, resulting in a 75% reduction in cost.

Shingleton Design
"Advanced, High Reliability, System Integrated 500-kW Photovoltaic Inverter Development"

- Developed a roadmap toward reducing costs of the drive system.
- Reduced costs by >50% for the bearing housing and insert sections of the single axis tracker.
- Developed guidance manuals to assist with design, installation, operation and maintenance of tracking systems.
- Improved system design software, resulting in time savings and quality improvements.

Schott Solar, Inc.
"High Performance Multicrystalline Silicon Modules and Products"

- Reduced impurities in in silicon feedstock by installing new processing equipment.
- Utilized a protective coating for vulnerable furnace components that allows higher oxygen content within the device and results in higher efficiencies.
- Modified and successfully tested a new hot-zone design for growth furnaces to reduce stress.
- Improved device efficiency through the use of B-doped wafers.
- Developed materials, patterning designs, and an approach for the integrated module manufacture of backplane interconnects.
- Developed module designs for several building-integrated photovoltaic (BIPV) applications.

4. Planned FY 2006 Activities

PVMR&D Project procurements are framed to specifically address milestones under the Solar Program. Under the continuing IDIP procurement, PVMR&D will continue to focus on integrating state-of-the-art process controls with current production technology in support of the FY 2007 EERE cost goal and conduct end-of-year measurements to meet the FY 2007 EERE Joule Milestone for U.S.-made, commercial crystalline silicon PV modules of 14.5% conversion efficiency. The focus of the subcontracts under the YDR procurement will be on enhancing field reliability and durability, as well as manufacturing yield, which also supports the FY 2007 EERE milestones mentioned above.

The major task milestones and expected accomplishments of this project during FY 2007 include:

- Verify a conversion efficiency of 14.5%, using standard laboratory measurements, of U.S.-made, commercial crystalline silicon PV modules. (4^{th} Q JOULE milestone) (09/07)
- Complete initial incremental funding of subcontracted research under "Large-Scale Module and Component Yield, Durability, and Reliability" prior to identification of Technology Pathway Partnerships. (11/06)
- Analyze the FY 2006 U.S. PV industry cost/capacity/recapture data to identify the capacity-weighted, industry average. (05/07)
- Complete research under "In-Line Diagnostics and Intelligent Processing." (06/07)
- Complete required redirections and incremental funding of subcontracted research under "Large-Scale Module and Component Yield, Durability, and Reliability" (09/07)

The research addressed by the PVMR&D Project is chosen by the U.S. PV industrial participants in the form of proposals received in response to competitive solicitations. As such, these are systems-driven issues and are of the highest importance to PV manufacturers. Actual projects are chosen primarily by evaluators external to the government using criteria constructed to select, in a technology-neutral manner, those activities most likely to contribute to the PVMR&D Project goals and objectives.

Subcontracts under this project have continued to contribute to both the reduction of PV system costs and the improvement of PV manufacturing processes and products. In addition, representatives of the PV industry have generally identified this project as one of the most, if not the most, important and successful projects in the DOE Program. As such, the PVMR&D Project will continue to support manufacturing R&D consistent with the Systems-Driven Approach that has been established under this partnership of industry, laboratories, and government by implementing multi-year subcontracts that address industry-identified problems selected through competitive and fair processes.

5. Major FY 2006 Publications

Margolis, R., Mitchell, R., and Zweibel, K., "Lessons Learned from the Photovoltaic Manufacturing Technology/PV Manufacturing R&D and Thin-Film PV Partnership Projects," NREL/TP-520-39780, September 2006.

Nowlan, M.J., Murach, J.M., Sutherland, S.F., Miller, D.C., Moore, S.B., and Hogan, S.J., "Development of Automated Production Line Processes for Solar Brightfield Modules," Final Annual Technical Progress Report, 1 July 2004–15, October 2005, NREL/SR-520-40406, August 2006.

Rand, J.A., and Culik, J.S., "High Volume Manufacturing of Silicon-Film Solar Cells and Modules," Final Subcontract Report, 26 February 2003–30 September 2003, NREL/SR-520-38677, October 2005.

Wohlgemuth, J., Narayanan, M., "Large-Scale PV Module Manufacturing Using Ultra-Thin Polycrystalline Silicon Solar Cells," Final Subcontract Report, 1 April 2002–28, February 2006, NREL/SR-520-40191, July 2006

Wohlgemuth, J., Narayanan, M., "Large-Scale PV Module Manufacturing Using Ultra-Thin Polycrystalline Silicon Solar Cells," Final Subcontract Report, 1 April 2002–28 February 2006, NREL/SR-520-40191, 2006.

Friedman, D.J.; Mitchell, R.L.; Keyes, B.M.; Bower, W.I.; King, R.; Mazer, J., "PV Manufacturing R&D Project Status and Accomplishments under In-Line Diagnostics and Intelligent Processing and Yield, Durability and Reliability," *Proceedings of the 4th World Conference on Photovoltaic Energy Conversion* (Hawaii, 2006), NREL/CP-520-39904, May 2006.

Botkin, J., "Accelerating PV Cost Effectiveness Through Systems Design, Engineering, and Quality Assurance," Phase I Annual Technical Report, 4 November 2004–3 November 2005, NREL/SR-520-40335, July 2006.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2006.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)	Cost Share ($K)
BP Solar International, Inc. John Wohlgemuth	Frederick, MD john.wohlgemuth@bp.com	Large-Scale PV Module Manufacturing Using Ultra Thin Polycrystalline Silicon Solar Cells	20 0*	27 0*
Energy Conversion Devices, Inc. Tim Ellison	Troy, MI time@ovonic.com	Implementation of a Comprehensive On-Line Closed-Loop Diagnostic System for Roll-to-Roll Amorphous Silicon Solar Cell Production	0 500*	0 500*
Spire Corporation Michael Nowlan	Bedford, MA mnowlan@spirecorp.com	Development of Automated Production Line Processes for Solar Brightfield Modules	395 30*	384 29*

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)	Cost Share ($K)
Schott Solar, Inc. Miles Russell	Billerica, MA miles.russell@us.schott.com	Plug and Play Components for Building-Integrated PV Systems	0 0*	0 0*
Specialized Technology Resources, Inc. Ryan Tucker	Enfield, CT susan.agro@strus.com	Development of New Low-Cost, High-Performance PV Module Encapsulant/Packaging Material	5 0*	5 0*
Dow Corning Corporation Barry Ketola	Midland, MI barry.ketola@dowcorning.com	High Performance Packaging Solutions for Low Cost, Reliable PV Modules	215 550*	215 550*
Evergreen Solar, Inc. Jack Hanoka	Marlboro, MA hanoka@evergreensolar.com	Low-Cost Manufacturing of High-Efficiency, High-Reliability String Ribbon Si PV Modules	390 668*	390 668*
GE Energy, LLC James Rand	Newark, DE im.rand@ps.ge.com	Solar Cell Design for Manufacturability	270 375*	274 377*
PowerLight Corporation Jonothan Botkin	Berkeley, CA jbotkin@powerlight.com	Accelerating PV Cost Effectiveness Through Systems Design, Engineering, and Quality Assurance	232 120*	779 346*
SolarWorld Industries America Theresa Jester	Camarillo, CA Theresa.jester@shellsolar.com	Manufacturing Improvements in CZ Silicon Module Production	445 500*	442 499*
SunPower Corporation Doug Rose	Sunnyvale, CA Doug.Rose@sunpowercorp.com	Automated Manufacturing of High Efficiency Modules	385 300*	407 325*
Xantrex Technology, Inc. Raymond Hudson	San Luis Obispo, CA Ray.Hudson@xantrex.com	Advanced, High Reliability, System Integrated 500-kW Photovoltaic Inverter Development	79 250*	79 250*
First Solar, LLC Greg Helyer	Perrysburg, OH ghelyer@FIRSTSOLAR.COM	Implementation of Reliable Manufacturing of Higher Efficiency Module	320 100*	324 101*
Shingleton Design, LLC Jefferson Shingleton	Auburn, NY jefferson@shingleton.com	One-Axis Trackers – Improved Reliability, Durability, Performance, and Cost Reduction	50 170*	109 371*
BP Solar International, Inc. John Wohlgemuth	Frederick, MD john.wohlgemuth@bp.com	Development of Large High-Voltage PV Modules with Improved Reliability and Lower Cost	288 150*	270 140*
SCHOTT Solar, Inc. Mark Rosenblum	Billerica, MA mark.rosenblum@us.schott.com	High Performance Multicrystalline Silicon Modules and Products	100 310*	97 300*

* Funded with prior years (FY 2004 & FY2005) funds.

Technology Development

The U.S. Department of Energy, in cooperation with the U.S. photovoltaics industry, seeks to advance PV performance and systems engineering, bolster the U.S. market for PV, and develop technology suitable for integration into residential and commercial building. This work also includes building-integrated photovoltaics (BIPV), a rapidly growing solar application in which PV modules serve the dual purpose of replacing conventional building materials and generating electricity. By offering more than one functionality, BIPV systems will help cross the profit threshold essential to significant growth in distributed, grid-connected electricity markets.

DOE recognizes that outreach and analysis activities are necessary for a national R&D program to remain viable in a rapidly changing energy sector. Through the Million Solar Roofs (MSR) Initiative, which concluded in FY 2006, the Solar Program helped to develop local and regional markets for all solar technologies by working with communities to identify and encourage new applications. The success of MSR helped lay the foundation for the Solar America Initiative (SAI), which President George Bush announced in February 2006.

The Solar Decathlon—an intercollegiate competition to design, build, and operate attractive, energy-efficient, and totally solar-powered houses—is a high visibility event held on the National Mall in Washington, D.C. Between the two Decathlons (held in 2002 and 2005), as many as a quarter of a million people have come to visit the homes and learn about the architectural appeal and myriad benefits of solar energy in the built environment.

A sample of FY 2006 accomplishments in Technology Development follows.

PV System Evaluation and Optimization

- Recorded and analyzed long-term (months) system performance data for eight array/inverter combinations providing system, array, and inverter performance characteristics based on daily energy production.

PV Systems Engineering

- Provided systems performance analyses and results and feedback to industry, including multiple long-term, small systems monitoring at NREL; new systems from SunPower and Shell Solar installed at NREL at industry request; damp heat and thermal cycling for SunPower; and soiling tests for GE Energy.

Domestic PV Applications

- Loaned solar electric charging stations to help residents of Kiln, MS, recover from the devastation of Hurricane Katrina. The systems provided much-needed power to this town of about 2,000 people, located 13 miles north of Bay St. Louis, MS, and the Gulf of Mexico.

PV Systems Analysis

- Expanded the number of default markets/systems included in the Solar Advisor Model, and used the model to support the SAI Technology Pathway Partnership (TPP) activities.

Building-Integrated Photovoltatics

- Concluded the implementation of the 2005 Solar Decathlon university competition, releasing the final regulations, solidifying sponsors, supporting teams, and scoring, monitoring, and carrying out all aspects of the event.

Million Solar Roofs Initiative

- Closed out program, published final report, and held wrap-up meeting in fall 2006 at the Solar Electric Power Association Conference.

Regional Experiment Stations

- Participated in Federal Opportunity Announcement Technical Committee to determine accuracy of all data submitted in SAI TPP proposals.

PV System Evaluation and Optimization

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contacts: David King (SNL Primary Contact), 505-844-8220, dlking@sandia.gov
Sig Gonzales, (DETL, Inverter Contact), 505-845-8942, sgonza@sandia.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2006 Budget: $620K

Objectives

The key FY 2006 objectives for this R&D project were to:

- Implement and operate a versatile fully instrumented PV System Optimization Laboratory (PVSOL) for system and inverter performance, modeling, and reliability research.
- Develop, validate, and apply new testing and analysis protocols, based on energy production, which are needed to verify and optimize the performance and reliability of PV systems.
- Provide manufacturers, integrators, and software developers accurate comprehensive test data required to model and verify system, module, and inverter performance.
- Coordinate a multi-site research effort to evaluate the long-term, field-aging behavior of systems and inverters, in collaboration with manufacturers, system integrators, the Florida Solar Energy Center (FSEC), the Southwest Technology Development Institute (SWTDI), and Behnke, Erdman & Whitaker Engineering (BEW).
- Investigate advanced PV system concepts, manufacturing methods, and deployment strategies that improve performance, reliability, and cost, and accelerate deployment.

Accomplishments

- Recorded and analyzed long-term (months) system performance data for eight array/inverter combinations providing system, array, and inverter performance characteristics based on daily energy production. Initial results documented in the 4th World Conference on Photovoltaic Energy Conversion (WCPEC) publication.
- Initiated a comprehensive testing and analysis effort to develop a generally applicable PV inverter performance model. The beta version developed is widely applicable, easy to implement, and provides the accuracy required for energy modeling, technology comparisons, and system monitoring.
- Conducted detailed module performance characterization of 15 SunPower 220-W modules with three types of glass superstrate—standard, sputtered antireflection (AR) coating, and solution-deposited AR coating—and then installed three 1-kW systems using the modules to evaluate their relative energy production. Verified improved angle-of-incidence characteristics and 4% greater energy production with AR-coated glass. Documented in 4th WCPEC publication.
- Arizona State University PV Testing Lab (ASU/PTL) successfully implemented SNL's module/array outdoor testing and data analysis protocols for generating performance coefficients for the "module database" used by Maui Solar, the DOE Solar Advisor Model (SAM), and others. 4th WCPEC publication.
- Completed grid-tied performance evaluation per IEEE 1547 for PV Powered 30-kW prototype inverter and GE 3600 inverter deliverable from High Reliability Inverter Initiative.
- Provided product development assistance for PV Powered to improve their maximum power point tracking (MPPT) algorithm and address difficulties meeting C62.45 surge suppression compliance for their commercial PVP-2800XV inverter.
- Provided lab test support for Professor Michael Ropp of South Dakota State University (SDSU) for early validation of a detailed electrical model of internal inverter functions (e.g., MPPT, anti-islanding, switching frequency, and non-linear loads). Three 4th WCPEC publications.

- Provided initial concepts for a System Testing Protocol needed to evaluate DOE Solar America Initiative (SAI) system-level deliverables, and supported the development of a residential-scale system and inverter testing protocol requested by the Rural Utility Service (RUS) and to be conducted by FSEC.
- Developed and applied new nondestructive ultrasonic imaging procedure intended for rapid evaluation of solder bond quality during production line cell tabbing (interconnection) process. Used capability to assist Advent Solar and Sharp (PowerLight) in module diagnostics and production process improvement.

Future Directions

- Continue the development and implementation of system and inverter test and evaluation protocols in support of industry participants in the SAI, providing both field-testing of large systems as well as laboratory optimization of small (<5kW) systems or components.
- Complete development and documentation of general inverter performance model for PV system performance modeling, including an initial database with inverter parameters derived from manufacturer specification sheets, system field tests, and test results recorded by laboratories supporting the California Energy Commission (CEC).
- Perform concerted research effort to characterize, document, and model PV system, array, and inverter performance (energy production) and reliability through detailed analysis of fully integrated and instrumented PV systems. Research conducted in coordination with module/inverter manufacturers, system integrators, FSEC, SWTDI, BEW, and CEC.
- Develop improved field-data acquisition techniques and analysis protocols for monitoring PV system performance and providing real-time performance assessment, as well as diagnostics.

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1. Introduction

The System Evaluation and Optimization activities at Sandia National Laboratories closely match the needs of manufacturers and system integrators. The research effort provides laboratory and field-test information needed to establish the performance and reliability status of current PV systems, and to identify improvements in system design and component integration for next-generation systems. These activities are key to meeting the *DOE Solar Energy Technologies Program Multi-Year Program Plan* targets, the goals of the *U.S. PV Industry Roadmap,* and the objectives of the new DOE Solar America Initiative (SAI). As such, the System Evaluation and Optimization Project is the focal point within the DOE Solar Program at which the technical issues of PV component manufacturers, system integrators, and users converge.

2. Technical Approach

Major research activities for FY 2006 included detailed module, array, inverter, and system research aimed at understanding and improving the performance, reliability, and cost of fully integrated PV systems. Capabilities and expertise associated with SNL's PV Systems Optimization Lab (PVSOL) and the companion Distributed Energy Technology Lab (DETL) were used to conduct this research.

The PVSOL accurately evaluates the performance of both component (modules, arrays, inverters) and complete systems based on energy production. Continuous recordings of energy flow in and out of all system components provide detailed performance information, as well as long-term aging characteristics, for both inverters and arrays under all weather conditions. Accurate performance modeling for the array, inverter, and system provide real-time system performance metrics and diagnostic capabilities.

The project had three subtasks, funded as indicated in the following table.

Task Title	FY 2006 Budget ($K)
PV System Performance Testing and Modeling	260
Inverter Performance Testing and Industry R&D Support	260
Advanced PV System Concepts	100

The *System Performance Testing and Modeling Task* focused on module and array performance characterization and modeling, development of a new generally applicable inverter performance model, and development of system testing and monitoring protocols based on energy production. Experience gained in this task supports the Modeling Leadership Team associated with the SAI.

The *Inverter Performance Testing and R&D Support Task* conducted a variety of comprehensive inverter testing to aid inverter development, evaluate new concepts, benchmark performance and utility compatibility of commercial inverters, initiate long-term field aging at SNL, FSEC, and SWTDI, and provide performance parameters needed for new inverter performance model. This activity addresses the "Inverter Testing and Industry Support" section of the *Solar Program Multi-Year Plan* and is a key element of the SAI beginning next fiscal year.

The *Advanced PV System Concepts Task* addresses improvements in PV system manufacturing methods, new inverter design concepts, and new equipment and procedures for real-time performance monitoring of PV systems and components. Limited funding was available this fiscal year, but several concepts were identified for next fiscal year, all complementary to objectives of the SAI.

3. Results and Accomplishments

The primary results and accomplishments for this project were summarized previously. FY 2006 milestones for the three subtasks included:

- Transfer of SNL module/array outdoor testing procedures to ASU/PTL with intercomparison measurements completed March 2006; documented in 4th WCPEC publication (May 2006).
- Performance characterization and modeling of eight PV arrays completed in September 2006 in support of energy modeling analyses and long-term inverter testing.
- Using fully instrumented PVSOL systems, demonstrated new procedures and high accuracy for energy-based performance models and monitoring of systems. Documented results in 4th WCPEC publication (May 2006). Results led to draft protocol for system performance testing associated with SAI deliverables.
- Completed baseline performance evaluation of five commercial inverters in January 2006, now in long-term system aging at FSEC, SWTDI, and SNL. Plus, evaluation of three additional inverters by industry request completed September 2006.
- Completed development of beta version of a general inverter performance model in September 2006, with final version for use in DOE SAM model and in commercial system design software planned for February 2007.
- Investigation and analysis of system manufacturing, reliability, installation cost, PV technology, and system design sensitivities conducted in support of DOE SAM model development and analyses preceding funding opportunity announcement for SAI.
- A continued effort resulted in the development of an innovative high-reliability micro-inverter design for the advanced "AC Building Block" PV system concept. Documented in 4th WCPEC publication. See the Inverter and BOS Development project for additional information on development of new high-reliability inverter concepts.

One highlight from the project was the development of a widely applicable inverter performance model for use in system-performance analyses and field-performance monitoring and diagnostics. The model was found to be applicable and accurate for a wide variety of both residential and commercial-scale inverters, provided the inverter had stable and repeatable performance characteristics. Three levels of accuracy are possible with the model, depending on the type of test data available: specification sheet data, field-test data during system operation, or detailed laboratory measurements as performed by SNL and CEC testing laboratories. Figure 1 illustrates measured performance results by a CEC laboratory for a typical inverter at six power levels and three input DC-voltage levels, along with modeled performance. Factors included in the model are peak (rated) AC power, peak DC power with DC voltage dependence, DC power (self consumption) required to initiate the inversion process with voltage dependence, nonlinear AC-power versus DC-power relationships with voltage dependence, and night time "tare" power required for sensing array voltage.

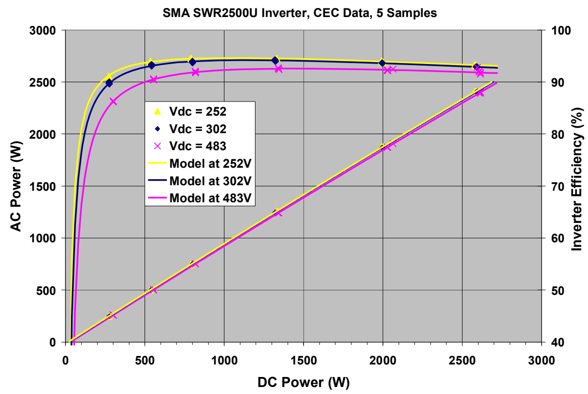

Fig. 1. SNL inverter performance model (lines) using CEC-measured data (symbols) at six power levels and three voltage levels. AC power and efficiency as a function of DC power are shown.

4. Planned FY 2007 Activities

Activities planned for FY 2007 will be largely defined by the test and evaluation requirements stemming from industry partnerships associated with the DOE Solar America Initiative.

5. Major FY 2006 Publications

B. Li, D. King, W. Boyson, G. Tamizmani, "Implementation of Sandia Outdoor Photovoltaic Test Method and Performance Model at Arizona State University," 4^{th} *WCPEC*, Hawaii, May 2006.

D. Rose, O. Koehler, N. Kaminar, B. Mulligan, D. King, "Mass Production of PV Modules with 18% Total-Area Efficiency and High Energy Delivery Per Peak Watt," *4th WCPEC,* Hawaii, May 2006.

D. King, G. Galbraith, S. Gonzales, A. Murray, J. Ginn, "Array Performance Characterization and Modeling for Real-Time Performance Analysis of Photovoltaic Systems," 4^{th} *WCPEC*, May 2006.

W. Bower, R. West, A. Dickerson, "Innovative PV Micro-Inverter Topology Eliminates Electrolytic Capacitors for Longer Lifetime," 4^{th} *WCPEC*, Hawaii, May 2006.

C. Whitaker, J. Newmiller, W. Bower, "Inverter Performance Certification: Results from the Sandia Test Protocol," 4^{th} *WCPEC*, Hawaii, May 2006.

M. Ropp et al., "Discussion of a Power Line Carrier Communication-Based Anti-Islanding Scheme Using a Commercial Automatic Meter Reading System," 4^{th} *WCPEC*, Hawaii, May 2006.

M. Ropp et al., "Simulation and Experimental Study of the Impedance Detection Anti-Islanding Method in the Single-Inverter Case," 4^{th} *WCPEC*, Hawaii, May 2006.

M. Ropp et al., "Discussion of the Physical Mechanisms Behind the Observed Behavior of Motors in Islanded Loads," 4^{th} *WCPEC*, May 2006.

J. Wiles and W. Bower, "Changes in the National Electric Code for PV Installations," 4^{th} *WCPEC*, Hawaii, May 2006.

6. University and Industry Partners

In FY 2006, a $10K contract was placed with ASU/PTL involving the technology transfer, implementation, and validation for the SNL outdoor module testing and data analysis protocol required to determine parameters for the "module database" initiated by SNL.

PV Systems Engineering and Performance

Performing Organizations: National Renewable Energy Laboratory (NREL)
Sandia National Laboratories (SNL)
DOE Golden Field Office (DO/GO)

Key Technical Contacts: Carol Riordan (NREL, Primary Contact), 303-384-6780, carol_riordan@nrel.gov
Carl Osterwald (NREL PV Systems Performance & Standards), 303-384-6764, carl_osterwald@nrel.gov
Daryl Myers (NREL Solar Radiometry & Radiometry), 303-384-6768, daryl_myers@nrel.gov
Ward Bower (SNL, Codes, Standards & Certification), 505-844-5206, wibower@sandia.gov
Glenn Doyle (DOE/GO, Codes, Standards & Certification), 303-275-4706, glenn.doyle@go.doe.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2006 Budgets: $1,475K (NREL), $100K (SNL)

Objectives

The key FY 2006 objectives for the Systems Engineering and Performance Project were to:

- Determine, characterize, and document the near- and long-term performance and reliability of candidate, emerging PV technologies in the context of a small, grid-connected, system; provide benchmark-type data and analyses, in a continuing fashion, to the Systems-Driven-Approach activities.
- Assist the PV industry and community with the development and implementation of codes, standards, and certification practices to assure safe installations that perform as expected.
- Provide the DOE Solar Technologies Program with world-class and traceable solar radiometric capabilities, measurements, and standards.

Accomplishments

- Provided systems performance analyses and results and feedback to industry (e.g., multiple long-term, small systems monitoring at NREL; new systems from SunPower and Shell Solar installed at NREL at industry request; damp heat and thermal cycling for SunPower; soiling tests for GE Energy).
- NREL and SNL continued collaborations with industry to evaluate performance-based assessments of module/system performance using a combination of models, which fed into the benchmarking and systems modeling to support the Solar America Initiative (SAI); implemented improvements to PVWATTS systems analysis software and posted on the Web.
- Chaired American Society for Testing and Materials (ASTM) standards activities and provided standards support for PowerMark and Sunset Technologies (International Electrotechnical Commission [IEC] Secretariat).
- Led Industry Forum and introduced 42 proposed changes for the 2008 edition of the *National Electrical Code*.
- Led IEC standards developments related to inverter and systems test methods.
- Chaired North American Board of Certified Energy Practitioners (NABCEP) test committee with two sets of test updates to correspond to testing schedules.
- Supported SAI Market Transformation formulations.
- Transferred World Radiometric Reference to NREL Reference Absolute Cavity Radiometers through the International Pyrheliometer Comparison X.

Future Directions

- The draft (pre-appropriations) of the FY 2007 Annual Operating Plan specifies continuing R&D on PV systems engineering and performance R&D, solar radiation and metrology R&D, and codes, standards, and certification, with the objective of improving PV performance, providing broadband and spectral irradiance measurement capability with traceability to world radiometric standards, and removing barriers and facilitating system deployment through codes, standards and certifications to meet the mid- and long-term SAI cost goals for competitive PV systems.
- Assuming the launch of the SAI, these PV systems engineering and performance, solar radiometry and metrology R&D, and codes/standards/certification agreements will play a major part in the test and evaluation of deliverables from the SAI Technology Pathway Partnerships, including application and development of test and evaluation protocols for module performance and energy modeling.

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1. Introduction

The major thrust of this project is the near-term and long-term performance monitoring, characterization, and modeling of current- and emerging-technology, small (<5 kWp), grid-connected, prototype systems installed and operating at NREL's Outdoor Test Facility (OTF). Critical to this effort is a supporting task that provides world-class and traceable measurements and instrumentation for solar radiometry. The resultant precision and accuracy of the PV system (and module) performance measurements is determined by the quality, precision, and accuracy of the measurements of the incident (on the PV arrays) solar irradiance (i.e., "power in"). This project also includes very important activities aimed at supporting the development of industry-consensus/adopted codes, standards, and certification that cover PV systems, components, and installation practices. The project provides leadership and support in creating and implementing codes and standards for quality, safe, and cost-effective systems. This work insures that codes, standards and certifications are in place to pave the way for wide varieties of PV installations and to insure interconnect issues with utilities are resolved.

This project is integral to the Solar Energy Technologies Program multi-year technical plans because it provides credible/independent data, analyses, and assessments of the performance and reliability metrics that are required in benchmarking the candidate technologies and supporting the Systems Driven Approach (SDA) to R&D management.

2. Technical Approach

The technical approach for this project included providing:

- Quarterly engineering test reports on at least seven small PV systems at the NREL OTF that provide the module manufacturers and the DOE Solar Program with independent analyses of energy performance ratings and long-term degradation rates at the system level.
- An improved, on-line, PVWATTS software program/model that provides decision makers, the public, and the industry with credible estimates of PV system electric generation and costs for specific geographic locations nationally and internationally.
- Robust technical support of important national standards, codes, and testing and certification activities, which are needed to assure safe installations that perform as expected.
- Continued world-class solar radiometric, and therefore PV system performance, measurements and instrumentation.
- PV system performance and reliability data and analyses required by the DOE Solar Program's SDA activities (e.g., benchmarking) and analyses.

Agreements under this project were:

Agreement Title	FY 2006 Budget ($K)
PV System Performance and Standards (NREL)	780
Solar Radiometry and Metrology (NREL)	695
Codes, Standards, and Certification (SNL and DOE/GO)	100

Subcontracts included support for PV module and systems certification to PowerMark Corp., and support for the IEC-TC Secretariat position to Sunset Technologies. A contract to BEW Engineering supported IEC Working Group 6 Convener for leading standards-writing activities related to inverters and systems. A detailed table of subcontractors and funding is included below in section 6.

3. Results and Accomplishments

3.1. PV System Performance and Standards (Osterwald/NREL)

- Delivered quarterly, small-PV system performance reports and analyses to module manufacturers (9/30/06); 7/06 report was skipped due to staff loss, resumed 10/06 (ongoing).
- Implemented improvements to PVWATTS systems analysis software (4/06) (see http://rredc.nrel.gov/solar/codes_algs/PVWATTS).
- Continued collaboration with SNL and industry to evaluate performance-based assessments of module/system performance using a combination of models (9/30); fed into "benchmarking"/systems modeling to support SAI (reported to DOE).
- Installed new technology—Shell Solar Eclipse 80 CIGS—small PV system at the OTF (and initiated long-term testing) and three new SunPower 1-kW grid-tied systems for long-term performance monitoring.
- Provided industry support: e.g., damp-heat and thermal cycling for SunPower, soiling tests for GE Energy, long-term module/small system testing being initiated for SunPower; participation in standards activities (e.g., Chair, ASTM 44.09), external standards support through PowerMark and Sunset Technologies contracts (ongoing).

This R&D received very high ratings in the DOE Solar Program Peer Review for relevance and value (3.8 out of 4.0), with comments such as "The relevance of the work is seen as 'critical to the achievement of DOE goals' and the development of sustainable PV markets" and "technical approach is 'well defined and focused.' "

3.2 Solar Radiometry and Metrology (Myers/NREL)

- Transferred World Radiometric Reference to NREL Reference Absolute Cavity Radiometers through results of the International Pyrheliometer Comparison-X (9/30); this provides traceability of NREL solar measurements to the world reference standard.
- Submitted three solar radiometer calibration standards to ASTM; revised and passed final ballot approval (7/06).
- Submitted paper for publication on environmental influences on solar radiometer calibration, "Environmental Thermal Effects on the Eppley Normal Incidence Pyrheliometer," to *Solar Energy*; publication expected as both journal article and NREL report (9/06).

This agreement is critical to reporting the accuracy, traceability, and measurement uncertainty for NREL measurements (cell, module, performance, etc.). Activities in FY 2006 included implementing and upgrading the radiometer calibration and characterization software; calibrating more than 180 broadband and spectral radiometers; characterizing 5 research and industry solar simulators for PV performance testing; updating spectral solar radiation models; responding to more than 190 technical requests from industry, academia, government organizations, and the public; and revising and improving pulse spectral solar simulator and software. This R&D received very high ratings in the DOE Solar Program Peer Review for relevance and value. Reviewers commented that the activities were "clear, relevant, and necessary; an essential element of PV development, providing a clear measurement standard supporting the goals and objectives of the DOE Solar Technologies Program extremely well."

3.3 Codes, Standards, and Certification (Bower, SNL and Doyle, DOE/GO)

- Led SNL Industry Forum and introduced 42 proposed changes for the 2008 edition of the *National Electrical Code*.
- Led IEC standards developments related to inverter and systems test methods
- Chaired NABCEP test committee with two sets of test updates to correspond to testing schedules
- Supported UL Standards Technical Panel in revising UL1741 to add testing methods for transformerless inverters and to correlate the standard with IEEE1547 for anti-islanding and interconnect requirements.

4. Planned FY 2007 Activities

FY 2007 planned activities are given in the draft (pre-appropriations) FY 2007 Annual Operating Plan, which is organized differently from previous years.

Systems Engineering and Performance and Solar Radiometry and Metrology will be performed under the Technology Evaluation Activity, PV System Testing and Evaluation Project, and the Component Testing and Evaluation Project Agreement on “Solar Radiometry and Metrology,” with aspects related to the Systems Analysis Project Agreement on “Systems Performance Modeling and Database Development.” The R&D under these agreements emphasizes PV system performance characterization and analysis; development of codes and standards/protocols for PV module and system performance, and R&D on solar radiometry and metrology to maintain traceability to world radiometric standards and allow measurement uncertainty analysis for cell and module performance measurements. These agreements also include related tasks on inverter, balance of systems, and systems testing and evaluation, as well as proposed SAI Market Expansion/Transformation Agreements on codes and standards. Work under the agreements will also support the Test & Evaluation plan for the Technology Pathway Partnerships as the SAI moves forward.

5. Major FY 2006 Publications

C.R. Osterwald, J. Adelstein, J.A. del Cueto, W. Sekulic, D. Trudell, P. McNutt, R. Hansen, S. Rummel, A. Anderberg and T. Moriarty, “Resistive Loading of Photovoltaic Modules and Arrays for Long-Term Exposure Testing,” *Prog. Photovolt: Res. Appl.* 2006; **14**:567–575.

S. Wilcox, J.R. Hickey, and D.R. Myers, “Environmental Thermal Effects on the Eppley Normal Incidence Pyrheliometer,” submited to *Solar Energy*, Sep 2006.

I. Reda, J.Hickey, C. Long, D. Myers, T. Stoffel, S. Wilcox, J.J. Michalsky, E.G. Dutton, and D. Nelson, “Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error during Outdoor Calibration Using the Component Sum Method.” *Journal of Atmospheric and Oceanic Technology,* vol. 22, October 2005; pp. 1531–1540. NREL Report No. JA-560-36646.

S. Wilcox, M. Anderberg, W. Beckman, A. DeGaetano, R. George, C. Gueymard, W. Marion, D. Myers, R. Perez, N. Lott, D. Renne, P. Stackhouse, F. Vignola, “Towards Production of an Updated National Solar Radiation Database.” Campbell-Howe, R., ed. *Proceedings of the Solar 2006 Conference,* 9-13 July 2006, Denver, Colorado (CD-ROM). Boulder, CO: American Solar Energy Society (ASES) 6 pp.; NREL Report No. CP-560-39597.

C. Whitaker, J. Newmiller, W. Bower, “Inverter Performance Certification: Results from the Sandia Test Protocol,” *4th WCPEC*, May 2006.

W. Bower and C. Whitaker, “Test Protocol for Certification of Inverter Performance,” *Proceedings of the DOE 2005 Solar Program Review*, Denver, CO, Nov 2005.

J. Wiles and W. Bower, “Changes in the National Electric Code for PV Installations,” *4th WCPEC*, Hawaii, May 2006.

6. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2006 (no cost share).

Organization/Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)[(a)]
PowerMark Corp. Steve Chalmers	Phoenix, AZ Chalmers@powermark.org	U.S. PV module and systems certification program support	43.2
Sunset Technologies Howard Barikmo	Scottsdale, AZ hbarkimo@aol.com	IEC-TC Secretariat support	33.5
Behnke, Erdman & Whitaker Engineering Chuck Whitaker	San Ramon, CA Chuck.Whitaker@bewengineering.com	Standards, codes, and certification and begin related performance modeling	68

[(a)] Without fees

Domestic PV Applications

Performing Organizations: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: John Thornton (NREL) retired 7/06
Cécile Warner (NREL) 8-9/06, 303-384-6516, cecile_warner@nrel.gov

DOE HQ Technology Manager: Dan Ton, 202-586-4618, dan.ton@ee.doe.gov

FY 2006 Budgets: $816K (NREL), $30K (SNL)

Objectives

- Address the markets and applications issues raised in the *PV industry Roadmap* (NREL).
- Provide a focal point for DOE activities through dissemination of information, raising public awareness, and technical facilitation (NREL).
- Support U.S. Department of Agriculture (USDA) Farm Bill Solar Program (NREL and SNL).
- Support development of DOE Systems-Driven Approach (NREL and SNL).
- Continue program-related outreach to Native Americans with interest in solar energy (SNL).
- Extend rural utility support to additional PV systems applications and extend list of accepted systems (SNL).

Accomplishments

- Conducted three consumer workshops at the Denver Western Stock Show with public attendance of approximately 380 (NREL).
- Supported the U.S. DOE/USDA joint conference in St. Louis, MO, with the development of an exhibit on PV applications in the agriculture sector (NREL) to be staffed by NREL personnel at the conference.
- Continued partnership with DOE Rocky Mountain Oilfields Testing Center to test use of PV for oil transport in oilfields (NREL).
- Loaned solar electric charging stations to help residents of Kiln, MS, recover from the devastation of Hurricane Katrina. The systems provided much-needed power to this town of about 2,000 people, located 13 miles north of Bay St. Louis, MS, and the Gulf of Mexico (NREL).

Future Directions

- Continue support of joint DOE/USDA Conference in St. Louis, October 2006 (NREL).
- Conduct expanded consumer workshops, jointly with Xcel Energy, at the Denver Western Stock Show (NREL).
- Transition from Domestic Applications project to a broader scope of market transformation, supporting DOE in development of plans, review and selection of proposals, and technical support in the City Strategic Partnerships and Solar America Showcases projects (NREL).

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1. Introduction

The Domestic PV Applications Project, which concluded in FY 2006, supported the analytical, applications, and market development activities of the DOE Photovoltaic Subprogram and the development and use of a Systems-Driven Approach (SDA). The objective of the project was to provide a focal point for DOE activities through project development, dissemination of information, increasing public awareness, subcontract management, and technical assistance. Our work was carried out in-house at NREL as well as externally with and/or through a wide range of federal, state, and local groups. This project concluded in 2006. A new project, PV Market Transformation, is replacing this project in the 2007 fiscal year and beyond.

2. Technical Approach

During FY 2006, this task addressed some of the critical challenges posed by the *U.S. PV Industry Roadmap*—namely, raising the awareness of PV in numerous market sectors where significant penetration has not yet been attained, developing information that effectively conveys the potential of PV (and other solar technologies) to both technical and non-technical audiences, and providing support to organizations to develop standardized system specifications and acceptance criteria. We also supported several DOE-requested activities, including planning for the phase-out of this project while ramping up planning to support the Solar America Initiative in the area of market transformation.

Task Title	FY 2006 Budget ($K)
Training, Education, and Technical Assistance (NREL)	816
Domestic Technical Support (SNL)	30

3. Results and Accomplishments

3.1 National Renewable Energy Laboratory

During FY 2006, our highest priority was planning for the transition of this project to support the DOE's Solar America Initiative. The new project, known as PV Market Transformation, replaces this domestic applications activity.

National Western Stock Show. In January, we again conducted workshops (with attendance approaching 400) and hosted an exhibit at the National Western Stock Show in Denver, CO. According to Stock Show staff, more than 600,000 visitors attended the 16-day event.

Rocky Mountain Oilfields Testing Center. We investigated ways to use PV to enhance the production, distribution, and use of traditional fossil fuels, such as oil and natural gas. We collaborated with the DOE Rocky Mountain Oilfields Testing Center (RMOTC) and installed an experimental PV-powered, oil-pumping unit in operation at the federally owned Teapot Dome oil field of Wyoming. The goal of this project is to demonstrate a solar-powered, oil-shipping pump at this DOE Fossil Energy facility in Casper, WY. During the spring and summer of 2006, NREL staff facilitated shipping oil reliably through modified system design using an alternative pump type. Equipment choice and data acquisition issues were resolved, and the system is now operating without interruption. The overall system design and implementation was difficult because it is the first of its kind and there was no prior work. Fruitful collaborations with experts in a variety of fields helped to solve the pumping and data-acquisition challenges. Documentation and dissemination of the system design and performance will be reported in FY 2007. We anticipate this project could be replicated manifold by the DOE Fossil program, given the large number of similar systems in its network.

DOE and NREL Special Requests. We supported special requests for PV power as requested. For example, we provided PV power for the Science and Technology Facility dedication at NREL (July 2006).

USDA/DOE Conference. DOE and the U.S. Department of Agriculture (USDA) hosted a joint conference October 10–12, 2006, in St. Louis, MO, that focused on elements of President George W. Bush's Advanced Energy Initiative, specifically biomass, wind, and solar research and commercialization. The conference, *Advancing Renewable Energy: An American Rural Renaissance* brought together key stakeholders in renewable energy to identify major issues including partnership opportunities facing decision makers both within government and in the private sector and advance understanding of the opportunities and issues involved in the integration of distributed energy production into legacy systems. Our team planned, organized, and staffed the Solar Energy section of the DOE exhibit (see Fig. 1).

Fig. 1. Energy Secretary Samuel W. Bodman spoke to NREL's Byron Stafford about the laboratory's work on solar energy during a tour of the Advancing Renewable Energy exhibit hall on October 11, 2006.

Solar Energy and Colorado Golf Course Owners. We prepared and presented elements of a workshop on “Renewable Energy for Golf Clubs” to members of the Colorado Golf Course Owners Association (CGCOA). Topics included solar energy and energy efficiency. Energy (and the closely related topic, water) usage and costs are increasingly important to golf clubs for business reasons, but also for the stewardship of the natural resources that they manage. There are about 15,000 golf courses (18-hole equivalent) in the United States and each course ranges in size from 150 to 200 acres of total land. The opportunities for PV applications in this sector are vast. Prior to the workshop, NREL staff toured a course with the CGCOA in Denver, CO. We discussed their energy concerns, usage, and costs as they relate to the golf industry. Not unexpectedly, energy and water are critical to maintaining a successful golf course and clubhouse. We gave an overview of the importance and value of energy efficiency measures that the golf course owners could implement immediately, especially in their club houses, and gave presentations on PV systems and a summary of opportunities for golf course owners based on NREL’s walkthrough. The workshop was well received by the golf course owners with requests for another workshop and possibly a workshop at their National Golf Course Owners Association’s annual conference.

4. Planned FY 2007 Activities

This project concluded, based on guidance from DOE, at the end of FY 2006. Some existing activities, notably technical assistance, will be folded into the new PV Market Transformation activities that are part of the Solar America Initiative, including City Strategic Partnerships and Solar America Showcases. We will continue to provide technical support to Federal, state, and local organizations, such as the Rocky Mountain Oilfields Testing Center in Casper, WY. DOE Headquarters activities will be supported on request.

PV Systems Analysis

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL)
Key Technical Contacts:	Robert Margolis (NREL, Primary Contact), 202-646-5053, robert_margolis@nrel.gov David Mooney (NREL), 303-384-6782, david_mooney@nrel.gov Charles Hanley (SNL), 505-844-4435, cjhanle@sandia.gov
DOE HQ Technology Manager:	Dan Ton, 202-586-4618, dan.ton@ee.doe.gov
FY 2006 Budgets:	$616K (NREL), $150K (SNL)

Objectives

- Develop the PV components of the Solar Advisor Model including performance, cost, and financing modules, allowing detailed system, component, and subcomponent sensitivity studies.
- Develop a user-friendly and intuitive graphical interface for the Solar Advisor Model.
- Use the Solar Advisor Model to support program planning and evaluation.
- Work with private-sector partners (utilities and industry) and Federal agencies to study the key component failures, costs and times to repair, and other operation and maintenance issues.
- Document performance (such as kWh production) for various module technologies.
- Determine the overall levelized cost of energy for fielded PV systems in key reference applications, and apply projections of technology improvements to determine future-year costs and overall targets.
- Develop long-term market penetration projections for PV technologies.
- Develop the Solar Deployment Systems (SolarDS) model—a PV market-penetration model that will serve as an alternative to the National Energy Modeling System (NEMS) and be compatible with the broader Systems-Driven Approach model-development effort.
- Evaluate policies, as well as other factors, that impact the value of solar energy technologies in a variety of markets.

Accomplishments

- Expanded the number of default markets/systems included in the Solar Advisor Model.
- Used the Solar Advisor Model to support the Solar America Initiative (SAI) Technology Pathway Partnership (TPP) Federal Opportunity Announcement process.
- Expanded partnered activities on residential PV systems to further refine determinations of installation and overall life-cycle cost, system reliability, and system availability.
- Developed functional version of the SolarDS model.
- Completed functional version of Web-based distributed PV cost-benefits clearinghouse.
- Provided technical and analytical support to the Western Governors' Association Solar Energy Task Force.

Future Directions

Continue to:

- Develop the PV components of the Solar Advisor Model.
- Exercise the Solar Advisor Model in support of the SAI.
- Focus benchmark activities to directly support the SAI TPPs.
- Work on technology-policy tradeoff studies and value analysis.
- Support the annual Government Performance and Results Act (GRPA) analysis.

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1. Introduction

The PV Systems Analysis Task consists of systems performance and cost modeling, market/value/policy analysis, and benchmarking projects. The primary function of the Solar Advisor Model is to allow users to investigate the impact of variations in physical, cost, and financial parameters to better understand their impact on key figures of merit. Figures of merit related to the cost and performance of these systems include, but are not limited to, system output, peak and annual system efficiency, levelized cost of energy (LCOE), and system capital and operations and maintenance (O&M) costs. The benchmarking effort is structured to document the current status of these and other key figures of merit. The Solar Advisor Model is intended for use by DOE and laboratory management and research staff and is a critical element in the implementation of the Systems-Driven Approach (SDA) to Solar Program planning. The model may be used by members of the solar industry to inform internal R&D direction and to estimate systems cost and performance. The analysis portion of the task is structured to consider market-penetration models and to capture the value of PV systems in various markets. During FY 2006, the work under this task was focused specifically on supporting the implementation of the Solar America Initiative (SAI).

2. Technical Approach

For the Solar Advisor Model, particular emphasis was placed upfront on the design of a user interface that could meet the needs of a diverse set of users. User profiles were developed to provide a general description of DOE, laboratory, and industry users and their motivation for using the modeling tool.

The working model consists of a user-interface module for selecting and providing input data on the system configuration and operating environment, a system-performance module that simulates the hour-by-hour output of the selected system for the lifetime of a project, a cost-input module for providing simple or detailed cost inputs for system components, and a financial-analysis module for calculating system economics. The modules work in concert to generate the physical and financial figures of merit relevant to the particular user.

Developing the PV components of the Solar Advisor Model, defining its inputs (based on data gathered through benchmarking), and carrying out detailed analysis with the model has been a central focus of the modeling and benchmarking areas during FY 2006.

The analysis team focuses on two main tasks. The first is developing long-term market-penetration projections for solar technologies. This effort involves examining both the system and policy drivers of solar technologies in various markets in both the short and long term, as well as improving the analytical basis for projecting the Solar Program's economic and environmental benefits. Here, our emphasis has been on models and modeling: using existing models—such as the Energy Information Administration's NEMS, MARKAL, and others—to carry out analysis, examining the structure of various models and providing feedback on how to improve the representation of solar technologies to modelers, and developing new models such as SolarDS that will help meet the needs of the broader SDA modeling effort.

The analysis portion of this task also evaluates policies, as well as other factors, that impact the value of PV technologies in a variety of markets. This task involves using existing models, spreadsheets, and other tools. Here, our emphasis is on using analytical tools to quantify how changing policies, rate structures, system designs, and other factors will impact the value of solar technologies to consumers, utilities, governments, and other players.

During FY 2006, a key emphasis of the analysis team was to identify best practices for implementing performance-based incentive structures, in particular, in the context of the shifts taking place under the California Solar Initiative. While this work was aimed at specifically supporting California, it developed the framework for broadly informing state-level policymaking with respect to incentive design.

In carrying out these projects, we use resources at NREL and SNL (described in the table below), as well as subcontracts (described in Section 6).

Task Title	FY 2006 Budget ($K)
PV Advisor Modeling	180
PV Market, Value, and Policy Analysis	436
System Reliability and Cost Analysis	150

3. Results and Accomplishments

The primary objective of the modeling and benchmarking activities during FY 2006 was to continue development of the PV portions of the Solar Advisor Model, to carry out analyses to determine the overall LCOE for fielded PV systems in key reference applications, and to apply projections of technology improvements to determine future-year costs and overall targets. The results of this process provided direct support to completion of the Multi-Year Program Plan early in the year, and implementation of the Solar America Initiative later.

Further refinement to PV system benchmark data focused mainly on residential installations and costs related to O&M of these systems. This was done in partnership with Tucson Electric Power, through monitoring and tracking of its installed systems. Table 1 lists some key characteristics of the residential reference system. The “baseline” system configuration uses crystalline silicon modules with an efficiency of 13.5% that are located in Tucson, AZ. These costs are typical of the systems supported by cost sharing under the Arizona renewable portfolio standard. The new information related to O&M provides a starting point for further investigation and for applying the Systems-Driven Approach to define and execute technology improvements in line with the goal of reducing overall levelized energy costs for residential systems.

Table 1. Characteristics of Residential PV System as Reference Application

	Residential
Sys Power (kW)	1.2-5.9
Module Cost ($/Wdc)	3.14
Inverter ($/Wdc0	1.04
Installation ($/Wdc)	1.67
Overhead/Profit ($/Wdc)	1.47
Installed Price ($/Wdc)	7.32
O&M[a] (%)	1.7[b]

[a]O&M is listed as percent of initial capital cost per annum.
[b] O&M equates to about $.09/kWh

As part of the efforts to further develop and refine benchmarking data for residential PV systems, a set of telephone interviews was conducted with PV suppliers and installers to gain insight into two areas. The first was to further refine the cost categories into which installation procedures and balance-of-system (BOS) components can be divided. The second was to then populate these categories. These insights can further feed the Systems-Driven Approach as a basis for the development of more detailed cost models and to study the relative impacts of technology and design changes on overall LCOE for installed systems.

This study of residential grid-tied systems resulted in the identification of two areas for technical improvement through partnership with PV module and BOS manufacturers:

- The accuracy and credibility of Standard Test Conditions (STC) ratings for PV modules can and should be improved through the development of standardized procedures, including statistical sampling and measurements in the UL process. Through implementation of such a process, module specification sheets would be a more reliable source of information for system design.
- The reliability and accuracy of measurements by power electronics equipment (i.e., inverters) must be improved. System installation costs can be reduced using these measurements when combined with intelligent reporting capability and wireless technology.

In partnership with a major Arizona electric utility, an initial cost study was conducted of a one-axis tracking system, comparing tradeoffs between crystalline and thin-film module technologies. Cost categories included component and installation cost and the tradeoffs related to differences in efficiency and BOS components. For the case based on the most likely cost structure in this study, thin-film system cost is approximately 13% higher than for the crystalline silicon baseline system cost of $5.15/Wdc.

4. Planned FY 2007 Activities

- Continue to develop a suite of analysis, modeling, and benchmarking tools that are needed for the Solar Energy Technologies Program’s planning, technology evaluation, and decision-making (e.g., stage gate).
- Partner with the U.S. PV and CSP industries to improve and advance systems design tools development, component and systems performance database development, systems performance prediction tools, and market penetration models.
- Exercise the Solar Advisor Model in support of the Solar America Initiative.
- Focus benchmark activities to directly support the SAI Technology Pathway Partnerships.

- Take full advantage of relationships and access to information offered by the monitoring of selected SAI Technical Pathway Partnerships.
- Fully implement Web-based distributed PV cost-benefits clearinghouse.
- Complete beta version of SolarDS model for external use and feedback.
- Continue to support the GRPA process.

5. Major FY 2006 Publications

Denholm, Paul, and Robert M. Margolis, "Very Large-Scale Deployment of Grid-Connected Solar Photovoltaics in the United States: Challenges and Opportunities," paper presented at *Solar 2006*, Denver, CO, July 9–13, 2006

Denholm, Paul, Ken Zweibel, and Robert M. Margolis, "Tackling Climate Change in the U.S.: The Potential Contribution from Solar Photovoltaics," paper presented at *Solar 2006*, Denver, CO, July 9–13, 2006.

Margolis, Robert M., Richard Mitchell, and Ken Zweibel, "Lessons Learned from the Photovoltaic Manufacturing Technology/PV Manufacturing R&D and Thin-Film PV Partnership Projects. Golden, CO: National Renewable Energy Laboratory, NREL Technical Report (NREL/TP-520-39780). September, 2006.

Margolis, M. Robert and Jarett Zuboy,. "Nontechnical Barriers to Solar Energy Use: Review of Recent Literature." Golden, CO: National Renewable Energy Laboratory. NREL Technical Report (NREL/TP-520-40116), September, 2006.

Moore, Larry, Harold Post, Tom Hansen, Terry Mysak, "Residential Photovoltaic System Experience at Tucson Electric Power," internal draft.

Perez, Richard, Robert Margolis, Marek Kmiecik, and Marc Perez, "Update: Effective Load Carrying Capability of Photovoltaics in the United States," paper presented at *Solar 2006*, Denver, CO, July 9–13, 2006.

U.S. Department of Energy, *Solar Energy Technologies Program Multi-Year Program Plan 2007–2011*, DOE Office of Energy Efficiency and Renewable Energy, Washington, DC. January, 2006.

Wiser, Ryan, Mark Bolinger, Peter Clappers, and Robert Margolis, "Letting the Sun Shine on Solar Costs: An Empirical Investigation of Photovoltaic Cost Trends in California." Golden, CO: National Renewable Energy Laboratory, NREL Technical Report (NREL/TP-620-39300), January, 2006.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2006 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
Clean Power Research Thomas Hoff	Napa, CA tomhoff@clean-power.com	Designing Incentives for Customer-Owned PV Systems	100
Lawrence Berkeley National Laboratories Ryan Wiser	Berkeley, CA RHWiser@lbl.gov	Providing Technical Assistance to the CPUC During the Design and Implementation of the California Solar Initiative	100
SENTECH, Inc. Jonathan Hurwitch	Bethesda, MD jwitch@sentech.org	Case Study of a PV-Covered Parking Installation	5
MRG & Associates Marshall Goldberg	Nevada City, CA mrgassociates@earthlink.net	Development of Jobs and Economic Development Impact Models	12

Building-Integrated Photovoltaics

Performing Organizations: National Renewable Energy Laboratory (NREL)
DOE Golden Field Office (DOE/GO)

Key Technical Contacts: Cécile Warner (NREL, Primary Contact), 303-384-6516, cecile_warner@nrel.gov
Glenn Doyle (DOE/GO), 303-275-4706, glenn.doyle@go.doe.gov

DOE HQ Technology Manager: Richard King, 202-586-1693, richard.king@ee.doe.gov

FY 2006 Budget: $2,260 K (NREL)

Objectives

- Conduct the next Solar Decathlon university competition of 100% solar-powered homes, which demonstrate building-integrated photovoltaic (BIPV) and solar technologies in marketable residential applications.
- Support deployment of BIPV technologies through subcontracted R&D projects in BIPV and through development of a greater understanding of BIPV system performance.
- Accelerate adoption of BIPV in new residential and commercial construction through technical assistance and successful collaborative partnerships.

Accomplishments

- Concluded the implementation of the 2005 Solar Decathlon university competition, releasing the final regulations, solidifying sponsors, supporting teams, scoring, monitoring, and carrying out all aspects of the event. (October 2005)
- Held "Building Industry Day" for builders at the Solar Decathlon. (October 2005)
- Developed and released a solicitation for the 2007 Solar Decathlon event. (October 2005)
- Selected teams for the 2007 Solar Decathlon and launched the activities leading toward execution of the 2007 event. Awarded 2-year, $100,000 contracts to these 20 teams. (September 2006)
- Published the technical report, *Solar Decathlon 2005: The Event in Review*. (May 2006)

Future Directions

- Conduct the 2007 Solar Decathlon in the first quarter, FY 2008, and release a solicitation for the 2009 event.
- Monitor and guide the development of BIPV through the subcontracted university programs.
- Assess performance of selected, occupied former Solar Decathlon entries to assess longer-term implications of PV in buildings.
- Continue and expand productive interactions with the building industry.

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1. Introduction

The Building-Integrated PV (BIPV) Project fosters the widespread acceptance of PV-integrated buildings by overcoming technical and commercial barriers and by facilitating the integration of PV into the built environment through technology development, applications, and key partnerships. Through this project, PV will become a routinely accepted building technology in the 21st century.

2. Technical Approach

The project's goal is to develop and facilitate widespread adoption of PV in the built environment, resulting in solar-powered homes and businesses that demonstrate building-integrated PV and solar technologies in marketable applications and partnerships that build on successes. There are two interrelated activities within this overall effort, which are the Solar Decathlon and R&D on PV in buildings.

2.1 Conduct the 2005 Solar Decathlon

The Solar Decathlon is an intercollegiate competition to design, build, and operate the most attractive and energy-efficient solar-powered home. Eighteen teams of students from the United States, Canada, and Spain competed in the 2005 event. Teams were selected through a competitive procurement in 2003 and worked on their projects over the intervening 2 years under our supervision and guidance. They transported their houses to the National Mall in Washington, D.C., where they built a “solar village” and opened their homes to the visiting public from October 7 to October 16, 2005. They competed against one another in ten contests that tested the teams’ abilities to produce electricity and hot water from solar panels to perform all the functions of home—from turning on the lights to cooking, washing clothes and dishes, powering home electronics, and maintaining a comfortable temperature. These homes were also required to provide the power for an electric car. In addition to the energy-related contests, each team was judged on its home's architecture and livability. And expert homebuilders evaluated each home’s “build-ability” (ease of construction and replication of design). The teams provided documentation about their homes’ designs and communicated about their homes to the public. We hosted a Web site that informed visitors about the competition and scoring.

Production of the event, including scoring, selection of judges, review of designs, instrumentation, development of communications materials and review of exhibit designs, coordination of teams, sponsors, and volunteers, procurement of stagecraft and assembly of the village, and safe conduct of the entire event comprised the activities of this project for the NREL organizers and its subcontractors. Some contests were scored by measuring performance, and others were scored by judges representing expertise in appropriate fields. For more information, visit the Solar Decathlon Web site (www.solardecathlon.org). The primary sponsors of the 2005 Solar Decathlon were the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy, with its National Renewable Energy Laboratory, the American Institute of Architects, the National Association of Home Builders, and private-sector sponsors BP, the DIY Network, and Sprint-Nextel.

2.2 Develop and Release Solicitation for 2007 Solar Decathlon Event

While preparing for the 2005 event, the concept for expanded BIPV R&D at the universities participating in the 2007 event evolved, culminating in the development of a solicitation for the 2007 event (prepared by NREL), which was announced by the Secretary of Energy in early October at the start of the 2005 event. New to this solicitation, each winning university proposal was set to receive $100K in research funding (over two years) to support the innovative development of BIPV technology in its entry

2.3 Plan Post-Decathlon Monitoring Program

A PV building benchmarking effort to assess long-term performance of occupied Solar Decathlon homes after the competition was developed during FY 2006. A comprehensive monitoring and instrumentation plan, together with a building simulation and modeling effort, was conceived, with the goal of understanding and improving the design and performance of BIPV homes.

Task Title	FY 2006 Budget ($K)
Solar Decathlon (NREL)	2,160*
PV in Buildings R&D	100

* Includes activities that are reported in the Communications and Outreach section of the annual report.

3. Results and Accomplishments

3.1 Major Accomplishment: Solar Decathlon 2005

During FY 2006, we successfully carried out the 2005 Solar Decathlon, held September 29–October 19, 2005 on the National Mall in Washington, D.C. Activities included scoring for the 10 contests; expert judging for contest such as dwelling, architecture (see Fig. 1), engineering, Web sites, and house tours; review of team designs for code and regulation compliance; instrumentation system development, acquisition, and shakedown, as well as installations of equipment; distribution of communications materials (brochures, media kits, official program, Web site materials, and graphics); coordination of teams; coordination of sponsors; coordination of volunteers (including a procurement for management of volunteers); procurement of stagecraft and assembly of the solar village; and execution of procedures for safe conduct of the entire event. We managed crowds of more than 100,000 visitors to the Solar Decathlon and a massive media interest to view the future of solar energy and the next generation of solar practitioners and solar homes.

Fig. 1. At the 2005 Solar Decathlon, the Architecture Jurors debated the merits of each entry, including the pictured New York Institute of Technology home.

3.2 Major Accomplishment: Solicit and Select Teams for the 2007 Solar Decathlon and Launch the Activities Leading toward Execution of the 2007 Event

We selected 20 teams (from proposal responses to a solicitation) to participate in the 2007 Solar Decathlon (see Section 6 for a list). In the 2005 event, teams were encouraged to use building-integrated PV systems, but were not explicitly scored on the degree to which they implemented BIPV, except as evaluated by the aesthetic assessment of the Architecture Jury. Because BIPV development is a major goal of the DOE Solar Program, in the upcoming 2007 Solar Decathlon, the teams will be more explicitly scored on their ability to innovate in BIPV applications and the execution of cost-effective BIPV techniques for their entries.

Milestones Supported by DOE Funding

Milestone or Deliverable	Due Date	Status
Carry out Solar Decathlon 2005 event on the National Mall in Washington, D.C., beginning September 29, 2005.	11/1/05	Complete
Announce participants in the 2007 event.	1/31/06	Complete

4. Planned FY 2007 Activities

- Convene a workshop for the 2007 Solar Decathlon Teams in the first quarter, FY 2007.
- Continue the activities leading toward execution of the 2007 Solar Decathlon event.
- Monitor and guide the development of BIPV through the subcontracted university programs and through evaluation of long-term performance of selected entries.
- Develop a solicitation for teams and for subcontracted production of the 2009 Solar Decathlon.

5. Major FY 2006 Publications

Cécile L. Warner and Michael R. Wassmer, “Solar Decathlon 2005—PV System Strategies and Results.” *Proc. WCPEC, May 2006, Waikoloa, HI*, (2006).

Susan Moon, Ruby Nahan, Cécile Warner, and Michael Wassmer, *Solar Decathlon 2005: The Event in Review*, 62 pp., DOE/GO-102006-2328 (2006).

U.S. DOE, *Solar Decathlon Web Site,* www.solardecathlon.org.

6. University and Industry Partners

The following organizations partnered in the project's activities during FY 2006. Twenty teams were selected in FY 2006 to compete in the 2007 Solar Decathlon. DOE will award the selected teams $100,000 over two years to support the Solar Decathlon's research goal of reducing the cost of solar-powered homes and advancing solar technology. In most cases, this amount is less than half of the funds needed to mount a Solar Decathlon entry. Team members dedicate considerable time, energy, and ingenuity to enlisting community and industry support for the remaining funding.

Organization/ Principal Investigator or Contact	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
Colorado Code Consulting, LLC Thomas Meyers	Berthoud, CO codeconsultant@gmail.com	Complete three plan reviews of 20 sets of drawings and specifications and perform 20 on-site building inspections of the competition houses after they are installed on the National Mall in fall 2007, for the Solar Decathlon competition	70
Carnegie Mellon University Stephen R. Lee	Pittsburgh, PA stevelee@cmu.edu	2007 Solar Decathlon team	50
Cornell University Zellman Warhaft	Ithaca, NY zw16@cornell.edu	2007 Solar Decathlon team	50
Georgia Institute of Technology Chris Jarrett	Atlanta, GA chris.jarrett@coa.gatech.edu	2007 Solar Decathlon team	50
Kansas State University R. Todd Gabbard	Manhattan, KS rtodd@ksu.edu	2007 Solar Decathlon team	50
Lawrence Technological University Philip Plowright	Southfield, MI pplowright@ltu.edu	2007 Solar Decathlon team	50
Massachusetts Institute of Technology Kurt Keville	Cambridge, MA kkeville@mit.edu	2007 Solar Decathlon team	50
New York Institute of Technology Thomas Rochon	New York, NY thomas@thomasrochon.com	2007 Solar Decathlon team	50
Pennsylvania State University David R. Riley	University Park, PA driley@engr.psu.edu	2007 Solar Decathlon team	50
Santa Clara University Jorge E. Gonzalez	Santa Clara, CA jgonzalezcruz@scu.edu	2007 Solar Decathlon team	50
Team Montréal (École de Technologie Supérieure, Université de Montréal, McGill University) Hughes Rivard	Montréal, Quebec, Canada hughes.rivard@etsmtl.ca	2007 Solar Decathlon team	50
Technische Universität Darmstadt Manfred Hegger	Darmstadt, Germany fg@ee.tu-darmstadt.de	2007 Solar Decathlon team	50
Texas A&M University Pliny Fisk	College Station, TX pfisk@cmpbs.org	2007 Solar Decathlon team	50
Universidad Politécnica de Madrid José Manuel Paéz Borrallo	Madrid, Spain upm_faculty_contact@solar decathlon.upm.es	2007 Solar Decathlon team	50

Organization/ Principal Investigator or Contact	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
Universidad de Puerto Rico Rafael A. Olivencia-Martínez	Mayagüez, Puerto Rico solar@uprm.edu	2007 Solar Decathlon team	50
University of Colorado Michael Brandemuehl	Boulder, CO michael.brandemuehl@colorado.edu	2007 Solar Decathlon team	50
University of Cincinnati Dale L. Murray	Cincinnati, OH dale.murray@uc.edu	2007 Solar Decathlon team	50
University of Illinois Ty Newell	Urbana, IL tynewell@uiuc.edu	2007 Solar Decathlon team	50
University of Maryland Amy Gardner	College Park, MD turbine@umd.edu	2007 Solar Decathlon team	50
University of Missouri - Rolla Stuart W. Baur	Rolla, MO baur@umr.edu	2007 Solar Decathlon team	50
University of Texas at Austin Samantha Randall	Austin, TX samrandall@mail.utexas.edu	2007 Solar Decathlon team	50

Million Solar Roofs Initiative

Performing Organizations:	DOE Headquarters and Regional Offices (ROs) National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL) Interstate Renewable Energy Council (IREC) National Energy Technology Laboratory (NETL)
Key Technical Contacts:	Carol Tombari (NREL, Primary Contact), carol_tombari@nrel.gov John Thornton (NREL, Technical Contact); Charles Hanley (SNL); Denise Riggi (DOE/NETL)
DOE HQ Technology Manager:	Glenn Strahs, 202-586-2305, glenn.strahs@ee.doe.gov
FY 2006 Budgets:	$250K (NREL), $100K (SNL), $200K (DOE/ROs), $300K (DOE/IREC)

Objectives

- Facilitate the reduction of institutional barriers to marketplace adoption of Million Solar Roofs (MSR) technologies (PV, solar domestic water, pool heating, and solar thermal heating).
- Help to develop local and regional markets for solar technologies by working with communities to identify and encourage new applications.

Accomplishments

- Closed out program. Regional DOE Offices closed.
- Published final report, held wrap-up meeting in fall 2006 at Solar Electric Power Association Conference.
- Provided limited engineering support, economic analysis, and directed market studies for MSR Partnerships. Segue Consulting, NREL's subcontractor, responded to many technical assistance e-mail requests from the partnerships and prepared analyses ranging from 2–20 pages.

Future Directions

- None. Project concluded in FY 2006, per DOE new priority direction.

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1. Introduction

The objective of the Million Solar Roofs Initiative was to facilitate the installation of solar energy systems (PV, solar domestic water, pool heating, and solar thermal heating) on all types of buildings throughout the United States. The initiative supported the development of local and regional markets for solar technologies by working with states and local communities to address and remove institutional barriers.

In addition to helping create markets, MSR has provided the Solar Program with critical feedback on performance and consumer preferences.

2. Technical Approach

To achieve its objective, MSR worked through a nationwide network of officially designated partnerships and their local partners. Businesses, utilities, government agencies, and/or advocacy groups interested in official partnership status were required to commit to facilitating the installation of a specified number of "solar roofs" by 2010. These partnerships used a variety of means to build markets in their local communities, including: identifying and addressing local barriers; using solar technologies to meet important public policy goals; leveraging state and local incentives for solar; and educating the next generation of consumers and their parents.

3. Results and Accomplishments

Investing in solar equipment directly would have required a large amount of funding to make an impact, so MSR invested in people instead. Between 1997 and 2005, 94 coalitions across the country signed on with DOE as official MSR partnerships. These partnerships comprised 971 private sector firms, electric utilities, builder/developers, nonprofit organizations, and governmental entities—all voluntarily committed to facilitating the installation of a specified number of "solar roofs." This fundamental metric, embedded in the program name, gave the program an outcome-oriented focus.

Key areas where MSR made significant contributions were in addressing barriers to technology acceptance and market expansion efforts, and developing best practices examples for market transformation.

The national network of local partnerships imbued the program with a grassroots nature and exemplified successful public-private collaboration. DOE invested 68% of its program funding in competitively awarded grants to these partnerships, which focused on reducing barriers to technology acceptance and on expanding the market for solar technologies.

The remaining funds supported the participation of the Interstate Renewable Energy Council (IREC), technical experts, and national laboratories in the core program team, providing expert underpinnings for the program, as well as a built-in feedback mechanism from the marketplace to the R&D community and solar industry.

When the program concluded, the Federal government's investment of $16 million had leveraged roughly $7.1 million in cash; it also leveraged in-kind resources and incentive programs throughout the country. This synergy has contributed to the following outcomes:

- Installation of the equivalent of more than 377,000 solar water heating, photovoltaic (PV), and solar pool heating systems
- Installation of 200 MW of grid-connected PV capacity and 200 MW_{th} of solar water heating capacity
- Dramatic growth in PV technology acceptance, from 8% of solar installations in 1997 to 41% in 2005
- Economic and environmental benefits that resulted from grid-connected PV installed between 1997 and 2005, including:
    - Health benefit savings of $90 million
    - Decreased CO_2 emissions of 3.3 million tons
    - Cumulative GNP increase of $1.6−$2.6 billion, depending on installed cost (range of $8–$10/watt)
    - Increase in job-years of 23,000 to 31,000.
- MSR conducted more than 26 peer exchange workshops, attended by more than 650 people. More than 79% of MSR's partners attended at least one workshop. Between 2003 and 2005, some 910 people participated in 10 interactive telephone seminars.

In addition, MSR efforts contributed to the body of knowledge about best practices for facilitating market transformation and technology diffusion.

Task Title	FY 2006 Budget ($K)
MSR Project Management (DOE/RO)	200
Technical Assistance through NREL	250
Performance Coordination with SNL	100
Communication and Outreach Support through IREC	300

4. Planned FY 2007 Activities

- None. Project concluded.

5. Major FY 2006 Publications

G. Strahs, C. Tombari, "Laying the Foundation for a Solar America: the Million Solar Roofs Initiative, Final Report" 43 pp.; NREL Report BK-710-40483 (October 2006).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2006 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
Segue Consulting Christy Herig	Redington Shores, FL cherig@tampabay.rr.com	Economic, regulatory, financial, and value analysis (individualized response to technical assistance requests; generic analysis and document production)	106
Interstate Renewable Energy Council Jane Weissman	Latham, NY jane@irecusa.org	Communication and outreach activities aimed at the 91 MSR Partnerships and their participating members	300

Regional Experiment Stations

Performing Organizations: Sandia National Laboratories (SNL)
DOE Golden Field Office (DOE/GO)

Key Technical Contacts: Michael Quintana (SNL), 505-844-0574, maquint@sandia.gov
Glenn Doyle (DOE/GO), 303-275-4706, glenn.doyle@go.doe.gov

DOE HQ Technology Manager: Dan Ton, 202-587-4618, dan.ton@ee.doe.gov

FY 2006 Budget: $1,750K (DOE/GO)

Objectives

- Team with the national laboratories to meet Solar Program Annual Operating Plan objectives and milestones.
- Position photovoltaics (PV) systems and technologies to become a cost-effective, major source of energy for the United States.
- Assure that education, training, outreach, and technical support required to accelerate the rate of the nation's PV deployment efforts are available and effectively implemented to support growth of the PV market.
- Provide leadership and/or support for: (1) systems, module, and inverter testing, (2) creating and implementing procedures, codes, and standards for quality, safe, and cost-effective installed systems, (3) hardware certification, and (4) addressing system engineering issues observed in fielded systems.
- Provide technical support to DOE, national laboratories, and industry in the execution of the Solar America Initiative (SAI).

Accomplishments

- Transitioned former Regional Experiment Station (RES) annual earmark-funded contract to a three-year, program-funded, and cost-shared contract through DOE/GO.
- Continued long-term operation and monitoring of five inverters (Fronius, PV Powered, SMA, Solectria, and Xantrex) at each RES.
- Southeast Regional Experiment Station (SERES) and Southwest Regional Experiment Station (SWRES): Developed the first implementation plan for the Photovoltaic Systems Assistance Center (PVSAC). Identified nine outstanding board members and held the first PVSAC Board of Advisors meeting for additional planning and guidance.
- SERES and SWRES: Participated in Federal Opportunity Announcement (FOA) Technical Committee to determine accuracy of all data submitted in SAI Technology Pathway Partnership (TPP) proposals.
- SWRES: Assisted the town of Woodside, CA, in developing and implementing a standardized process for permitting of PV plans.
- SERES and SWRES: Continued work with eight countries through the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) Task 2 to expand the comprehensive PV database containing performance and economic data for selected countries, including the United States, Germany, and Japan.
- SWRES: Developed industry survey form for use by Test and Evaluation Team in assessing industry needs, existing data, and level of support required.
- SWRES: Participated in final review for the California Energy Commission $35M PIER Commonwealth Energy Renewables Resources Program.
- SERES: Completed more than 200 PV System Design Reviews for the U.S. Department of Agriculture (USDA), as part of its Renewable Energy Program, and for the State of Florida.
- SERES: Completed four weeklong training programs for PV Installers. About 80 people were trained this year.

- Provided design reviews and acceptance testing for PV systems operated by the U.S. Virgin Islands Energy Office to encourage the Water and Power Authority to permit interconnection of PV systems to the grid.
- SERES: Continued detailed monitoring of grid-connected PV systems to the utility in Florida and other states.
- SERES: Continue testing the performance of commercially available PV modules to compare our results with those from industry.
- SERES: Worked with several modular homebuilders in the design of PV systems. One such system will be on display at the International Builders Show in Orlando, FL.

Future Directions

- Support DOE/GO administration of the RES cooperative agreements by implementing technical activities to meet R&D emphases, assuring that milestones align with program priorities and that deliverables are met on time.
- Present the PV System Assistance Center function that was a hallmark of the SNL/RES programs of the 1990s and transition this into a nationwide resource.
- Develop advanced PV designs for integrated manufacturing and deployment.
- Conduct a continuous review of activities to improve alignment with the Systems-Driven Approach.
- Continue to evolve priorities to remove barriers to PV system deployments in targeted markets, targeted regions, and nationwide.
- Continue monitoring the performance of new PV systems entering the market, with a focus on evolving PV products and high-value/profile applications such as disaster shelters.

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1. Introduction

The Southeast and Southwest Regional Experiment Stations (SERES and SWRES, respectively) are partners in the DOE Solar Program. Each RES has a university affiliation (University of Central Florida for SERES and New Mexico State University for SWRES) and university-level capabilities, which have been developed over the years to provide systems-level R&D for DOE, the U.S. PV industry, other government agencies, and PV consumers. The RES work is aligned with activities conducted in the Technology Development and Advanced Materials and Devices portion of the DOE PV Subprogram.

RES goals are to provide value-added technical support to the Solar Program that effectively and efficiently meets the R&D needs identified by the Systems-Driven Approach in pursuit of targets specified by the *DOE Solar Program Multi-Year Program Plan.*

The Regional Experiment Stations have contributed to the DOE National Photovoltaic Program for two decades. This work is integrated into DOE's Annual Photovoltaic Program plan and is highly collaborative. Throughout the years, RES support has been an integral part of program projects, such as:

1. Module Reliability R&D
2. Inverter and Balance-of-System Development
3. PV Systems Engineering
4. Domestic PV Applications
5. System Evaluation and Optimization
6. PV System Analysis
7. Education and codes and standards development.

Collaborations with SNL, NREL, the National Center for Photovoltaics (NCPV) R&D partners, and industry counterparts are focused on reducing systems costs, improving systems reliability, improving system performance, and removing barriers to deployment, thereby promoting market growth.

2. Technical Approach

Work conducted by the Regional Experiment Stations builds on expertise with fielded systems that is unique to the DOE Solar Program. Expertise acquired as a result of extensive field investigations provides a system perspective that is the foundation for solving technical problems that are barriers to widespread deployment. A high volume of requests from the PV industry, as well as the alignment to an evolving *U.S. PV*

Photovoltaic Program, provides continuous feedback on the relevance of RES activities. The following tasks describe the technical approach to applying the RES capabilities in pursuit of DOE and industry needs.

2.1 PV Systems Assistance Center

The PVSAC is a virtual laboratory comprising engineers and staff from both of the RES. The objective of the PVSAC is to become a national one-stop resource for public policy support, design reviews, specialized training and training materials, and technical field-support activities. In this way, the PVSAC will be a major gateway for technical education, training, and outreach to the U.S. PV community.

The PVSAC will impanel a board of advisors, with whom they will develop a comprehensive strategic plan for PVSAC prioritization of activities. The board will provide annual review of progress and revise PVSAC planning to reflect changes in the needs of the U.S. PV community.

2.2 Infrastructure Development

This activity consists of training, design review and approval, and codes and standards development activities. Training occurs through multiple venues and in several subject areas. A key issue with fielded systems is poor installation, which has been addressed consistently by the RES staff. Activities began by providing training to interested parties and have evolved to the creation and establishment of a National Installer Certification Program, an independent activity that the RES's were instrumental in creating. Similarly, training of inspectors and installers is now evolving to a system of "training the trainers," providing an opportunity to reach a greater audience while minimizing investment.

Technical assistance to the industry and users has resulted in an evolving design review and approval standard that provides guidance for uniform designs and system documentation. This activity promotes a level of quality recognized and practiced by other industries that provide recognized products in successful markets.

Development of codes, standards, and certification addresses compliance to a set of prescribed recommendations in order to assure quality and safety. The RES's proactive approach provides the opportunity to guide development of codes and standards that assure performance, quality, and safety without creating a cost burden for the industry. Certification of hardware creates and applies a uniform set of standards in a recognizable format that instills consumer confidence. Certification is also the basis for assuring optimal awards from government incentive programs.

2.3 Long-Term Component Testing

The RES's provide unique environments for environmentally stressing PV components. Initially, they provided long-term exposure in hot/dry and hot/humid climates for stressing PV modules deployed in a field-like setting. More recently, a similar approach has begun to study the long-term performance of inverters in field-like outdoor configurations. Additional activities include placing the inverters in a distributed-generation scenario to address issues associated with controls and generator interactions. Both of these activities are complementary to SNL's baseline tests, which establish initial component performance parameters

3. Results and Accomplishments

- Trained more than 300 code officials in one-day workshops in New York, California, Colorado, Minnesota, and Texas.
- Performed complete assessment of utility-scale PV power plants in Tucson, AZ, and San Mateo, CA, for performance, reliability, and cost benchmarks.
- John Wiles (SWRES) served as Secretary of the PV Industry Forum; drafted recommended changes to the 2008 *National Electrical Code.*
- SWRES and SERES: Participated in FOA Technical Committee review of all data submitted in TPP SAI proposals.
- SWRES: Provided design reviews to dozens of major PV system developers (e.g., PowerLight, RWE Schott Solar) and purchasers (e.g., utilities, Federal agencies) for code compliance and proper design.
- SERES: Provided design reviews for more than 200 PV systems for both the USDA and the State of Florida. This includes systems using equipment from companies such as Solarworld, Solar Integrated Technologies, Beacon Power, SMA America, Sharp, Xantrex, and Sunwize.
- SERES: Provided module performance testing for eight modules from companies such as GE, Sharp, Sanyo, and Sunwize.
- SWRES and SERES: Provided testing and analysis of c-Si and thin-film modules in

support of the Module Long-Term Exposure Program.

- SWRES: Begin process of obtaining American Association of Laboratory Accreditation (A2LA) for PV system testing laboratories in accordance with ISO 17025.
- SERES: Continued our accreditation from the American Association of Laboratory Accreditation and Powermark to certify both completely integrated PV systems and PV module performance.

4. Planned FY 2007 Activities

RES projects will focus on the following tasks:

- Design and implementation of the PV Systems Assistance Center Web pages
- PV systems analysis and engineering
- Codes and standards development
- R&D of advanced system concepts.

Expected results for FY 2007 include the following:

- Continuing update of 2006 benchmarking, including evaluation of first-year Technical Improvement Opportunities for the Solar Program.
- Continued work to resolve codes and standards differences between the European Union and the United States.
- Gather inverter long-term performance data and participate with SNL in the creation of a well-defined and documented inverter model.
- Refinement of the PV Systems Assistance Center and introduction to the U.S. PV community. PVSAC will work to provide outreach, training, support, and Web development to get the maximum system information into the hands of the designers, installers, and policy makers who require it.
- Continued work in PV module performance testing and design review work.
- Maintain ISO 17025 accreditation in PV module performance testing and PV system design review.

5. Major FY 2006 Publications

A. Rosenthal, *SMUD Performance Index Program and Results–Final Report*, Submitted, March 2006.

J. Wiles, "Recent Changes in the National Electrical Code," Presented at the DOE Annual Program Review, Q4 2005.

A. Rosenthal, *Salt River Project Performance Index Program User's Manual*, Submitted, May 2006.

J. Wiles, "Making the Utility Connection," *Home Power Magazine*, March 2006.

J. Wiles, "Working with Inspectors," *Home Power Magazine,* February 2006.

J. Wiles, "Back to the Grid," *International Association of Electrical Inspector News,* January 2006.

J. Wiles, "Plan Check," *International Association of Electrical Inspector News*, March 2006.

K. Lynn, W. Wilson, "Early Results from the Long-Term Testing of Inverters," *Proceedings of ASME International Solar Energy Conference,* July 8–13, 2006, Denver, CO.

K. Lynn, J. Szaro, W. Wilson, M. Healey, "A Review of the PV System Performance and Life-Cycle Cost for the SunSmart Schools Program," *Proceedings of ASME International Solar Energy Conference,* July 8–13, 2006, Denver, CO.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2006 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2006 ($K)
Florida Solar Energy Center Kevin Lynn	Cocoa, FL klynn@fsec.ucf.edu	PV System Research	875
Southwest Technology Development Institute Andrew Rosenthal	Las Cruces, NM arosenth@nmsu.edu	PV System Research	875