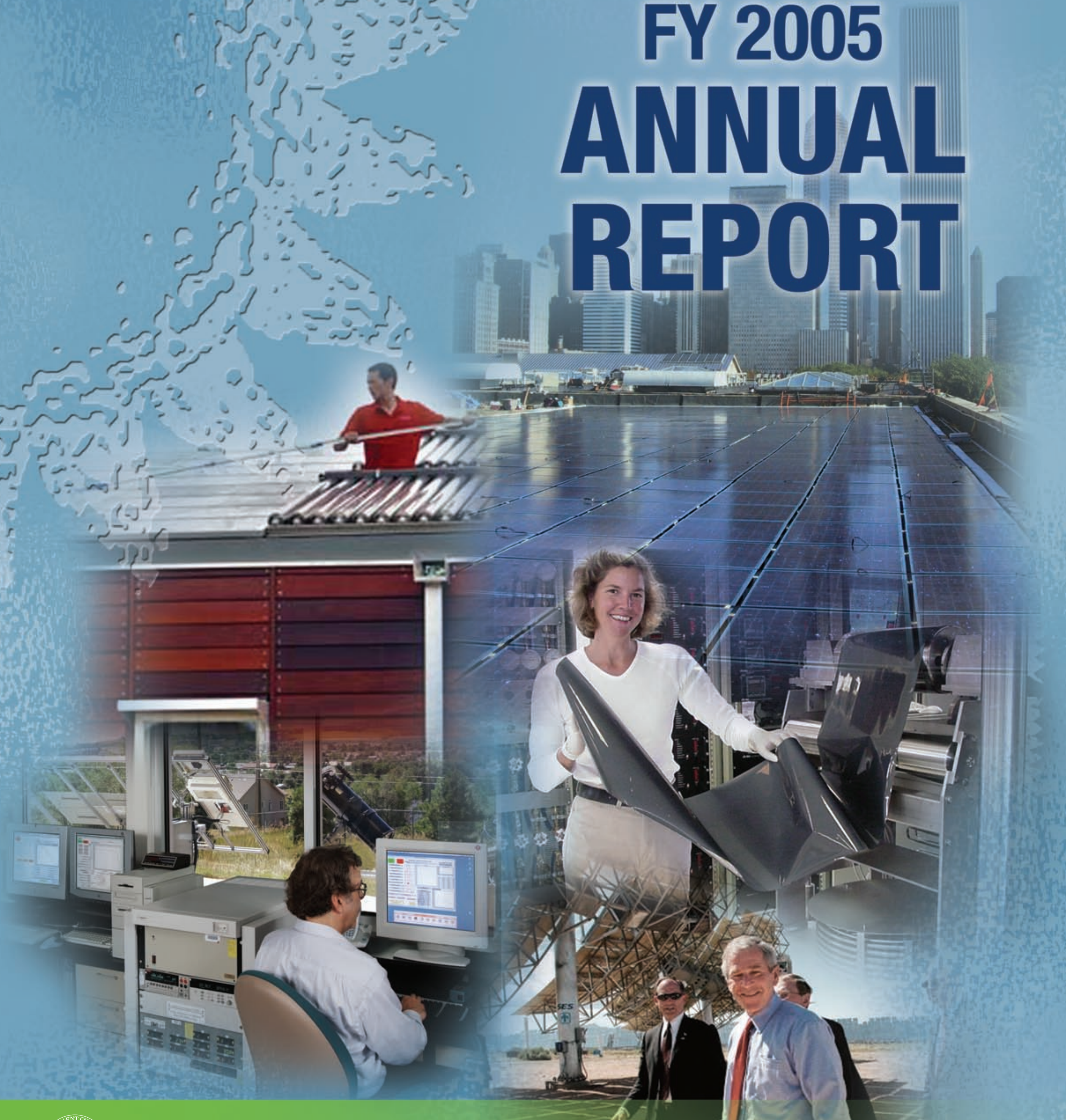
DOE Solar Energy Technologies Program

FY 2005 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 (clockwise from lower right):

On August 8, 2005, President George W. Bush visited the National Solar Thermal Test Facility at Sandia National Laboratories as part of his signing of the Energy Bill. *R.J. Montoya Photo*

National Renewable Energy Laboratory researchers use a computer-controlled data acquisition system at the laboratory's Outdoor Test Facility to characterize the performance and reliability of PV cells and modules. *Jim Yost, PIX14094*

A Cornell University student cleans the solar-powered rooftop of his team's entry in preparation for the 2005 Solar Decathlon competition in Washington, D.C. *Stefano Paltera/Solar Decathlon*

Global Solar Energy, a member of the Thin Film PV Partnership, produces PV material by depositing CIGS (copper indium gallium diselenide) on a lightweight, flexible polymide substrate in roll form. *Global Solar Energy, PIX13419*

The DOE Solar Energy Technologies Program

Raymond A. Sutula, Manager, 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 energy 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.

This is a great time to be involved with solar energy. Photovoltaic (PV) systems are being installed in the United States and around the world in unprecedented quantities. The concentrating solar power industry has broken ground on its first major plant in more than 10 years, and, with strong support from the Western Governor's Association, more plants are planned over the next few years. One of the largest segments of the solar industry is solar pool heating, and we are working with U.S. industry to leverage this expertise into new solar water heating products for residential and commercial use.

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

The Solar Program consists 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, covers crosscutting activities that reflect a new Systems-Driven Approach to managing the Solar Program. This subprogram provides 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.

This subprogram is divided into five crosscutting areas:

- Systems Integration and Coordination
- Technology Portfolio Integration
- Stakeholder Collaboration
- Communications, Education, and Outreach
- Planning, Budget, and Analysis

Future Program Direction

We have ambitious plans for the next few years. Our focus is on realizing the benefits identified for EERE in the Government Performance and Results Act (GPRA) of 1993. The principal metric is gigawatts of capacity (electric or equivalent) installed in the United States during the mid- and long-term horizon. To accomplish these goals, our efforts must impact markets whose potential size can be measured in gigawatts. And, we must meet levelized energy cost goals that will open those markets.

Analytical techniques, based on the Systems-Driven Approach, are used to optimize our research portfolio. We must 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.

Our multi-year program plan, annual operating plan, and subcontracts contain robust milestones, as defined in the stage-gate model for both commercialization and research paths. With the assistance of external experts, we continue to evaluate proposed activities and milestones against a number of criteria, such as strategic fit, market impact, technical feasibility and risk, critical success factors and showstoppers, and plans to proceed. The stage-gate process is being applied to graduate programs to the next phase or to recycle, suspend, or end efforts.

On top of all this, we have some major events scheduled. The biggest one is the Solar Decathlon in October 2005—an effort that is being closely worked on not only by us, but also by our top management at DOE. The inaugural event in 2002, which featured teams of college students vying to design and build the most effective solar-powered house, captured the attention of the American public. It put solar technologies on center stage for several weeks before, during, and after the competition, and we expect even bigger results in 2005.

About This Report

In the body of this report, you will read about R&D results and achievements from across our Program. The work performed at the participating DOE national laboratories—National Renewable Energy Laboratory, Sandia National Laboratories, Oak Ridge National Laboratory, and Brookhaven National Laboratory—is highlighted, along with the vital contributions of our industry and university partners. A CD of Proceedings from the 2005 Solar Program Review Meeting is also included as part of this document. This annual meeting reviews developments and achievements within the DOE solar energy arena during the preceding year.

We who have the opportunity to work in the field of solar energy are the luckiest people in the world. Solar offers virtually limitless promise of vast quantities of clean, affordable, renewable energy for our nation's future.

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Photovoltaic R&D Subprogram Overview

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

The bulk of the Photovoltaic Subprogram's activities are carried out through two primary research centers: the National Renewable Energy Laboratory (NREL) in Golden, Colorado, and Sandia National Laboratories (SNL), in Albuquerque, New Mexico. Brookhaven National Laboratory (BNL), in Upton, Long Island, New York, 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, DOE's Golden Field Office (GO), in Golden, Colorado, and the Albuquerque Operations Office (ALO), in Albuquerque, New Mexico, administer and manage contracting activities assigned by headquarters.

The 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

By 2006, the goal is to reduce the average cost of all grid-tied (battery-free) PV systems to the end user to $4.50/watt (W), from a median value of $6.25/W in 2000. This requires a reduction in the direct manufacturing cost of the PV module itself to $1.75/W, compared with a cost of $2.50/W in 2000. The result would be a reduction in the average cost of electricity generated by PV systems from $0.24/kWh in 2000 to $0.18/kWh in 2006. These are broad program goals that must be refined for specific applications. Objectives for utility-scale applications go beyond the general goal because of the nature of utility applications. Objectives for residential grid-connected systems are somewhat less aggressive than the overall goal because of specific conditions in these applications.

Results and Accomplishments

NREL-supported research resulted in 13.5%-efficient crystalline silicon and 11%-efficient thin-film modules being made commercially in the United States, an important JOULE milestone. Equally significant, world-record efficiencies were attained for six solar cells and one module. The Boeing-Spectrolab cell world record of 39% efficiency is the highest achieved for any monolithic cell under concentrated sunlight. In addition, the charge-state defect that causes light-induced metastability in B-doped Czochralski-grown crystalline silicon was identified for the first time, representing a significant research contribution toward improving the semiconductor used in more than 90% of the solar cells sold in the market last year. These accomplishments advance the long-term objectives for low-cost PV and competitive electricity.

The NREL Measurements and Characterization Division assisted more than 70 PV research partners in the areas of analytical microscopy, surface analysis, electro-optical characterization, and cell and module performance. The division achieved a very significant priority 3 milestone in FY 2005 by expanding its ISO 17025 accreditation to include primary reference cell and secondary module calibration, in addition to the existing accreditation for secondary reference cell calibration under ASTM and IEC standards, making NREL the only laboratory in the world to hold accreditations for both. This is significant because module certification and qualification test laboratories require module and cell calibrations from an ISO 17025 accredited source. ISO accreditation provides manufacturers with confidence that the performance reported for these products is verifiable and internationally accepted.

The Thin Film PV Partnership supported the transition to successful first-time manufacturing 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. Global Solar Energy fabricated a 10.2%-efficient, 88.9-W thin-film CIGS power module, the highest-wattage CIGS module in the world. First Solar and United Solar Ovonic broke ground on major thin-film factory expansions (50 MWp of cadmium telluride and 25 MWp of amorphous silicon, respectively). Overall, production of thin films in the United States grew from 12 MWp in 2003 to an estimated >40 MWp in 2005.

The PV Manufacturing R&D Project received a 2005 R&D 100 Award with Sinton Consulting for a quasi-steady-state photoconductance Silicon Evaluation System. This process gives manufacturers information to identify substandard silicon before it is made into PV cells, thereby increasing the number of efficient cells produced, boosting yields, and reducing manufacturing costs. The evaluation system will enable the solar industry to keep up with product demand and growth and to produce consistently better silicon at the lowest possible price. Manufacturing R&D achieved major technical progress in other areas, as well, by: implementing production-line improvements that resulted in an 85% increase in yield and a 13% increase in cell efficiency (ITN Energy Systems); demonstrating the integration of diagnostic equipment and statistical methods for high-speed monitoring of wafers, cells, and processes in 60-MW manufacturing facility, resulting in a 15% increase in throughput (RWE Schott Solar); and initiating manufacturing of PV modules using new Gemini II-based String Ribbon silicon wafers (Evergreen Solar).

Construction of the Science and Technology Facility (S&TF) at NREL is well under way, with the grand opening of the completed facility expected in May 2006. The new facility will provide 71,000 square feet of office and laboratory space. The S&TF includes a substantial investment in new equipment that will be capable of greater process integration. Researchers will be able to experiment in conditions much closer to the situation likely to be found in manufacturing. This will dramatically narrow the gap between discoveries in the laboratory and their application in the market.

The second Solar Decathlon, an intercollegiate competition that tests which team can build the most effective solar-powered home, began in late September, just as FY 2005 was drawing to a close. Eighteen teams brought their houses to the National Mall in Washington, D.C., where they competed in ten contests encompassing architecture, livability, and power generation to heat and cool space, heat water, and power lights, appliances, and an electric car. The Solar Decathlon reaches out to the public in a major way. Between the two Decathlons (held in 2002 and 2005), as many as a quarter of a million people have come to learn about the architectural appeal and myriad benefits of solar energy in the built environment.

A Growth Industry

For the past decade, the average growth of the world PV market has exceeded 30%, which makes the PV industry one of the most consistent high-growth industries in the world. Critical to the success of PV technologies in the marketplace has been DOE's role in advancing module efficiencies, costs, and reliability; inverter performance, reliability, and cost; and improvements in balance of systems. Continued success will depend on a strong government R&D program and the resources, scientific and technological approaches, and continued efforts of the "best and brightest" among industry, laboratory research organizations, and our educational institutions.

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 2005 marked a host of accomplishments in the Fundamental Research area, including these:

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.
- Expanded ISO 17025 accreditation from secondary reference cells to include primary reference cells and modules.

Electronic Materials and Devices

- Invented fire-through agents that enable inkjet-written Ag contacts to silicon solar cells through silicon nitride antireflection coating.
- Achieved major improvements and record efficiencies in new and conventional PV devices, including: 16.2% in a CIGS cell produced from a 1-micron-thick absorber layer; 14% in CdTe solar cells, with absorber layers of half the conventional thickness; and 37.9% (10 suns concentration) in a novel inverted growth structure used to produce a thin-film GaInP/GaAs/GaInAs triple-junction solar cell.

Crystalline Silicon Project

- With the University of California at Berkeley, identified and characterized metallic defects affecting most commercially available c-Si solar cells as a function of processing conditions, including a defect-engineering solution to the "dirty silicon" problem.
- With various research partners, achieved a number of record high efficiencies on readily manufacturable screen-printed, low-cost-material PV cells.

High-Performance Photovoltaics

- Demonstrated a four-terminal polycrystalline thin-film tandem cell consisting of a CdTe-based top cell and a CIS-based bottom cell, officially measured by NREL at 15.3% efficiency.
- With Boeing Spectrolab, demonstrated a 39%-efficient GaInP/GaInAs/Ge cell verified by NREL at 236 suns.

Solar Resource Characterization

- Evaluated performance of three candidate solar radiation models for the National Solar Radiation Data Base (NSRDB) and developed recommendations for an NSRDB update plan.

Environmental Health and Safety

- Conducted a life-cycle analysis of the balance of systems of the Tucson Electric Power Springerville 3.5-MW c-Si plant; computed energy payback times to be 70% lower than the previously published estimates.

Measurements and Characterization

Performing Organization: National Renewable Energy Laboratory (NREL)

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

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FY 2005 Budget: $6,895K

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.
- Develop diagnostic tools that advance manufacturing 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.
- Expanded our ISO 17025 accreditation from secondary reference cells to include primary reference cells and modules.
- Carried out detailed investigation of the structural, chemical, and electrical properties of the crystalline Si/amorphous Si interface in HIT cells.
- Organized the 15th Workshop on Crystalline Silicon Solar Cell Materials and Processes.
- Investigated surfactant-assisted growth of CdS thin films, leading to a substantial improvement of thin-CdS/CIGS device performance.
- Developed, constructed, and tested an automated resonant-coupled, photoconductive decay (RCPCD) minority-carrier lifetime mapping system (one- or two-dimensional) that incorporates auto-tuning, and is capable of accepting samples up to 6” in diameter.
- Studied plasma surface modification of polymer backsheets to investigate the origin of interfacial barrier/backsheet failure.
- Developed a prototype minority-carrier lifetime measurement system capable of accurately measuring both crystalline and multicrystalline Si wafers in an in-line manufacturing environment.
- Developed a scanning tunneling microscope within a scanning electron microscope (SEM) and investigated the transport properties of grain boundaries in polycrystalline thin films.
- Investigated the nature, origin, and generation mechanism of defects in lattice-matched and lattice-mismatched III-V structures.
- Completed a secondary ion mass spectrometry (SIMS) study of elemental diffusion during solid-phase crystallization of amorphous silicon films.
- Completed international module intercomparison involving PV module calibration and certification laboratories.

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 secondary cell and module measurements. Complete periodic audits.
- Organize the 16th Workshop on Crystalline Silicon Solar Cells Materials and Processes.

- Complete capability to evaluate multiple junction concentrator cells and modules to 1000x with lowest possible uncertainty.
- Investigate the structural, chemical, and electrical properties of front and back screen-printed contacts to industrial Si cells. Demonstrate improved process robustness and performance.
- Develop a prototype tool capable of screening Si wafers with microcracks in an in-line manufacturing environment.
- Conduct experiments to examine the structural, chemical, and electrical properties of the c-Si/a-Si interface in HIT cells and correlate these properties with device performance.
- Conduct a study correlating composition and structure of moisture barrier layers grown on flexible substrates with growth conditions, water vapor transport rates, and adhesion properties.
- Study the reaction kinetics of nanoscale Cu_xTe films.
- Conduct studies of wet-chemical processing of PV material surfaces.
- Plan and initiate operations in the Science and Technology Facility.

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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 internal research groups, external research partners in university and industry laboratories, and PV manufacturers. 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 2020. 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, CIS, CdTe, III-Vs, and future-generation materials. 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; and (4) develop diagnostic tools that advance manufacturing 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 2005 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. However, during the past year, we have collaborated with well over 70 research groups from industry, universities, and national laboratories. FY 2005 priority milestones in each task are listed below.

2.1 Analytical Microscopy Task

- Study the nature, origin, and three-dimensional distribution of structural defects in lattice-matched and mismatched III-V structures on Si substrates.
- Investigate the chemical, structural, and electrical properties of the c-Si/a-Si interface in Si HIT cells.
- Complete the development of a scanning tunneling microscope within an SEM and investigate the transport properties of grain boundaries in polycrystalline thin films.

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

2.2 Cell and Module Performance Task

- Maintain ISO 17025 Accreditation for secondary cell calibration under ASTM and IEC standards and expand to include primary reference cell and secondary module calibration.

- Complete International Module Intercomparison study and publish results.

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

2.3 Electro-Optical Characterization Task

- Organize the 15th Workshop on Crystalline Silicon Solar Cell Materials and Processes.
- Develop a prototype minority-carrier lifetime measurement system capable of accurately measuring both crystalline and multi-crystalline Si wafers in an in-line manufacturing environment.
- Apply Dessis 2-D device modeling software to elucidate fundamental limitations in crystalline and polycrystalline PV device designs. Submit at least one peer-reviewed paper that leads to an improved understanding of device performance and/or reliability.
- Develop, construct, and test an automated RCPCD minority-carrier lifetime mapping system (one- or two-dimensional) that incorporates auto-tuning and is capable of accepting samples up to 6" in diameter.

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

2.4 Surface Analysis Task

- Study plasma surface modification of polymer backsheets to investigate the origin of interfacial barrier/backsheet failure.
- Investigate surfactant-assisted CBD growth of CdS thin films in CdS/CIGS devices.
- Complete SIMS study of elemental out-diffusion during solid phase crystallization of amorphous silicon films on glass substrates.
- Specify and order mobile Auger tool for Science and Technology Facility.

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

Budget allocations by task are provided below.

Task Title	FY 2005 Budget ($K)
Analytical Microscopy	1,750
Cell and Module Performance	1,410
Electro-Optical Characterization	1,710
Surface Analysis	1,360
Management/Maintenance	665

3. Results and Accomplishments

Research results outlined in this section address only FY 2005 priority 3 and 4 milestones, which represents 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

The nature, origin, and three-dimensional distribution of structural defects in lattice-matched and mismatched III-V structures on Si substrates: In collaboration with NREL's III-V Group, GaP and GaP(N) epitaxial layers on Si substrates, which were grown by metal organic chemical vapor deposition (MOCVD), were investigated by transmission electron microscopy (TEM) and cathodoluminescence (CL). These structures are being developed for multijunction devices on Si. Particular emphasis was placed on the initiation of growth on Si substrates, because that determines the structural quality of the device layers. By optimizing MOCVD nucleation and growth conditions, nearly defect-free GaP(N) layers have been grown on Si substrates. A low-density misfit dislocation network was observed at the Si/GaP interface. However, very few threading dislocations propagate from it. Using these as templates, the first III-V/Si lattice-matched tandem cells were fabricated. We also obtained the first experimental evidence of atomic ordering in GaNP(As) dilute nitride alloys. This may have a marked effect on the alloy bandgap. We also investigated the structural properties of lattice-mismatched GaAsP on GaP(N) on Si. Both direct deposition and a variety of grading schemes were examined. The growth conditions for achieving the lowest density of dislocations were ascertained. Relatively low defect density ($<10^8$ cm^{-2}) MOCVD GaAsP layers were obtained by use of compositionally step-graded buffer layers (Fig. 1).

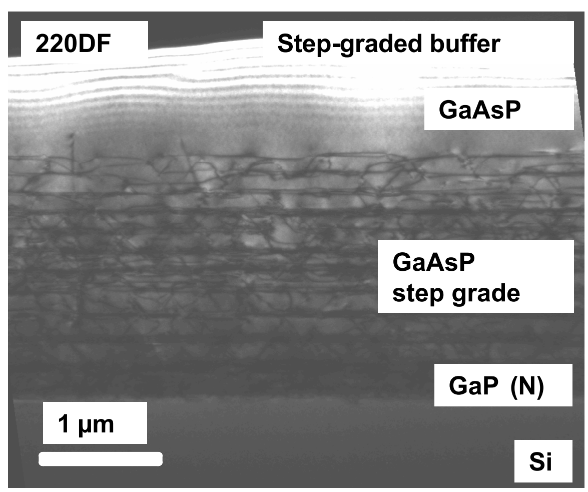

Fig. 1. TEM cross section of a step-graded GaAsP layer on GaP(N) on Si substrate

The chemical, structural, and electrical properties of the c-Si/a-Si interface in Si HIT cells:
In collaboration with NREL's Si Group, the microstructure and interface properties of Si heterojunction (SHJ) cells were investigated. Such cells have recently demonstrated world-record efficiency on single-side, untextured Si HIT structures. The atomic structure and electronic properties of the crystalline silicon/hydrogenated amorphous silicon (c-Si/a-Si:H) interface were examined by high-resolution transmission electron microscopy (HRTEM), atomic-resolution Z-contrast imaging, and electron energy loss spectroscopy. We found that all high-performance SHJ solar cells exhibit atomically abrupt and flat c-Si/a-Si:H interfaces and high disorder of the a-Si:H layers. These atomically abrupt and flat c-Si/a-Si:H interfaces can be realized by direct deposition of a-Si:H on c-Si substrates at a substrate temperature below 150°C by hot-wire chemical vapor deposition from pure silane.

Figure 2(a) shows a Z-contrast image of the front (100) c-Si/a-Si:H interface in a double-heterojunction SHJ solar cell with a high V_{oc} of 680 mV. The intrinsic and doped a-Si layers are not distinguishable in the images. On the c-Si side, the elongated bright spots directly represent the two closely spaced (110) silicon columns, or silicon "dumbbells." The amorphous feature is shown as continuous background in the Z-contrast image. Combining this Z-contrast image with other HRTEM images, we conclude that the interface is atomically abrupt and flat. To understand the electronic structure change across the interface, EELS spectra were taken at different points around the interface.

Figure 2(b) shows the Si-L edges spectra taken from three points indicated as p1, p2, and p3 in Fig. 2(a). Point 1 is inside the a-Si:H layer, point 2 is at the interface, and point 3 is inside the c-Si. It is seen that the intensity of the first peak (as indicated by black arrows) is reduced as the electron beam is moved from the c-Si region to the interface. It is further reduced when the electron beam is moved into the a-Si:H layer. The Si-L edges spectra represent the transition from the silicon *2p* band to the conduction band. The intensity reduction of the first peak indicates that the density of states is reduced around the minimum of the conduction band. The reduction at the interface and in the a-Si is likely caused by the disorder. Thus, the intensity of this peak tells us the quality of the a-Si:H layer, i.e., the lower the intensity, the more disorder, i.e., better a-Si. The EELS spectra in Fig. 2(b) indicate a high-quality a-Si:H layer is achieved.

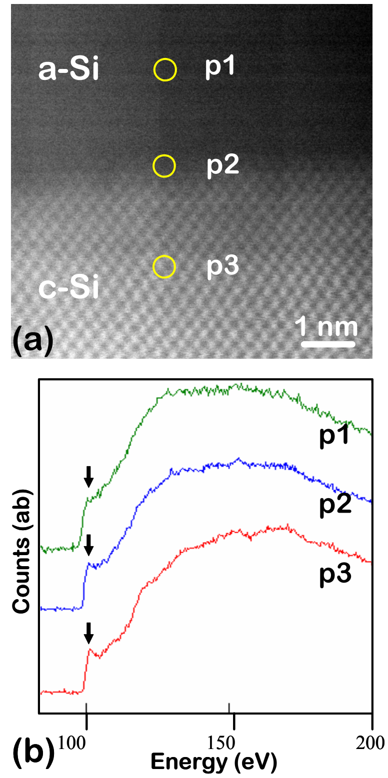

Fig. 2. (a) Z-contrast image of the front c-Si/a-Si:H interface in a double-heterojunction SHJ solar cell, and **(b)** Si-L edges spectra taken from different points around the c-Si/a-Si:H interface.

3.2 Cell and Module Performance Task

ISO 17025 Accreditation for secondary cell calibrations (MYTP M-4, T-1):
The Cell and Module Performance Group achieved a very significant priority 3 milestone by expanding ISO 17025 accreditation to include primary reference cell and secondary module calibration under ASTM and IEC standards. The American Association for Laboratory Accreditation (A2LA) awarded the accreditation to NREL on September 12, 2005.

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.


THE AMERICAN ASSOCIATION FOR LABORATORY ACCREDITATION

ACCREDITED LABORATORY

A2LA has accredited

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)
Golden, CO

for technical competence in the field of

Calibration

The accreditation covers the specific calibrations listed on the agreed scope of accreditation. This laboratory meets the requirements of ISO/IEC 17025 - 1999 "General Requirements for the Competence of Testing and Calibration Laboratories." This laboratory also meets the requirements of ANSI/NCSL Z540-1-1994 and any additional program requirements in the field of calibration.

Presented this 14th day of September 2004.

President
For the Accreditation Council
Certificate Number 2236.01
Valid to November 30, 2006

For the calibrations to which this accreditation applies, please refer to the laboratory's Calibration Scope of Accreditation.

Fig. 3. In FY 2005, the scope of NREL's A2LA ISO 17025 accreditation (awarded in FY 2004) was expanded to include primary reference cell and secondary module calibration under ASTM and IEC standards.

Reach the 90% completion point for the International Module Intercomparison study (MYTP M-24, T-6):
In FY 2005, the Cell and Module Performance Group had a priority 3 milestone to complete the next in series international intercomparisons. This is an important activity because it compares measurement procedures and results from all the key measurement organizations throughout the world. Currently, eight of the nine participants have tested the modules identified for this study. The groups participating are NREL, SNL, Arizona State Photovoltaic Testing Laboratory, FSEC, European Solar Test Installation, Fraunhofer Institute for Solar Energy Systems, and TUV in Germany. The modules have also been sent to the final participant, AIST, in Japan. China was removed from the list of invited participants based on a lack of interest. The study has been completed and was summarized at the 2005 Solar Program Review Meeting. An abstract has been submitted for the Forth World PV Conference.

3.3 Electro-Optical Characterization

Organize the 15th Workshop on Crystalline Silicon Solar Cell Materials and Processes:
The 15th Workshop on Crystalline Silicon Solar Cells & Modules: Materials and Processes was held on August 7–10, 2005, in Vail, Colorado. It was representative of eight countries and was attended by more than 135 scientists from 51 different colleges/universities, the Department of Energy GO and HQ offices, 53 industry members, and 2 DOE national laboratories (SNL and NREL).

The Silicon 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 seen by the community.

This is achieved at the workshop through a combination of oral presentations by invited speakers, poster sessions, and discussion sessions, all of which review recent advances in crystal growth, new cell designs, new processes and process characterization techniques, and cell fabrication approaches suitable for future manufacturing demands. In keeping with the tradition of guiding the fundamental research, the theme of this year's workshop was "Providing the Scientific Basis for Industrial Success," which reflected the workshop's contributions to advancing the fundamental science behind industrial development and to the success of the PV industry.

Develop a prototype minority-carrier lifetime measurement system capable of accurately measuring both crystalline and multi-crystalline Si wafers in an in-line manufacturing environment:
We have designed and built a prototype system that is capable of quickly and accurately measuring the decay of photoexcited carriers in crystalline and multicrystalline silicon and determining the carrier lifetime from these data. This system could be incorporated into an automated manufacturing environment with an estimated throughput of 6 to 12 wafers per minute.

This development was driven by the fact that commercially available equipment is limited to microwave reflection and quasi-static photoconductivity. Microwave reflection is costly and probes only a shallow skin depth, which potentially causes the results to be dominated by surface recombination. The quasi-static system is less expensive and avoids the skin depth issues, but there are concerns that this technique cannot account for changing silicon parameters that exist at grain boundaries (GBs) in polycrystalline silicon and thus gives questionable results.

Our goal was to combine the advantages of both techniques by using a relatively low frequency and calculating the lifetime based on fitting the actual photoconductive decay transient. The sensitivity is relatively high for measuring in the low-injection regime, which gives the most accurate minority-carrier lifetime. We achieve high sensitivity by tuning the sample as part of a resonant circuit; thus, we have described the system as resonant-coupled photoconductive decay, or RCPCD. Multiple wavelengths are available to change excess carrier profiles near the surface and provide information about surface recombination.

Apply Dessis 2-D device modeling software to elucidate fundamental limitations in crystalline and polycrystalline photovoltaic device designs. Submit at least one peer-reviewed paper that leads to an improved understanding of device performance and/or reliability:
Solar cell modeling has generally been limited to one-dimension and current-voltage curves. A new effort within our group in the past year has developed two-dimensional solar cell modeling and the ability to simulate multiple experiments including current-voltage curves, quantum efficiency, time-resolved photoluminescense, near-field scanning optical microscopy, electron-beam-induced current (EBIC), and cathodoluminescence.

This tool has been applied to understand how GBs affect $Cu(In,Ga)Se_2$ solar cell performance and the electro-optical experiments listed above. A number of recent articles indicate that CIGS GBs are positively charged. This has led many researchers in the $Cu(In,Ga)Se_2$ community to surmise that positively charged GBs screen out holes, attract electrons, and form minority-carrier current channels that enhance device performance. Some claimed that this is why polycrystalline $Cu(In,Ga)Se_2$ (and CdTe) solar cells outperform their single-crystalline counterparts. Although the study was limited to $Cu(In,Ga)Se_2$, it should be noted that strong minority-attractive charge has been measured in Si, GaP, GaAs, and many other solar cell materials. The simulations showed that, although it is true that the GBs can form minority-carrier current channels, recombination is often increased, and device efficiency suffers. GB charge that is sufficiently large enough to actually increase efficiency causes quantum efficiency to approach unity, measured lifetimes to decrease drastically, and EBIC diffusion lengths to be very large. These experimental signatures are generally not observed in $Cu(In,Ga)Se_2$ solar cells. These findings are important to understand what material properties do and do not contribute to solar cell efficiency, and to understand how grain boundaries affect electro-optical characterization.

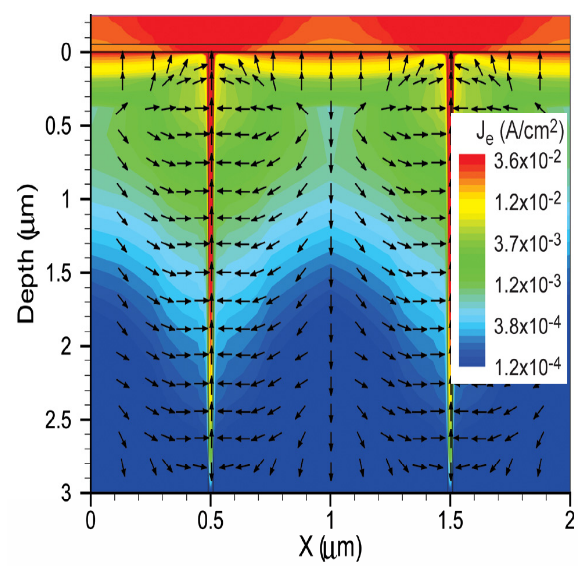

Fig. 4. Current density map incorporating grain boundaries

Develop, construct and test an automated RCPCD minority-carrier lifetime mapping system (one- or two-dimensional) that incorporates auto-tuning and is capable of accepting samples up to 6” in diameter:
Polycrystalline wafers and ribbons avoid the high cost of growing single crystal ingots, but non-uniformity and grain boundaries can degrade solar cell performance. Measuring the minority-carrier lifetime with spatial resolution across polycrystalline silicon can provide information toward understanding how detrimental these regions are. One of the reasons for the high cost of the commercially available microwave reflection lifetime measurement system described above is its scanning capability. Our goal was to develop a less costly scanning system with approximately the same spatial resolution of about 1 mm using the RCPCD system described above.

We have designed and built a one-dimensional scanning system capable of measuring the lifetime of crystalline and multicrystalline silicon. This system (Fig. 5) is capable of rapidly analyzing heterogeneities in as-grown and processed material. The mapping capability will prove very useful in tracking and understanding the non-uniformities that are known to exist in multicrystalline silicon.

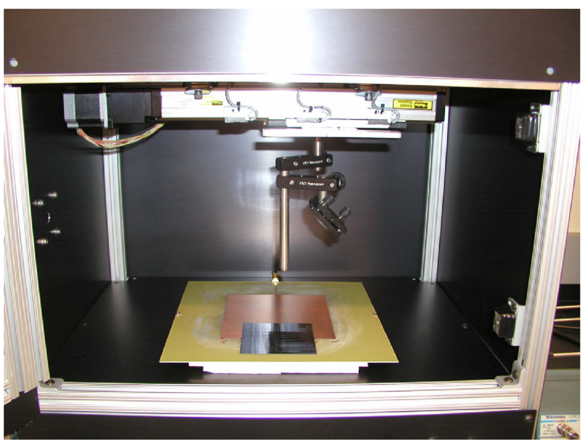

Fig. 5. Lifetime Mapping System

3.4 Surface Analysis

Complete experiments that correlate surface chemistry to the adhesion of polymer encapsulant and edge-seal materials used in module packaging designs. Investigate adhesion properties under both normal and damp heat conditions, with goal to facilitate 25-year module warranties:

Flexible polymer backsheet materials are being investigated as possible replacements for glass in double-glass thin-film module designs. The permeable nature of polymers, however, makes them unsuitable for long-term encapsulation. One possible solution is to deposit a thin moisture barrier on the polymer backsheet surface. The barrier efficacy is measured by its ability to impede moisture and by its adhesion to the polymer and the encapsulant. This project is jointly conducted with members of NREL’s Module Reliability team, who are investigating the use of silicon oxynitride layers on polyethylene terphthalate for such applications. The barrier films were deposited by plasma-enhanced chemical vapor deposition (PECVD) onto DuPont ST504 PET. Initial barrier results were inconsistent, and X-ray photoelectron spectroscopy (XPS) analysis found that the DuPont product had two different sides (i.e., one had been treated with an acrylic formulation, and this had not been tracked prior to the barrier depositions). A second issue was that the surface of the PET was treated with a plasma pre-etch step in the PECVD system prior to barrier layer deposition. Although initial performance of the barriers was generally good, the films on plasma-pretreated PET delaminated during damp heat testing. XPS was able to determine that failures were occurring at the PET/barrier film interface. Further, high-resolution XPS analysis from plasma-pretreated PET surfaces showed significant changes to the polymer, specifically chain scissioning with the concomitant creation of new chemical functionalities in a thin surface layer (<100 Å). Several experiments were performed to understand the stability of the reaction products. Temperature-programmed XPS was performed in which a treated PET film was heated *in-situ* while the photoelectron spectra for C1s, O1s, and N1s were monitored. Loss of nitrogen (N is indicative of plasma pretreatment) began at 70°C, near the polymer glass transition, with gradual restoration of the C and O signals of pure PET as the temperature was increased to the lamination temperature of 150°C. In addition, a plasma-treated film that had been water washed and transferred through inert atmosphere into the XPS also showed disappearance of the altered layer. Damp heat testing is performed at 85°C and 85% relative humidity (85/85). Our results yield a plausible explanation for loss of adhesion during damp heat testing; unstable reaction products at the PET surface create a weak interfacial layer that is affected by both temperature and humidity. Recent XPS depth profiles indicate that barrier film composition and thickness require better characterization to aid understanding of the 85/85 test results. Work has been hampered by problems with the PECVD system, however, this project will be continued in the coming fiscal year. Based on the success of the XPS results, Surface Analysis project personnel will lead more of this work in the coming year.

Complete experiments to quantify distributions of detrimental elements in recrystallized thin-film Si on foreign substrates:
The original intent of this work was to study crystallization of hot-wire CVD a-Si:H on a variety of substrates, however, because of technical challenges, it was decided to focus on glass substrates for this portion of the work. SIMS analysis of recrystallized films on stainless steel showed that without a barrier layer, large quantities of transition metals diffused into the Si films during recrystallization. Although Si_xN_y layers proved to be effective diffusion barriers, the nitride films tended to crack during recrystallization because of the large mismatch in the thermal expansion coefficient with the steel. Films on SnO_x-coated glass proved problematic due to the rough nature of the substrate-film interface, which degraded depth resolution and obscured diffusion information in the depth profiles. As a result, most of the studies were performed on borosilicate glass (Corning 1737F). Solid-phase crystallized (SPC) films on glass showed no evidence of impurities from the glass, even up to annealing temperatures of 575°C for up to 24 h. In addition, there was no change in the oxygen content, which remained at 10^{18} at/cm^3. This level is actually lower than the amount of oxygen present in CZ-grown Si (generally 10^{18} at/cm^3). Experiments were performed to study the devolution of hydrogen from SPC a-Si:H films. Hydrogen is known to diffuse from a-Si during high-temperature anneals even without recrystallization, so it is important to know at what point in the nucleation and crystallization hydrogen is evolved from the material. Comparisons were made between films grown with high (14%) and low (4%) initial concentrations of hydrogen. The films with high hydrogen must be grown at lower substrate temperatures and therefore contain more oxygen. After annealing, the hydrogen levels were found to remain higher in the initially “high” level films. This may indicate higher defect densities, possibly also affected by the higher oxygen levels in these films. We also studied the diffusion of dopants from n- and p-type layers into i-layers. SIMS results show that B diffusion is lower than P for all temperatures studied, although n-type P doped layers also had dopant concentrations of $1x10^{21}$ at/cm^3 versus $2x10^{19}$ at/cm^3 for the p-type doped layers. Phosphorus diffusion could be inhibited by annealing the n-type layer prior to deposition and crystallization of the i-layer. This work will continue in the coming year.

Conduct experiments to quantify surface reactions that occur when using aqueous bath chemistries in the deposition of window layers on CIGS films:
We have used our cluster tool for *in-situ* studies of the changes in surface chemistry and electronic structure that occur during chemical bath deposition of CdS. Results from this project can be roughly divided into three areas. **(1)** XPS and UPS determination of the chemical and electronic changes in the surfaces of CIGS thin films that are brought about by components (water and ammonia) of typical chemical bath deposition (CBD) of CdS window layers. We find that Group III elements are preferentially removed by aqueous ammonia, and that water alone is responsible for many but not all of the changes. Increasing duration air exposure of the ammonia treated surface results in the expected oxide formation, but also in the eventual increase in sodium. **(2)** XPS and ultraviolet photoelectron spectroscopy (UPS) determination of select electronic properties that are affected by exposure to aqueous reagents and how these changes are a function of the copper and gallium content of CIGS. We find that hot aqueous ammonia causes the n-type surface of as-grown CIGS to revert to p-type behavior as measured by quantitative determinations of the energetic position of the CIGS valence band maximum (VBM) relative to the Fermi energy. Band bending induced by the dopant cadmium was quantified and found to depend on the CIGS composition. The CIGS VBMs were found to be a function of copper content, as predicted theoretically, and to be n-type for very Cu-poor surfaces (Cu/(In+Ga) <0.3). These results are important in understanding the microscopic mechanism responsible for junction formation in the alloys that comprise CIGS. In the third part, **(3)** we have demonstrated an improved, surfactant-modified method of depositing CdS buffer layers with an aqueous chemical bath. We find that a non-ionic surfactant can be used as an additive in the chemical bath deposition of CdS buffer layers on CIGS and SnO_2/glass substrates without changing the chemical or electronic properties of the CdS layers, and that for very thin buffer layers, addition of the surfactant leads to CIGS-based PV cells with significantly higher performance relative to standard CBD. The

mechanism of this improvement is the elimination by the surfactant of bubbles on the substrate in the chemical bath.

4. Planned FY 2006 Activities

A list of selected FY 2006 planned activities is given below. A more complete list of planned activities and milestones can be found in the Measurements and Characterization FY 2006 Annual Operating Plan. In FY 2006, we will complete the following milestones:

- Provide 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, universities, and NREL.
- Maintain ISO accreditation for secondary cell and module measurements and complete periodic audits.
- Organize the 16th Workshop on Crystalline Silicon Solar Cells Materials and Processes.
- Complete capability to evaluate multiple-junction concentrator cells and modules to 1000x with lowest possible uncertainty.
- Conduct a study correlating composition and structure of moisture barrier layers grown on flexible substrates with growth conditions, water vapor transport rates, and adhesion properties.
- Investigate the structural, chemical, and electrical properties of front and back screen-printed contacts to industrial Si cells. Demonstrate improved process robustness and performance.
- Develop a prototype tool capable of screening Si wafers with microcracks in an in-line manufacturing environment.
- Conduct experiments to examine the structural, chemical, and electrical properties of the c-Si/a-Si interface in HIT cells and correlate these properties with device performance.
- Study the reaction kinetics of nanoscale Cu_xTe films.
- Conduct studies of wet-chemical processing of PV material surfaces.

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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 2005 Budget: $6,860K

Objectives

- Develop data mining tools and diagnostics for combinatorial methods in thin-film cells.
- Demonstrate inkjet writing of contacts for silicon solar cells, achieving 10% efficiency.
- Improve cost potential by demonstrating high efficiency in thinner CdTe and CIGS absorber layers.
- Complete a combinatorial-temperature stress system with illumination cycling capability for CIGS and CdTe devices.
- Achieve 34% efficiency with a novel, lattice-mismatched multijunction structure as a first step toward higher efficiency.

Accomplishments

- Invented fire-through agents that enable inkjet-written Ag contacts to silicon solar cells through silicon nitride antireflection (AR) coating.
- Achieved 16.2% efficiency in a CIGS cell produced from an absorber layer that is only 1 micron thick.
- Achieved 14% efficiency in CdTe solar cells, with absorber layers that are half the conventional thickness.
- Demonstrated a CdTe/CIS polycrystalline thin-film tandem cell with total-area efficiency of 15.3%, exceeding a FY 2006 milestone of the DOE/NREL High-Performance PV Project.
- Achieved 37.9% efficiency (10 suns concentration) in a novel inverted growth structure used to produce a thin-film GaInP/GaAs/GaInAs triple-junction solar cell.

Future Directions

- Apply inkjet processing to the fabrication of absorber layers for solar cells.
- Design and implement a CIGS processing cluster to explore new pathways to improving manufacturability.
- Achieve 40%-efficient concentrator cell.
- Relocate and initiate operations in the Science and Technology Facility (now under construction).

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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*. During FY 2005, research in the silicon task was consolidated with subcontracted research to form the new Crystalline Silicon Project. These closely related studies are reported in the next section.

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 systems 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

- Development of combinatorial materials science deposition, diagnostics, and data analysis
- Inkjet processing of electronic materials
- Organic and nanocomposite solar cells
- In-situ diagnostics for thin-film growth
- Process-evaluation Cooperative Research and Development Agreements (CRADAs) (GTI, Evergreen Solar, and AKT).

2.2 Thin-Film Polycrystalline Compounds

- Examination of device performance in progressively thinner absorber layers.
- Transparent conducting oxides (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 4-junction GaInP/GaAs/GaInAsN/Ge or similar cell
- Multijunction III-V on silicon
- Novel lattice-mismatched cell.

Budget allocations by task are provided below.

Task Title	FY 2005 Budget ($K)
Processes and Advanced Concepts	1,800
Thin-Film Polycrystalline Compounds	2,860
Concentrator Crystalline Cells	1,900
EM&D Technical Coordination	300

3. Results and Accomplishments

2.1 Process and Advanced Concepts

The major thrust of this task is development of technology to enable combinatorial materials science. Conventional materials science and device research has traditionally operated in a linear fashion: i.e., performing an experiment, analyzing the results of the experiment, and then using these results to decide on the next experiment. The now ubiquitous use of computers for both data acquisition and analysis has enabled high-throughput approaches to materials discovery experiments: i.e., parallel rather than serial sample preparation, characterization, and analysis. Here many nearly simultaneous experiments are performed and analyzed at each step. This parallel approach can greatly accelerate the rate at which science can be done and knowledge acquired. As an example, the chemical industry has found that complex catalysts have been discovered 10 to 30 times faster than they would have been using conventional approaches. Perhaps the biggest challenge of combinatorial science is that vast amounts of data from hundreds, thousands, or millions of experiments must be usefully and rapidly analyzed or else the benefits of this parallel approach are largely lost. This is typically accomplished by developing "data mining" software with the ability to mine the data for important trends and results. Such combinatorial experimental methods, combined with intelligent experiment choice based on the traditional scientific method, are becoming the foundation of new knowledge discovery in a number of areas, including catalyst discovery, drug discovery, polymer optimization, phosphor development, and chemical synthesis.

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 multi-head inkjet printing system, which can deposit samples with either continuously graded or discrete local compositions. The routinely used approaches based on physical vapor deposition (PVD) have produced hundreds of libraries in those material systems mentioned above that are specific to the PV Subprogram, as well as on other materials systems for outside customers. The inkjet system is fully developed, but has not yet been used extensively for combinatorial experiments.

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. Specific tools have been developed to do optical (Raman, reflection/ transmission) characterization, electrical (4 point probe), structural (x-ray diffraction and atomic force microscopy) characterization of the libraries above in a high-throughput fashion. These tools are broadly applicable to the materials science problems being pursued by EERE.

Mining of Data. This really consists of two separate areas. First is the development of information archiving and display for the vast amounts of data being acquired and, in this area, we have been successful in developing databases and data-handling approaches that make data taking and initial analysis quite facile. The second area is in the development of smart software tools to analyze multi-dimensional phase space so as to extract key data and trends.

Custom software tools must be developed to extract useful information from the large amounts of characterization data produced using our automated mapping characterization tools described above. In addition, with appropriate modeling and fitting, the optical data can yield structural and electronic information such as the local film thickness, the carrier concentration, and the carrier mobility. 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.

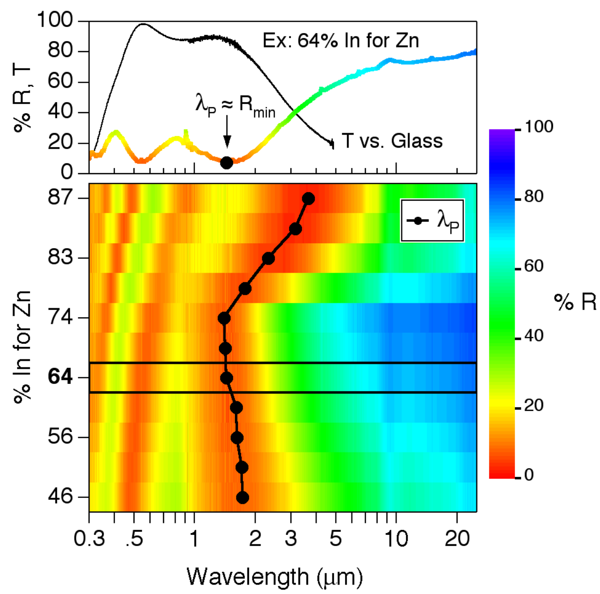

Fig. 1. Top: Typical R (color), T (black) spectra for an IZO. Bottom: Color intensity map of reflectance spectra for an IZO library with variation in plasma wavelength (λ_p) overlaid.

A second major area of investigation is development of new technologies for very low-cost processing. Our current focus is to develop inkjet printing as a deposition system for electronic materials. 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. Key to the approach is the development of inks with the correct rheological and compositional characteristics. To evaluate the efficacy of the approach, we have focused initially on the direct writing of contacts for solar cells.

Developing contacts for crystalline silicon cells requires new inks, agents to burn through AR coatings, and techniques for writing contacts with optimum aspect ratio. As silicon wafers become thinner and more fragile, inkjet-patterned contacts are ideal as they are applied without direct contact to the cell surface. Silver lines 250 μm wide and 10 μm thick were inkjet-printed on SiN_x-coated Si ribbon p/n junctions provided by Evergreen Solar. Al back contacts of 1 μm thickness were deposited by e-beam evaporation. The two contacts were co-fired in a single annealing step at 850°C for 10 min in air, forming a solar cell with 8% efficiency, V_{oc}=0.529 V, J_{sc}= 22.67 mA, and a fill factor of 0.65. In this experiment, the ohmic contact between Ag and Si was formed through the SiN_x layer without the use of glass frits. The high temperature and long time required for the penetration of the Ag through the AR coating can be detrimental for the junction. Facilitating the process of burning through the AR coating is desirable to lower the temperature and time of annealing for inkjet-printed contacts.

2.2 Thin-Film Polycrystalline Compounds

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 at 19.5%. Our polycrystalline tandem solar cells of semi-transparent CdTe on top of CIS set the record at 15.3%, exceeding the FY 2006 milestone (15%) in DOE/NCPV's High-Performance PV Project.

The price of indium has risen sharply in recent times, and the concern about using it in large quantities resurfaces from time to time. Reducing the thickness of the absorbers from 2.5 μm to ≤1 μm reduces the quantity of In used in the cell. This must be done without adversely affecting the efficiency. This aspect has been studied previously by the group at Upsala University in Sweden, who showed a decrease in efficiency when the absorber thickness is reduced below 1 μm. We have revisited the growth of thin absorbers by using a modified three-stage process and a co-evaporation process. To apply the three-stage process for thinner films, the deposition rates of all the elements were reduced in the first two stages, and the heating rates were also adjusted. Compositional monitoring was still possible in spite of the reduced film thickness. In the co-evaporation process, film growth was initiated in a Cu-rich $CuGaSe_2$ layer, and the overall composition was converted to device quality, Cu-poor $Cu(InGa)Se_2$. This type of growth often resulted in some voids and poor adhesion at the Mo interface. However, compositional uniformity was easily achieved, and the deposition time was considerably shorter (5–10 min) than that used for thicker, record-efficiency cells. With the latter, it was possible to produce dense and smooth thin films. The distribution of Ga through the depth of the film was governed by the ramp rates and the kinetics of the reaction between the binary selenides. Hence, we observed a difference in the solar cell properties fabricated from absorbers made by the two methods. The following table shows the properties of the best solar cells fabricated as a function of absorber thickness.

Properties of Thin CIGS Solar Cells

Thickness (μm)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Eff. (%)
1.0 (3-stg)	0.654	31.6	78.3	16.2
1.0 (codep)	0.699	30.6	75.4	16.1
0.75 (codep)	0.652	26.0	74.0	12.5
0.5 (codep)	0.607	23.9	60.0	8.7
0.4 (3-stg)	0.565	21.3	75.7	9.1

The project also investigates several other materials systems and device concepts. We lead the development of thin-film CdTe solar cells. During the year, these devices have been adapted to serve as the top cell of high-performance tandem thin-film solar cells. We have successfully applied a Cu_xTe back contact to fabricate high-efficiency transparent CdTe cells, as required to pass lower energy light through to the CIS bottom cell. In the past, almost all R&D activities in this area focused on developing a transparent back contact with E_g larger than the E_g of the top cell, such as ZnTe:Cu or ZnTe:N with E_g of ~2.26 eV, or ITO with E_g of ~3.9 eV. The best result is a 10.1%-efficient CdTe cell with a ZnTe:Cu back contact that has a 60%–85% film transmission in the near-infrared (NIR) region. However, we exploited a thinner Cu_xTe back contact and modified device structure to fabricate high-efficiency poly-CdTe thin-film solar cells with higher NIR transparency. We fabricated several CTO/ZTO/nano-CdS:O/CdTe/Cu_xTe/ITO/Ni-Al grid cells with efficiencies of more than 13% by this technique. The best cell has an NREL-confirmed, total-area efficiency of 13.94% (V_{oc}=806.1 mV, J_{sc}=24.94 mA/cm^2, FF=69.22%, and area=0.41 cm^2) with ~60%–40% transmission in the wavelength range of 860–1300 nm. When combined with our CIS cell, this tandem device reached 15.3% efficiency.

Stability measurement infrastructure was improved by the design and construction of a combinatorial temperature stress system adopted from an earlier successful design. Both systems use a commercial Atlas Suntest CPS+ environmental chamber modified with heated substrate holders positioned under the chamber (Fig. 2). This system represents an improvement over other systems in the program because of its small footprint, long running capability, and in particular, its use of a calibrated solar AM 1.5 spectrum. Because of the latter advantage, the heater plates are designed to hold bandpass filters for testing under selective wavelengths.

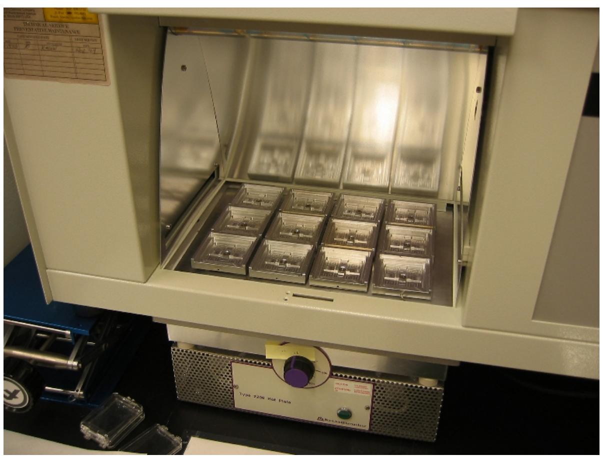

Fig. 2. Solar Matched Stress Test System

- 96 sample capability
- 1500 hour continuous runs
- Continuous temperature monitoring
- V_{oc} bias testing
- AM 1.5 calibrated solar spectrum.

2.3 Concentrator Crystalline Cells

We have embarked on a new approach for ultra-high-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. 3. 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 ultra-thin 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.

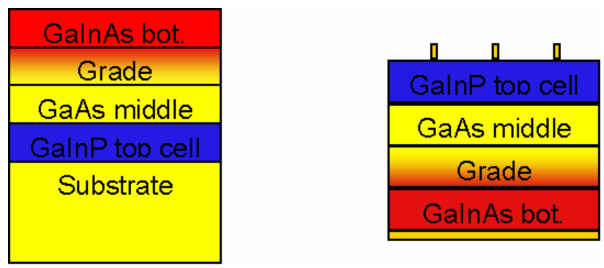

Fig. 3. Inverted growth and handle-mounted thin-film high-efficiency solar cell.

We have successfully grown, processed, and tested monolithic, series-connected, handle-mounted, ultra-thin GaInP/GaAs/GaInAs tandem solar cells. Quantum efficiency and reflectance data are given in Fig. 4. The data generally show excellent carrier collection across a broad spectral range for all of the subcells. The reflectance data, however, show that photocurrent gains are still possible at the far edges of the tandem response range. Improving the two-layer ZnS/MgF_2 ARC will be a focus of future work.

A second area of investigation is to develop very high performance devices on silicon. We are exploring lattice-matched GaNPAs-on-Si as a tandem cell combination. III-V semiconductors grown on silicon substrates are very attractive for lower-cost, high-efficiency multijunction solar cells. A two-junction device consisting of a 1.7–eV junction on a 1.1–eV silicon junction has the theoretical potential to achieve nearly optimal efficiency for a two-junction cell. Most of the previous work in such a structure focused on III-V top cells that were lattice-mismatched to the silicon bottom cell. Under the best conditions, this leads to a high density of threading dislocations in the III-V top cell. This dislocation density decreases the electronic quality of the top cell to the point that a lattice-matched tandem solar cell with a less optimal bandgap combination, such as GaInP/GaAs, is much more efficient. The III-V alloy $GaN_xP_{1-x-y}As_y$ (GaNPAs) is a direct-gap that can be grown lattice-matched to Si with very low structural defect densities. We have proposed the use of lattice-matched GaNPAs on silicon for high-efficiency multijunction solar cells. During this year, we have fabricated this monolithic III-V-on-silicon tandem solar cell. The cell is functionally comprised of an n-on-p silicon bottom homojunction, III-V tunnel junction, and 1.8-eV n-i-p GaNPAs top junction. The epitaxial portions of the structure are composed mainly of GaNPAs and GaNP layers that are lattice-matched to the single-crystal silicon.

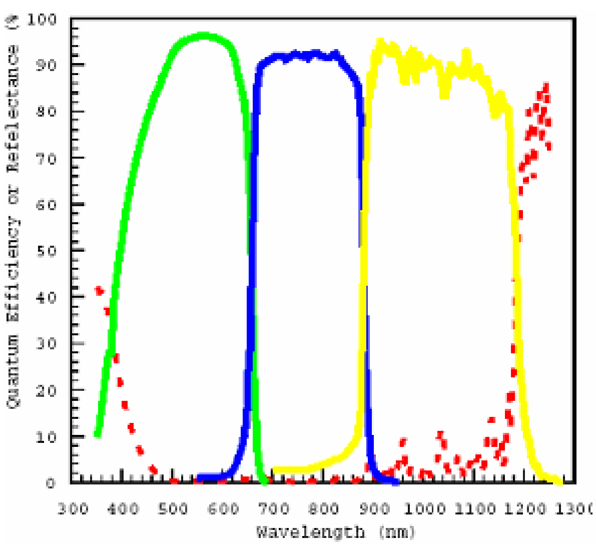

Fig. 4. Composite spectral absolute external quantum efficiency (solid lines) and spectral reflectance (dotted line) data for an ultra-thin, handle-mounted GaInP/GaAs/GaInAs series-connected tandem solar cell.

The electrical quality of GaNP(As) is highly dependent on growth conditions. In particular, growth conditions that minimize unintentional carbon and hydrogen contamination provide the highest carrier lifetimes. Thus, the GaNPAs top junction was grown at 700°C and a growth rate of 1 µm/h. Similar to the case of most GaInNAs material, GaNPAs grown to date appears to have very short diffusion lengths, even when special care is taken to minimize H and C contamination. Figure 5 shows how the spectral response of $GaN_{0.02}P_{0.98}$ grown on silicon increases dramatically with the depletion width. Thus, an n-i-p device employing field-aided collection was used to maximize quantum efficiency (QE). Unlike GaInNAs material grown by metal organic chemical vapor deposition, intrinsic GaNPAs has relatively low carrier concentrations so that high QEs can be achieved in an n-i-p structure.

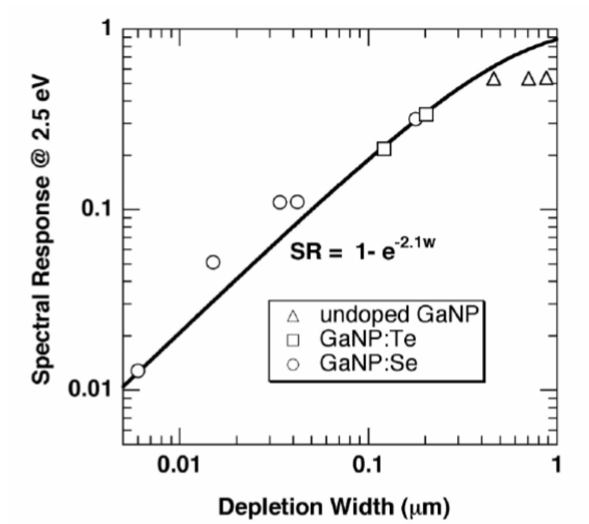

Fig. 5. Spectral response of $GaN_{0.02}P_{0.98}$ grown on silicon for a variety of n-type doping levels. The fit implies short diffusion lengths.

We have demonstrated the first lattice-matched III-V-on-silicon tandem solar cell. It reached only a V_{oc} of 1.53 V, FF of 54%, and J_{sc} of 6.3 mA/cm^2, resulting in an AM1.5G efficiency of 5.2% without any AR coatings. For such a tandem solar cell to achieve efficiencies greater than current state-of-the-art silicon cells and compete with GaInP/GaAs/Ge solar cells, the performance of the top GaNPAs junction and tunnel junction must be further improved. These improvements will require better control over nucleation of III-V on silicon substates, doping of GaP and GaNP(As) materials, and material quality of GaNP(As).

4. Planned FY 2006 Activities

During FY 2006, much of our attention will be focused on relocating facilities and building new tools in the new Science and Technology Facility. This is an important milestone for the PV Subprogram, requiring that most of the research will shut down for the last half of the year. Despite this interruption, this project will also complete several other accomplishments, including:

- Appling combinatorial methods to identify optimum material and demonstrate conductivity >6200 S/cm in In-Ti-O system
- Initiating deposition and processing of CIGS using inkjet-written precursor layers
- Designing and implementing a CIGS processing cluster to explore new pathways to improve manufacturability
- Demonstrating 40%-efficient PV conversion.

5. Major FY 2005 Publications

M.F.A.M. van Hest et al., “Titanium-Doped Indium Oxide: A High-Mobility Transparent Conductor,” *Applied Physics Letters 87,* 032111 (2005).

M.P. Taylor et al., “Combinatorial Growth and Analysis of the Transparent Conducting Oxide ZnO:In (IZO),” *Macromolecular Rapid Communications* 25, 344 (2004).

K. Ramanathan et al., “Properties of High-Efficiency CIGS Thin Film Solar Cells,” *Thin Solid Films* 499, 480–481 (2005).

X. Wu et al. “13.9%-Efficient CdTe Polycrystalline Thin-Film Solar Cells with an Infrared Transmission of ~50%,” accepted for publication, *Prog. In Photovoltaics: Research and Applications,* (August 2005).

Proc. 31st IEEE Photovoltaic Specialists Conference, Orlando, FL, January 3–7, 2005:

M.P. Taylor et al., “Direct Write Contacts for Solar Cells.”

D.J. Friedman et al., “Analysis of Depletion-Region Collection in GaInNAs Solar Cells,” p. 691.

M.W. Wanlass et al., “Lattice-Mismatched Approaches for High Performance III-V Photovoltaic Energy Converters,” pp. 530–535.

Crystalline Silicon Project

Performing Organizations:	National Renewable Energy Laboratory (NREL) DOE Golden Field Office (DOE/GO)
Key Technical Contacts:	David Mooney (NREL, 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 Richard Matson (NREL) University C-Si Research Project Brent Nelson (NREL) Science and Technology Facility
DOE HQ Technology Manager:	Jeffrey Mazer, 202-586-2455, jeffrey.mazer@ee.doe.gov
FY 2005 Budgets:	$3,910K (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 Silicon Center of Excellence for optimizing solar cells through university/industry collaborations on production processes.
- Address issues and further device performance through efforts in heterojunction a-Si:H/c-Si passivation and PV devices, B-O pair defects in p-Czochralski (CZ) wafers, theory and experiment, and c-Si films on glass. Develop novel approaches to low-cost deposition of advanced high-quality c-Si films on glass.
- Direct university research born of fundamental technological concerns of the c-Si PV industry.
- Design and procure a c-Si cluster tool for conducting process-integration R&D in the new NREL Science and Technology Facility

Accomplishments

- Demonstrated a 17%-efficient heterojunction silicon (a-Si/c-Si) solar cell.
- Demonstrated a 12.9%-efficient bifacial heterojunction Si solar cell for p-CZ wafers.
- Deposited 0.4 micron of homo-epitaxial Si on Si by the hot-wire chemical vapor deposition (HWCVD) process for use in templated c-Si film on glass technology.
- Identified and characterized metallic defects affecting most commercially available c-Si solar cells as a function of processing conditions, including a defect-engineering solution to the "dirty silicon" problem (University of California at Berkeley [UC Berkeley]).
- Demonstrated a correlation between in-plane stresses in Si sheet, cell processing, and the critical issue of wafer breakage (Georgia Institute of Technology [Georgia Tech], University of South Florida).
- Achieved a number of record high efficiencies on readily manufacturable screen-printed, low-cost material cells (mc: 18.4%, mc-heat exchanger method [HEM]: 17.1%, edge-defined, film-fed growth [EFG]: 16.6%, String Ribbon: 16.8%) and on c-Si (float zone [FZ]: 19%, Ga-doped CZ: 17.7%) (Georgia Tech).
- Achieved first proof of concept of strong light-bending using silicon textured with a photonic crystal backside (Massachusetts Institute of Technology [MIT]).
- Achieved scalable, uniform, high-pressure, low-temperature, fast HWCVD SiN_x antireflection [AR]/passivation coating on String Ribbon (η=>12.4%) (California Institute of Technology [Caltech]).
- Developed high-sensitivity technique for the detection and characterization of hydrogen and its role in passivation of Si to complement predictions from first principles (Texas Tech University/Lehigh University).

Future Directions

Study and mitigate factors limiting the high-yield manufacture of cost-effective PV devices by identifying and addressing issues related to c-Si materials, cells, and modules through:

- Facilitating an overall integrated effort in the c-Si PV community to produce the next-generation c-Si technology and technologists through university, industry, and NREL partnerships and collaborations.
- Recompeting the c-Si University Project in light of the above more integrative, comprehensive approach to the combined DOE c-Si R&D efforts.
- Finalizing current R&D tasks on high-efficiency, low-cost crystal Si production processes and recompete current Center of Excellence award.
- Developing novel approaches to low-cost deposition of advanced high-quality crystalline silicon films on glass by employing a combination of foreign template buffer layers, solid-phase crystallization, and epitaxial Si growth. Create the scientific understanding that will underlay this development.
- Developing improved heterojunction passivation of c-Si surfaces by use of HWCVD amorphous silicon. Developing both emitter and collectors for silicon heterojunction (SHJ) cells.
- Applying theoretical techniques to understand the mechanism of the increase in recombination after illumination of p-type CZ-Si due to O-B pairs.

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1. Introduction

Beyond the technological mandates for lower cost, higher performing, more durable PV, 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 NREL PV research. This directed, yet fundamental and exploratory, R&D 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; from theoretical studies of the role of hydrogen in passivation to the role of crucible contaminants, wafer sawing, and device processing on device performance; from NREL's leading-edge a-Si/c-Si heterojunction devices to world-class measurement and characterization facilities.

There are currently four distinct components of the DOE Crystalline Silicon Research Project: 1) the NREL in-house fundamental and exploratory research effort, 2) the subcontracted university research effort, 3) the DOE-funded PV Center of Excellence at Georgia Tech, and 4) NREL's new Science and 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. (The S&TF is under construction and scheduled to open June 2006.)

Given the near-term recompetition of both the university c-Si research projects and DOE's PV Center of Excellence contract, coupled with a constellation of other emerging pro-c-Si PV forces within the PV community, this is an optimal time to review the overall architecture of all the program efforts in light of new possibilities and new thinking (e.g., the Systems-Driven Approach). A fresh look at the needs of the technology as a whole, the considerable resources inherent in our universities, industry, and DOE labs, and a reconsideration of every group's strategic position in the game will most likely make for a more effective orchestration of the resources and, therefore, a greater technological impact. Facilitating this process is an ambition for the project in FY 2006.

2. Technical Approach

NREL researchers are working primarily on heterojunction devices, wafer passivation, theoretical and experimental fundamentals of the boron-oxygen defect in Si, thin-film c-Si on foreign substrates, modeling of optical, thermal, and electrical properties and SiN passivation, and some limited work on feedstock issues and crystal growth. Invaluable to the c-Si community at large are the annual NREL-sponsored Workshops on Crystalline Silicon Solar Cells and Modules: Materials and Processes. These workshops are a technical and practical mainstay for the whole community, theoreticians and industrialists alike.

Next, the task for the Georgia Tech Center of Excellence in Silicon Photovoltaics is to advance the current state of c-Si solar cell technology to make it more competitive with conventional energy. It emphasizes fundamental and applied research appropriate for education and advanced degrees, while also performing industry-relevant research.

Complementing the foregoing R&D is the University Crystalline Silicon Research Project, which currently provides applied and exploratory research in c-Si on research topics that serve industry's technical needs as determined by a consensus among the c-Si PV industry, the universities, and NREL staff and management. These topics currently 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 2005 Budget ($K)
NREL c-Si Material and Device Group	2,260
University c-Si PV Research Project	870
DOE/GO Center of Excellence, Georgia Tech	950
Process Integration (S&TF), c-Si Component	500
Technical Coordination	425

3. Results and Accomplishments

3.1 NREL c-Si Research

In 2005, the NREL cSi team developed a 17.1%-efficient heterojunction silicon (a-Si/c-Si) solar cell and demonstrated a bifacial heterojunction silicon solar cell process for p-type c-Si wafers that resulted in 12.5%-efficient cells. The team is also working with IOSIL, a company that has licensed the NREL c-Si group's chemical vapor transport process and is looking for venture capitalists.

In the NREL cSi/aSi heterojunction work, the crystallinity of the deposited layer was determined to be very sensitive to the deposition temperature and crystal orientation of the substrate. Crystallinity, in turn, affects an SHJ solar cell's performance dramatically. The best NREL HWCVD heterojunction cell had the following properties: 663 mV, 34.57 ma/cm^2, 77.75 fill factor (FF) with 17.5% efficiency. The group also developed new approaches to low-cost deposition of advanced high-quality c-Si films on glass by employing a combination of foreign template buffer layers, solid-phase crystallization, and epitaxial growth.

3.2 DOE Center of Excellence for Photovoltaic Research, Education, and Collaboration Program

This group achieved record-high-efficiency 4-cm^2 cells on low-cost materials using 1) photolithography on low-cost materials (17.9%–18.6%) and 2) the more cost-effective and manufacturable screen-printed contacts on low-cost materials (16.1%–18.1%). They also developed screen-printed contacts on textured high-resistance emitters, resulting in 1.2% efficiency enhancement.

3.3 University c-Si Research Project

The project continued targeting c-Si research toward industry needs, as identified at the DOE/NREL Crystalline Silicon Workshop. The research revealed defect passivation in SiN_x films via the growth of high-H content SiN_x films by HWCVD (Caltech); increased the lifetime in ribbon silicon materials 100-fold using a 1-s process (Georgia Tech); and identified and characterized the metallic defects affecting a wide range of commercially available solar cell materials (from four U.S. and five European PV companies) for different processing conditions, using synchrotron-based analytical techniques (UC Berkeley). Other university projects achieved the first quantitative detection of hydrogen introduced into bulk c-Si by the post-deposition annealing of a SiNx AR coating (Texas Tech/Lehigh U.); proved a correlation between in-plane stresses in silicon sheet, cell processing, and the serious problem of wafer breakage (Georgia Tech); and further developed a first proof of concept of strong light-bending using textured silicon with a photonic crystal backside (MIT).

3.4 Crystalline Silicon PV Research Project Management

This component 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.

3.5 Summary of Technical/Technological Impacts

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 if adequate resources are applied to Si R&D. Given the abundance of possible solar-grade and purer silicon, evolving methods for expanding the utility of the anticipated silicon feedstock, a comparatively enormous technological infrastructure to leverage any improvements in the cost and/or performance characteristics of c-Si PV, the global bet (≥94% market share) is placed on c-Si PV for the foreseeable future—most likely at least for the next decade. As such, there is a very compelling case for a dramatically increased U.S. engagement in the global c-Si PV competition in parallel with its existing R&D programs in other PV material and device systems. The most immediate and cost-effective way of augmenting the current U.S. strategic position in this race is to optimally configure existing resources. The National Center for Photovoltaics, DOE PV Center of Excellence, University c-Si Research Project, as well the c-Si PV industry itself represent pools of considerable talent and resources to bring PV to the next level in performance and cost.

4. Planned FY 2006 Activities

- 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 and recompete current Center of Excellence award.
- Continue array of sophisticated experimental and theoretical investigations into the properties of efficiency-limiting defects in c-Si and other material systems and their remediation.
- Form a systematic and integrated effort among the DOE-supported c-Si PV R&D efforts—NREL, Georgia Tech, subcontracted universities, and industry—specifically aimed at reducing costs, increasing performance, *and* improving manufacturing technologies.

5. Major FY 2005 Publications

T.H. Wang, E. Iwaniczko, M.R. Page, D.H. Levi, Y. Yan, V. Yelundur, H.M. Branz, A. Rohatgi, and Q. Wang, "Effective Interfaces in Silicon Heterojunction Solar Cells," *Proc. 31st IEEE Photovoltaic Specialists Conference, 2005*, p. 955.

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*, in press (avail. online), 2005.

C. Wang, H. Zhang, and T. Wang, "Solidification Interface Shape Control in a Continuous Czochralski Silicon Growth System," *J. Crystal Growth,* in press, 2005.

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," submitted to *Phys. Rev. Letters*, July 2005.

Y. Yan, Q. Wang, M. Page, M.M. Al-Jassim, H.M. Branz, and T.H. Wang, "Z-contrast Imaging of the Atomic Structure of c-Si/a-Si:H Interfaces," submitted to *Appl. Phys. Letters,* Sept. 2005

D.H. Levi, C.W. Teplin, E. Iwaniczko, Y. Yan, T.H. Wang, and H.M. Branz, "Real-Time Spectroscopic Ellipsometry as an In Situ Probe of the Growth Dynamics of Amorphous and Epitaxial Crystal Silicon for Photovoltaic Applications," *Materials Research Symposium Proceedings,* Vol. 862 A14.2, 2005.

T.H. Wang, E. Iwaniczko, M.R. Page, Q. Wang, D.H. Levi, Y. Yan, Y. Xu, and H.M. Branz, "High-Performance Amorphous Silicon Emitter for Crystalline Silicon Solar Cells," *Materials Research Symposium Proceedings*, Vol. 862, A23.5, 2005.

6. University and Industry Partners

These organizations partnered in the project's research activities during FY 2005 (no cost share).

University c-Si PV Research Project

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
California Institute of Technology Harry Atwater	Pasadena, CA haa@caltech.edu	Si Passivation and CVD of Si Nitride	43
UC Berkeley Eicke Weber	Berkeley, CA weber@gsonet.org	Efficiency Improvement of Si Solar Cells	112
Georgia Tech Ajeet Rohatgi	Atlanta, GA ajeet.rohatgi@ee.gatech.edu	Fundamental R&D for Improved Crystalline Solar Cells	112
Texas Tech Stefan Estreicher	Lubbock, TX Stefan.estreicher@ttu.edu	Hydrogen Passivation of Si Solar Cells	124
North Carolina State University George Rozgonyi	Raleigh, NC rozgonyi@ncsu.edu	Improved Efficiency and Yield R&D	81
Georgia Tech Steven Danyluk	Atlanta, GA steven.danyluk@ma.gatech.edu	Birefringence of Stresses in Thin Si Sheet	113
MIT Lionel Kimerling	Cambridge, MA lckim@mit.edu	Super Reflector for Thin Crystalline Si Cells	65

DOE Center of Excellence in Crystalline Silicon Project

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
Georgia Tech Ajeet Rohatgi	Atlanta, GA ajeet.rohatgi@ee.gatech.edu	University Photovoltaic Research, Education, and Collaboration Program	950

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 2005 Budget: $6,230K

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
- Multijunction precommercial 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 NREL polycrystalline group demonstrated a four-terminal polycrystalline thin-film tandem cell consisting of a CdTe-based top cell and a CIS-based bottom cell, officially measured by NREL at 15.3% efficiency.
- 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 39%-efficient GaInP/GaInAs/Ge cell that was verified by NREL at 236 suns.
- NREL demonstrated a 37.9%-efficient inverted GaInP/GaAs/GaInAs tandem structure.
- Concentrating Technologies demonstrated a concentrator system using III-V multijunction solar cells.
- Quantum yields of up to 300% (three electron-hole pairs per photon) have been measured in PbSe and PbS quantum dots at photon energies four times the quantum dot bandgap.
- Princeton discovered a new material $Ru(acac)_3$ that is useful as an exciton-blocking layer in organic PV cells.

Future Directions

The project will continue to address key R&D issues in supporting the next phase, "Implementation of Pathways," in late FY 2006.

- Continue development of wide-bandgap material, tunnel junction, and bottom cell toward a 25%-efficient polycrystalline thin-film tandem cell.
- Demonstrate a 40% III-V multijunction solar cell incorporated into a high-concentration module.
- Design 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 Basic Sciences Center, 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.

Sixteen groups, selected competitively, for HiPerf PV Phase IB, "Accelerating and Exploring Ultimate Pathways," will be ending in FY 2006 (see section 6 below).

The Future Generation 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 2005 Budget ($K)
High-Performance PV Management	900
Technical Coordination	340
Thin-Film Polycrystalline Tandems	1,100
III-V Multijunction Concentrators	1,400
Future Generation Project	700
MURA	390
High-Efficiency Concepts	1,400

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 and developing plans for the implementation phase. (09/05) MYTP: Task 1 of Section 4.1.2

The subcontracts under the Polycrystalline Thin-Film Tandems and the III-V Multijunction Concentrators are aimed toward exploring and accelerating issues that will lead into the implementation phase. This implementation phase is expected to occur 01/31/06. The Future Generation subcontracts have been awarded and will be funded for 3 years. MURA subcontracts have been awarded and will be funded for 3 years.

3.2 Thin-Film Polycrystalline Tandems

- Demonstrated 14%-efficient polycrystalline thin-film tandem. (11/05) MYTP: Task 1 of Section 4.1.1.5

The NREL Polycrystalline Thin-Film Group recently demonstrated a four-terminal polycrystalline thin-film tandem cell consisting of a CdTe-based top cell and a CIS-based bottom cell, officially measured at NREL with efficiency of 15.3%. The top CdTe-based cell structure is: Corningglass/Cdstannate/Znstannate/CdS:O/CdT e/Cu_xTe/ITO. The transparency of this structure is about 50%. The device parameter of this cell measured at: V_{oc} = 0.786 volts, J_{sc} = 25.55 ma/cm^2, FF = 68.9, efficiency = 13.8%. The CIS bottom cell structure is: glass/Mo/CIS/CdS/ZnO. Its efficiency as measured under the transparent CdTe cell is 1.5%. This achievement represents a benchmark and a first step for this device; work is ongoing to design material improvements and develop a more optimal structure.

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 EDS, of 23.9% Cu, 11.8 % In, 13.9% Ga, 28.5% Se, and 22.2% S. This composition indicates a bandgap of E_g = 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 39%-efficient III-V multijunction cell under concentration. (09/05) MYTP: Task 1 of Section 4.1.2
- Addressed the operating issues assessed for high-efficiency multijunction cells under a Fresnel lens. (09/05) MYTP: Task 1 of Section 4.1.2

The III-V Multijunction Concentrator Group at NREL demonstrated an inverted GaInP/GaAs/GaInAs tandem structure. This structure was measured at 37.9% efficiency under 10.1 suns.

Boeing Spectrolab achieved a record efficiency of 39.3% for a three-junction terrestrial concentrator cell. This is the highest NREL-confirmed efficiency ever measured for any PV device. This record used three-junction GaInP/GaInAs/Ge concentrator solar cells grown on a Ge substrate incorporating epitaxial device features to optimize their performance under the concentrated terrestrial spectrum and processed at Boeing Spectrolab.

The California Institute of Technology (Caltech) demonstrated the fabrication of the first direct-bond interconnect multijunction solar cell (GaAs/InGaAs two-junction cell). Amonix addressed the operating issues assessed for high-efficiency multijunction cells under a Fresnel lens and will continue efforts.

3.3 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.

Northwestern University identified donor-dopants and negligible grain boundary effects in CdO, the transparent conducting oxide (TCO) with the highest electrical conductivity, and which has potential for high-efficiency organic PV applications. Princeton University discovered a new material $Ru(acac)_3$ that is useful as an exciton-blocking layer in organic solar cells.

3.4 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 the Basic Sciences Center and works directly with NCPV scientists.

Researchers discovered a strong causal link between recombination and transport in dye-sensitized solar cells; demonstrated that the morphological properties of core-shell nano-particle films are profoundly affected by the core; measured extremely high quantum yields of 300% (three excitons per photon were created via efficient multiple-exciton generation [MEG] in quantum dots [nanocrystals]) and developed a totally new theory to explain this phenomenon; and developed a quantitative assessment of the probability of (1) carrier multiplication and (2) hot electrons in quantum dots for solar cells.

Efforts are under way on monolithic multijunction tandem ultra-thin strain-counterbalanced solar photovoltaic converters with optimal subcell bandgaps. The approach involves inverted, lattice-mismatched heterostructures that can contain two to five (or possibly more) subcells (i.e., absorber bandgaps). The inverted structures allow the monolithic integration of high-, medium-, and low-bandgap materials through the use of transparent compositionally graded layers.

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

3.5 Minority University Research Associates
Continuation of awards from the RFPs of fall 2003 includes eight minority-serving universities (six HBCUs and two Hispanic-serving universities). Accomplishments include: identification and integration of a software tool for the design and analysis of solar concentrating systems; development and implementation of simulation tools for analysis of solar concentrating systems (University of Texas at Brownsville); and fabrication of ZnO thin film and nanorods, TiO_2 thin film and nanorods, and the development of highly transparent and durable nanolayer polymer substrate in collaboration with Case Western Reserve University. The Renewable Energy Academic Partnership (REAP) Review Meeting was held August 7–10, 2005, in conjunction with the Crystalline Silicon Workshop in Vail, CO. Presentations generated interesting discussions, which demonstrated great enthusiasm by participants towards the individual projects. The DOE NREL MURA Program is receiving worldwide recognition for its unique efforts. The MURA effort produced 43 publications during the year.

4. Planned FY 2006 Activities

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

Next-phase implementation efforts in the area of Polycrystalline Thin-Film Tandems and III-V Multijunction Concentrators are expected to result from the subcontracts and in-house R&D under the FY 2005 activities. The stage-gate process will provide go/no-go decisions. The Future Generation subcontracts will continue as planned. MURA subcontracts will continue as planned.

- Finalization of subcontracts under "Exploring and Accelerating Pathways towards High Performance PV: Phase I-B" through FY 2006/2007. Begin Implementation efforts and solicitation for letters of interest to be issued. This will be based on the stage-gate process. Complete an award under this Implementation phase by January, 2007.
- Demonstrate 15%-efficient polycrystalline thin-film tandem.
- Demonstrate a 40%-efficient III-V multijunction cell under concentration.
- Continue modeling of the enhanced performance of quantum-dot-based solar cells ial configurations to see how far one can push the MEG effect in various PV cell configurations to maximize cell efficiency.
- Continue studies of properties and determine dopability of wide-gap top cell candidate materials, including $CuGaSe_2$ and related compounds.
- 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 2005 Publications

R. McConnell, M. Symko-Davies, S. Kurtz, “Concentrator Photovoltaic Technologies,” *ISES Refocus Magazine,* July/August (2005).

R. McConnell, M. Symko-Davies, “DOE High Performance Concentrator PV Project,” *International Solar Concentrator Conference*, (2005).

M. Symko-Davies, “High Performance PV Future: Polycrystalline Thin-Film Tandems” (presentation and paper), *20th European PV Solar Energy Conference and Exhibition,* Barcelona, Spain, June 2005.

McConnell, R., Symko-Davies, M., S. Kurtz, PV FAQs. “What’s New in Concentrating PV?” U.S. Department of Energy, EERE, NREL Report No. CD-520-35349.

R.D. McConnell and M. Symko-Davies, “High-Performance PV Future: III-V Multijunction

Concentrators" (plenary presentation and paper), *20th European PV Solar Energy Conference and Exhibition*, Barcelona, Spain, June 2005.

M. Symko-Davies, "Status of High Performance PV: Polycrystalline Thin-Film Tandems," *31st IEEE PVSC,* Florida, 2005.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
Polycrystalline Thin-Film Tandems				
Georgia Institute of Technology Ajeet Rohatgi	Atlanta, GA Ajeet.Rohatgi@ece.gatech.edu	Thin-Film Si Bottom Cells for Tandem Device Structures	130 20*	0
University of Delaware Bill Shafarman	Newark, DE wns@udel.edu	High-Performance PV-Polycrystalline Thin-Film Tandem Cells	211	0
University of Toledo Alvin Compaan	Toledo, OH adc@physics.utoledo.edu	Sputtered II-VI Alloys and Structures for Tandem PV	235 20*	0
University of Florida Oscar Crisalle	Gainesville, FL crisalle@che.ufl.edu	Identification of Critical Paths in the Manufacturing of Low-Cost High-Efficiency CGS/CIS Tandems	50	0
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	104 14*	0
Oregon State University Douglas Keszler	Corvallis, OR Douglas.keszler@orst.edu	Novel Materials Development for Polycrystalline Thin-Film Solar Cells	160	0
III-V Multijunction Concentrators				
Spectrolab, Inc. Raed Sherif	Sylmar, CA rsherif@spectrolab.com	Ultra-High-Efficiency Multijunction Cell and Receiver Module	207 50*	40
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 48*	50
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	207	0
JX Crystals Lew Fraas	Issaquah, WA lfraas@jxcrystals.com	Toward 40% Efficient Mechanically Stacked III-V Terrestrial Concentrator Cells	150 12*	0
University of Delaware Christiana Honsberg	Newark, DE honsberg@ece.gatech.edu	Novel High Efficiency PV Devices Based on the III-N Material System	55 16*	0
Ohio State University Steve Ringel	Colombus, OH ringel@ee.eng.ohio-state.edu	Optimized III-V Multijunction Concentrator Solar Cells on Patterned Si and Ge Substrates	90	0

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)[a]	Cost Share ($K)
Concentrating Technologies Steven Kusek	Huntsville, AL kusek@bellsouth.net	A Scaleable High-Concentration PV System	75	0
Arizona State University Liang Ji	Phoenix, AZ Liang.ji@us.ul.com	Development of IEC Design Qualification Standard for Concentrator PV Modules	10	0
Future Generation Project				
Princeton University Steve Forrest	Princeton, NJ forrest@ee.princeton.edu	Approaching 10% Efficient Cells Using Tandem Organic PV Cell with Enhanced Optical Coating	95	0
University of Colorado-Boulder Josef Michl	Boulder, CO michlj@colorado.edu	Ultra-High Efficiency Excitonic Solar Cells	225	0
Northwestern University Tom Mason	Evanston, IL tmason@northwestern.edu	Interface and Electrodes for Next-Generation Organic Solar Cells	105 42*	0
University of Delaware Christiana Honsberg	Newark, DE honsberg@ee.udel.edu	Theoretical and Experimental Investigation of Approaches to >50% Efficient Solar Cells	73	0
Minority University Research Associates Project				
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	41	0
University of Texas, El Paso Gregory Lush	El Paso, TX glush@gerdau.com	Investigation, fabrication, characterization, and modeling of solar cells	40	0
Fisk University Richard Mu	Nashville, TN rmu@fisk.edu	Development of Si Q-dots for advanced solar cells with maximum efficiency	28	0
Howard University J.M. Momoh	Washington, DC jmomoh@msn.com	Developing automation/strategies to improve power management and distribution of renewable energy resources	39	0
N. Carolina Central University Joe Dutta	Durham, NC jmd@nccu.edu	Fabricating and characterizing bulk and non-phase PV materials for student research.	49	0
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.	33	0
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.	48	0
Central State University Clark Fuller	Wilberforce, OH cfuller@prodigy.net	Renewable energy technology and technology transfer in developing countries.	58	0

* Funded with prior year (FY 2004) funds.

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 2005 Budget: $450K

Objectives

- Produce a 10-year update (1991–2000) of the National Solar Radiation Data Base (NSRDB).
- Produce an enhanced 10-km gridded data solar product for the United States.
- Organize and implement a new task called "Solar Resource Knowledge Management" under the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme.

Accomplishments

- Evaluated performance of three candidate solar radiation models for the NSRDB.
- Developed recommendations for an NSRDB update plan.
- Task 36 "Solar Resource Knowledge Management" approved by the IEA SHC with NREL serving as Operating Agent.

Future Directions

- Produce and distribute a 10-year update along with single-year annual updates.
- Investigate methods of producing a 10-km gridded data set for 199–1998.
- 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 International Energy Agency "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. With the solar resource model performance evaluations completed, we are now in a position to produce an updated NSRDB. By examining tools, availability of input data, processing constraints, and uncertainties of the output product, we developed an NSRDB update plan and continued work to:

- Make recommendations on which model to use.
- Develop recommendations for NSRDB update methods.
- Solicit input from NSRDB stakeholders.
- Develop an NSRDB update plan.
- Produce a draft 10-year NSRDB update.

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. A technical Annex and Work Plan were finalized and approved at the Solar Heating and Cooling Executive Committee meeting in June 2005, and NREL was selected as the Operating Agent. Preparations are under way for the first task meeting, to be held at DLR near Munich, Germany, November 16–18, 2005. A second task meeting is contemplated for July 2006 in conjunction with Solar 2006 in Denver, Colorado. A first-year technical report will be issued in September 2006. Two task meetings per year are contemplated over the 5-year duration of the project, and a number of deliverables, spelled out in the Work Plan, will be produced as a result of the task work.

Total project funding for FY 2005 was $450K, broken down in the following table:

Task Title	FY 2005 Budget ($K)
IEA Task 36 Solar Resource Knowledge Management	100
NSRDB Update	350

3. Results and Accomplishments

3.1 National Solar Radiation Data Base

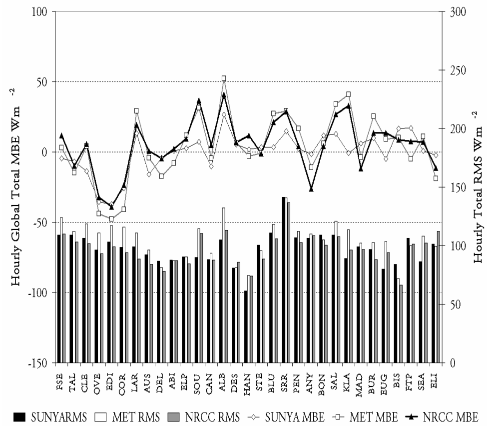
The changeover to automated stations by the National Weather Service eliminated the human observed total and opaque sky cover amounts used for inputs to the METSTAT model, which was used for the 1961–1990 NSRDB. To adapt the model to currently available data sets, we derived equivalent sky cover inputs (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.

A significant part of our effort was to find, acquire, and quality-assess surface solar measurements to form a data set for model evaluation. For the model evaluation work, 33 sites with nearby meteorological stations were identified and data acquired from various solar measurement networks, including the Surface Radiation Budget Network (SURFRAD), Integrated Surface Irradiance Study (ISIS), University of Oregon, University of Texas, and the NREL Historically Black Colleges and Universities (HBCU) network. All available data were downloaded to NREL computers and imported to an interim database for evaluation with quality-assessment tools.

One goal of the updated NSRDB is a spatial resolution greater than the ancillary interpolated products that were originally produced from the 239 NSRDB meteorological stations. Toward that end, the project evaluated a model from the Atmospheric Sciences Research Center (ASRC) at SUNY Albany. This SUNYA model derives 10-km pixel solar estimates based on differences between a pixel's clear-sky reflectance as seen by the satellite and the brighter values that occur with increasing cloud reflectance of incoming solar radiation.

The analysis of the test data sets included those hours from all sites for which measured and output data for all models were concurrent and compared the measured data to the output for each model using the statistical measures of root square mean error (RMSE), mean bias error (MBE), frequency distributions, probability distributions, correlation, and autocorrelation.

In the figure below, the analysis reveals little significant differences among the three candidate models (Northeast Regional Climate Center, SUNYA, and METSTAT).



Our analysis illustrates not only the closeness of the model performance, but also the similarity of excursions for all models in site-to-site variability. These excursions may indicate a common bias in the models or input data, or an error in the ground validation data. Whatever the cause, it is important in this context to note that all models perform similarly.

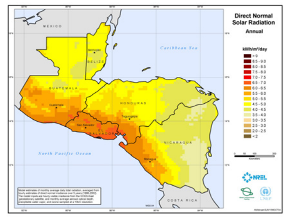
3.2 "Solar Resource Knowledge Management" IEA Task 36

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

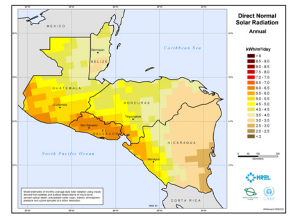
Subtask A: This is a standard qualification for solar resource products. This subtask will develop and produce deliverables designed to provide:

- Coherence and benchmarking of models producing surface irradiance values from satellite data (these will include SUNYA, NREL 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.

An example of visual benchmarking approaches is shown in the figures below, which compare the SUNYA with the NREL CSR model results applied for Central America.



SUNYA



NREL CSR

Subtask B: Common structure for archiving and accessing resource products. This subtask will develop and produce deliverables designed to provide:

- 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 the existing knowledge and precursor Web services, such as the portals SoDa or NASA services, to construct an advanced prototype of the 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 (e.g., NASA, German Aerospace Center [DLR]) are deemed to have a strong strategic interest in maintaining these resources, whether on a free or commercial basis. In the latter case, other sources of revenues may be obtained by opening to other domains such as agriculture or tourism. The Web service (entry point) will be made of core software only and will be easy to maintain, transfer, operate, and duplicate (to ensure reliability). This service will be maintained by motivated partners, such as Armines, with possible commercial revenues.

Subtask C: Improved techniques for solar resource characterization and forecasts. This subtask mainly covers R&D work and will result in deliverables providing:

- Short-term (hours) to medium-term (days) solar resource forecasting
- Climatological analysis of long-term variability and trends of solar resources
- Improved exploitation of existing satellite resources (e.g., very high spatial resolution for plant micro-siting)
- Adaptation of resource assessment techniques to the capabilities of new generations of satellites
- Development of new methods to provide improved products, such as spectrally or angularly resolved information.

4. Planned FY 2006 Activities

At the current level of funding, the planned release of the updated 1991–2000 NSRDB will occur in 2006, which will leave even the most recent data 5 years old. Part of our production plan includes a method to produce incremental annual updates, which will be immediately applied to years 2001–2005, then annually 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.

Benchmarking with International Data Sets: IEA Task 36 will provide standardization, better data reliability and availability, and improved spatial and temporal coverage, with customized solar resource products, including reliable solar radiation forecasts that are easily accessible to energy developers and planners throughout the world. In FY 2006, two technical workshops will be held to implement this work. The first will be held at DLR in Germany, November 16–18, 2005, where the three subtask leaders will develop final subtask plans and begin the process of assembling existing relevant studies and data. A follow-on workshop is planned for Denver in July 2006, where subtask participants will present activity progress and the first-year technical report will be drafted.

5. Major FY 2005 Publications

Gueymard, C. and R. George, “Gridded Aerosol Optical Depth Climatological Datasets over Continents for Solar Radiation Modeling,” *Proc. Solar World Congress,* International Solar Energy Society, 2005.

Myers, D., S. Wilcox, W. Marion, R. George, M. Anderberg, “Broadband Model Performance for an Updated National Solar Radiation Data Base in the United States of America,” *Proc. Solar World Congress,* International Solar Energy Society, 2005.

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. “Progress on an Updated National Solar Radiation Data Base,” *Proc. Solar World Congress,* International Solar Energy Society, 2005.

Renné, D.S. and Task Participants, 2005: “ Work Plan and Annex, Solar Resource Knowledge Management,” Task 36 of the IEA SHC Programme.

6. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($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.	25	8.1
Solar Consultant Services Chris Gueymard	New Myrna Beach, FL Chris@SolarConsultingServices.com	Investigate comparison of model performance using daily measured aerosol values versus monthly mean data sets.	15	0

Environmental Health and Safety

Performing Organization: Brookhaven National Laboratory

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 2005 Budget: $420K

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 life-cycle analysis (LCA) of the balance of systems (BOS) of the Tucson Electric Power Springerville 3.5-MW c-Si plant; computed energy payback times to be 70% lower than the previously published estimates (paper was accepted for publication in *Progress in Photovoltaics*).
- Advanced CdTe recycling by accomplishing a 99.99% separation of Cd from Te at a projected cost of 2¢ /W.
- Conducted fire-simulating experiments on CIGS PV modules.
- Prepared an Environmental Inventory Analysis of Metals (Zn, Cd, In, Ge, Ga, Cu, Se, Te) in PV modules.
- Began a project to compare greenhouse gas emissions during the life cycle of PV and nuclear fuel cycles.
- Conducted experiments of leaching indium and selenium from CIGS modules.
- Assisted DayStar Tech, First Solar, and the University of Toledo with site-specific EH&S issues.
- Organized a workshop for the International Energy Agency in conjunction with the 20th EURPVSEC, Barcelona, Spain.
- Answered several requests for EH&S information from the public and the industry.

Future Directions

- Update LCAs of all commercial PV technologies.
- Conduct and coordinate LCA-based comparisons of environmental and societal benefits and risks of PV versus other energy technologies.
- Continue industry outreach with guidance on hazard analysis and other EH&S issues.
- Communicate to the public, technical community, business partners and policy makers.
- Guide the pollution prevention and waste management in PV manufacturing facilities.
- Advance the technical and economic feasibility of recycling of manufacturing waste and spent modules.
- Assess safer delivery options for toxic and flammable materials in PV manufacturing.
- Assess safer alternative sources for toxic and explosive gases in PV manufacturing.
- Assess and guide fluorocarbon use and emissions reduction in current and future (large-scale) PV manufacturing.
- Contribute to studies for higher material utilization in PV manufacturing.
- Study potential EH&S issues related to new PV technologies, processes, and materials.

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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, 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. The Center works closely with the Thin-Film PV Partnership and other NREL projects.

2. Technical Approach

The major areas of Brookhaven National Laboratory's (BNL'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 2005, we conducted: (1) a life-cycle analysis (LCA) of the BOS of the Tucson Electric Power (TEP) Springerville plant; (2) fire-simulating experiments on CIGS modules; (3) quantification of emission factors for all the metallic elements used in PV modules; and (4) collaborative work on LCA-based comparisons of PV and nuclear power generation.

Task 2: Hazard Management. In FY 2005, we advanced the recycling of CdTe PV by accomplishing a 99.99% separation of Cd form Te at a projected cost of 2¢/W. Also, we started experimental research on recovering indium from CIGS PV modules.

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 2005 Budget ($K)
Hazard Identification/Characterization	200
Hazard Management/Recycling	90
Industry Outreach/DOE/NCPV	78
Information Dissemination	52

3. Results and Accomplishments

- Task 1. Conducted an LCA of the BOS of the TEP Springerville 3.5-MW c-Si plant; assessed energy payback times to be 70% lower than the previously published estimates (paper was accepted for publication in *Progress in Photovoltaics*).
- Conducted fire-simulating experiments on CIGS PV modules; put results in the context of emissions from coal power plants.
- Wrote a comprehensive report on the upstream emissions of metals used in PV modules.
- Task 2. Advanced the recycling of CdTe PV by accomplishing a 99.99 % separation of Cd from Te at a projected cost of 2¢/W. Papers were accepted by the *Journal of Hazardous Materials* and *Progress in Photovoltaics Research and Applications.*
- Task 3. Provided facility-specific assistance to First Solar and DayStar Tech. At the request of DOE, we organized a PV EH&S task workshop for IEA.
- Task 4. Answered several requests for EH&S information from different agencies, business partners, citizen organizations and the media.

4. Planned FY 2006 Activities

Hazard Identification/Characterization

- Complete an LCA of commercial CdTe PV systems.
- Conduct LCA-based comparisons of greenhouse-gas emissions and risks in the PV and nuclear fuel life cycles.
- Start LCA investigation of III/IV concentrator systems.

Hazard Management/Recycling

- Improve recovery and purity of Cd and Te in CdTe Recycling
- Guide pollution prevention and waste management in PV manufacturing

Industry Outreach/Support to DOE and NCPV
Support this activity as required.

Information Dissemination
Support this activity as required.

5. Major FY 2005 Publications

Fthenakis V.M., Alsema E., and M.J. de Wild-Scholten, "Life Cycle Assessment of Photovoltaics: Perceptions, Needs, and Challenges," *Proc. 31st IEEE PV Specialists Conference,* Jan. 3–7, 2005, Orlando, FL.

Wang W. and Fthenakis V.M., "Feasibility of Recycling of Cadmium-Telluride Photovoltaics," *The Minerals, Metals & Materials Society Extraction & Processing Division Congress 2005*, pp. 1053–1064.

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,* in press.

Wang W. and Fthenakis V.M., "Kinetics Study on Separation of Cadmium from Tellurium in Acidic Solution Media Using Cation Exchange Resin," *Journal of Hazardous Materials*, in press.

Fthenakis V.M. and Wang W., "Advances towards the Recycling of Cadmium Telluride Photovoltaic Modules," accepted for publication in *Progress in Photovoltaics*.

Mason J., Fthenakis V.M., Hansen T. and Kim C.. "Energy Pay-Back and Life Cycle CO_2 Emissions of the BOS in an Optimized 3.5 MW PV Installation," *Progress in Photovoltaics,* in press.

Fthenakis V., "Promising Advances in Photovoltaics," Critical Issues Editorial, *Chemical Engineering Progress*, 101(4), 5, 2005.

Fthenakis V.M. and Wang W., "Emission Factors in the Production of Materials Used in Photovoltaics," *20th EURPVSEC*, Barcelona, Spain, June 6–10, 2005.

Fthenakis V.M. and Wang W., "Advances on Recycling of CdTe and CIGS Photovoltaic Modules," *20th EURPVSEC*, Barcelona, Spain, June 6–10, 2005.

Fthenakis V.M., *International Energy Agency Environmental Health & Safety Workshop*, Barcelona, Spain, June 8, 2005.

Fthenakis V.M. (contributing author), "Electronics Industry Emissions," Draft 2006 Intergovernmental Panel for Climate Change Guidelines for National Greenhouse Gas Inventories, Aug. 17, 2005.

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 are comprised of laboratory, industry, and university researchers who work to solve generic issues as well as industry-specific problems.

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.

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 seeks to improve inverters and balance of systems (BOS) through the High-Reliability Inverter Initiative.

Achievements in FY 2005 include the following.

Thin Film PV Partnership

- With Global Solar Energy, fabricated a 10.2%-efficient, 88.9-W thin-film CIGS power module, the highest wattage CIGS module in the world.
- With First Solar and United Solar Ovonic, broke ground on major manufacturing expansions (First Solar 50 MWp and Uni-Solar 25 MWp).
- Overall, production of thin films in the United States grew from 12 MWp in 2003 to an estimated >40 MWp in 2005.

PV Manufacturing R&D

- With Sinton Consulting, received an R&D 100 Award for the quasi-steady-state photoconductance Silicon Evaluation System developed under an FY 2004 "In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up" subcontract for the measurement of bulk minority-carrier lifetime.
- With ITN Energy Systems, implemented production-line improvements that resulted in an 85% increase in yield and a 13% increase in cell efficiency.
- With PowerLight Corporation, completed a prototype foamless PV roof tile design and implemented production of PowerGuard tiles that do not require added insulation.

PV Module Reliability R&D

- Initiated unique high-voltage stress testing experiment that measures module leakage currents to ground on a bipolar array supplied by Shell Solar consisting of CIGSS modules.
- Initiated cooperative reliability testing program for SunPower's high-efficiency c-Si modules, including light soaking, thermal cycling, and damp heat exposure indoors and real-time outdoor exposure.

Inverter and BOS Development

- Completed Phase II of the High-Reliability Inverter Initiative with hardware deliverables from GE and Xantrex.
- Initiated "High-Tech Inverter, Balance-of-System, and Systems R&D" project with a FedBizOps announcement and draft of a request for proposal to begin the project.

Thin Film PV Partnership

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

Key Technical Contact: Ken Zweibel (NREL), 303-384-6441, ken_zweibel@nrel.gov

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

FY 2005 Budget: $9,096K (NREL)

Objectives

- Support the near-term transition to first-time manufacturing and commercial introduction of reliable thin-film a-Si, CIS, CdTe, and film silicon modules.
- Build a technology base upon which these advanced PV technologies can successfully improve 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 four Joule milestones.
- Two Technology Partners broke ground on major manufacturing expansions (First Solar 50 MWp, and Uni-Solar 25 MWp).
- Production of thin films in the United States grew from 12 MWp in 2003 to an estimated >40 MWp in 2005.

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 manufacturing.
- Direct CdTe research toward higher voltage.
- Investigate nanocrystalline bottom cells for thin-film silicon multijunctions.

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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 *DOE Solar Program Multi-Year Technical Plan* (MYTP) long-term goals for low-cost PV and the PV industry's 20-year roadmap. The Thin Film PV Partnership 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 internal 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 EH&S (the latter with Brookhaven National Laboratory). The National Teams are made up of leading researchers from U.S. industry, universities, and NREL, who work together to define and carry out shared activities.

2. Technical Approach

The Partnership had about 30 subcontracts (see below) during FY 2005, about eight of which are ending. The subcontract areas were broken down as shown in Table 1.

Table 1. Thin Film PV Partnership Funding

Task Title	FY 2005 Budget ($K)
Project Management and Team Coordination	830
In-House Collaborations	825
Thin Film Center of Excellence	1,110
Amorphous and Thin Film Silicon	1,958
CIS Devices	2,158
CdTe Devices	2,013
Module Testing and Analysis	202

Four subcontracts were major Technology Partner contracts: Shell Solar and Global Solar in CIS; First Solar in CdTe; and United Solar Ovonic (Uni-Solar) in a-Si. 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 (see Fig. 1). 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 2005 to more than 40 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 2006 to about 80 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). The following summarizes highlights from FY 2005.

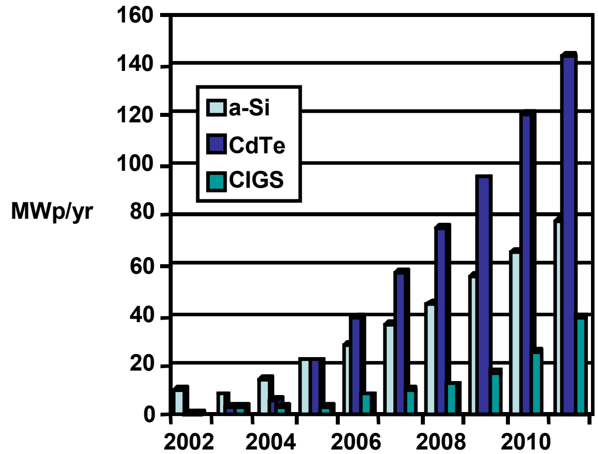

Fig. 1. Historical and predicted MWp thin-film module manufacturing in the United States, broken down by technology. A survey of the Partnership's Technology Partners suggests that U.S. thin-film manufacturing is going through a major growth period, and new thin films are joining amorphous silicon in the marketplace (FY 2005 is preliminary data; FY 2006 is planned sales).

3.1 First Solar 50-MWp Factory Expansion

The First Solar 50-MWp groundbreaking was a major event, with several hundred people in attendance, including media and political representatives from local, state, and federal levels (see Fig. 2). First Solar plans to produce about 22.0 MW_p in 2005, 40 MW_p in 2006, and 75 MWp in 2007.

Fig. 2. Those at the groundbreaking of First Solar's 50-MWp factory expansion include DOE Solar Program Manager Ray Sutula, First Solar COO Chip Hambro, and state government representatives, who provided funding support to help locate the expansion in Ohio.

We attended a tour of the First Solar 25-MWp facility before the ceremony. Substantial progress has been made in terms of (1) the new 25-MWp coater, which is now fabricating about 20% of the product; (2) reducing maintenance costs by substantially enhancing materials utilization rates; and (3) automating and improving most aspects of production. During his speech, Hambro stated that First Solar is now breaking even. He also provided information on his sales price and volume that would allow us to estimate his costs as among the lowest in all of PV. Separate discussions with Marketing Director Ken Schultz centered on 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.

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 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, Assistant Secretary, Energy Efficiency and Renewable Energy, and Under Secretary, U.S. Department of Energy.

3.2 Uni-Solar 25-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 announced plans to build a second 25-MWp plant, also in Michigan. 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 to large commercial rooftop projects, one for 1 MW on the GM building and another for 750 kW in California.

Fig. 3. The Uni-Solar a-Si factory produces peel-and-stick thin-film PV roofing material. The product's easy installation is demonstrated on a building in China.

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.

3.3 Completion of Four DOE Joule Milestones

Four DOE Joule milestones were completed within the Partnership. Three of them are related to achieving a higher efficiency thin-film module, progressing from 10% to 11% (the final milestone) by the end of the fiscal year. These milestones were all achieved by Shell Solar Industries (a Technology Partner) for selenized CIGS modules. The other Joule milestone concerned the completion of the Partnership's latest recompetition Letters of Interest and the signing of all the awardees in a timely manner.

3.4 Global Solar Fabricates Record CIGS Module

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. This result meets a level-4 milestone in the Thin Film Partnership/NCPV project due 8/31/05. 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.

3.5 Flow of Venture Capital to CIGS Start-Ups Accelerates

We note the acceleration of private and venture capital funding (over $100M) to CIGS 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. In the last month, announcements of major investment have come from: Wurth Solar (55M Euros), Miasole ($16M), Nanosolar ($20M), and Heliovolt ($8M). Wurth Solar is a German company that bases its technology on multi-source evaporation, harkening back to the original CIGS work at Boeing and within NREL (all DOE supported). Wurth has about 1–2 MWp of current CIGS production and makes the most efficient thin-film product in the world (about 11% total area efficiency).

The other three are U.S. start-ups that are pre-commercial; 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 (5%–10%). NREL support has been mostly from consultation or Cooperative Research and Development Agreements (CRADAs) with in-house CIGS experts and the NREL Measurements and Characterization Group; and work with the NREL CIS National Research Team. We are starting a new subcontract with one (Nanosolar) to do work in high-throughput selenization of foil-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 and Heliovolt, and another recent start-up, Daystar ($9M from a public offering in 2004), so 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 founder Billy Stanbery, was funded by the Partnership at Boeing and later at the University of Florida; Nanosolar head of R&D Chris Eberspacher was funded by the Partnership at Unisun; and Miasole received direct NREL in-house support via Rommel Noufi and his CIGS team.

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

3.6 Thin Film Partnership Management

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

Web Site. We completed a major update of the Partnership Web site to make it much more accessible. This was accomplished by:

- Including descriptive text with each entry.
- Making the whole site searchable by keywords and authors. This is a very powerful tool.
- Adding a "most recent" list of the last 10 items posted for those who just 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 films, we expect the site to be used frequently. Before even being announced, the Web site had 200 hits on April 4, 2005 (site URL: www.nrel.gov/ncpv/thin_film), and now averages over a thousand per day.

PV Materials FAQ. We added a new 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 BOS at Tucson Electric (3 months!) 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 2 and 3). Updated versions are posted on our Web site and can be found via the search page.

Table 2. Best Large-Area, Thin Film Modules
(standard conditions, aperture area)

Company	Device	Size (cm^2)	Efficiency	Power	Date
Mitsubishi Heavy*	Glass/a-Si	15625	6.4% (stabilized)	100 W	7/05
Global Solar Energy	CdS/CIGS/SS	8709	10.2%	88.9 W	5/05
Wurth Solar	CdS/CIGS/glass	6500	13%	84.6 W	6/04
United Solar	a-Si/a-SiGe/a-SiGe/SS	9276	7.6% (stabilized)	70.8 W	9/97
First Solar	Glass/CdS/CdTe	6624	10.2%	67.4 W	2/04
Shell Solar GMBH	CIS-alloy/CdS/glass	4938	13.1%	64.8 W	6/04
Sharp*	Glass/a-Si/nano-Si	4770	11% (stabilized)	52.5 W	7/05
Antec Solar*	Glass/CdS/CdTe	6633	7.3%	52.3 W	6/04
Kaneka	Glass/a-Si	8100	6.3% (stabilized)	51 W	7/04
Shell Solar Industries	CdS/CIS-alloy	3644	12.9%	46.8 W	5/05
Showa Shell*	$Zn(O,S,OH)_x$/CIGS/Glass	3459	13.4% (4 1-ft^2 modules laminated together)	46.45 W	8/02
EPV	Glass/a-Si/a-Si	7432	5.7% (stabilized)	42.3 W	10/02
United Solar	a-Si triple/SS	4519	7.9% (stabilized)	35.7 W	6/97

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

Table 3. 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	**WürthSolar** WS31050/80 (CIS)	80	Above $3	-0.36 %/ºC
9.4	**Shell Solar** ST-40 (CIS)	40	Above $3	-0.6 %/ºC**
9.0	**First Solar** FS65 (CdTe)	65	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	$3.3	-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; 8/2005
*Temperature coefficients will vary slightly depending on local spectral content.
**Company source reports -0.48%/ºC may be more accurate for recent product.
Disclaimer: Listing could be outdated or incomplete (missing manufacturers and/or some "best" product); prices are estimates for large quantities.

4. Planned FY 2006 Activities

In FY 2006, 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 2006, 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 40 MW in CY 2005, and perhaps doubling again in CY2006. Any setbacks in manufacturing yield or outdoor reliability could lead to multi-year setbacks or even technology abandonment in extreme cases.

5. Major FY 2005 Publications

Bolko von Roedern (Aug. 2005), "Silicon PV Technology at a Crossroad?" *15th Crystalline Silicon Workshop, Vail, CO Aug. 7-10, 2005.*

B. von Roedern, K. Zweibel, H.S. Ullal, 2005, "The Role of Polycrystalline Thin Film Technologies for Achieving Mid-Term, Market-Competitive, PV Modules," *Proceedings of the IEEE PV Specialists Meeting, Orlando, FL, Jan 2005*.

K. Zweibel (September 2005), *The Terawatt Challenge for Thin Film PV*, NREL/TP-5200-38350.

K. Zweibel, H. S. Ullal, B. Von Roedern (October and November 2004), "Finally: Thin Film PV!" in *Photon International*, M. Schmela (ed).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
Case Western University Frank Ernst	Cleveland, OH fxe5@po.cwru.edu	Liquid-phase deposition of α-CIS thin layers	35 (ended during FY)	0
Colorado School of Mines Tim Ohno	Golden, CO tohno@mines.edu	Characterization and analysis of CdTe cells	97 (plus 110 for FY 06)	0
Colorado School of Mines Don Williamson	Golden, CO dwilliam@mines.edu	Structure of silicon-based thin-film solar cell materials	10 (ended during FY)	0
Colorado State University Jim Sites	Ft. Collins, CO sites@lamar.colostate.edu	Analysis of CIS and CdTe devices	150	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	420	0
Energy Conversion Devices Scott Jones	Troy, MI sjones@ovonic.com	Improved multiplayer back reflectors and nc-Si low-bandgap sub-cells for a-Si multijunction solar cells	346 (ended during FY)	100
Energy Photovoltaics Alan Delahoy	Lawrenceville, NJ a.delahoy@epv.net	Advanced CIGS photovoltaic technology	337	70
Energy Photovoltaics Yuan-Min Li	Lawrenceville, NJ y.li@epv.net	Advanced deposition techniques for microcrystalline silicon solar cells and modules	0 (ended during FY)	0
First Solar, LLC Rick Powell	Perrysburg, OH rcpowell@firstsolar.com	Expanding the Limits of CdTe PV Performance	133	85
First Solar, LLC Rick Powell	Perrysburg, OH rcpowell@firstsolar.com	Research leading to high-throughput processing of thin-film CdTe PV technology	700	700
Florida Solar Energy Center Neelkanth Dhere	Cocoa, FL dhere@fsec.ucf.edu	CIGSS solar cells by selenization and sulfurization	116	10
Florida Solar Energy Center Neelkanth Dhere	Cocoa, FL dhere@fsec.ucf.edu	Module reliability testing in hot and humid climate	131	0
Global Solar Energy Markus Beck	Tucson, AZ mbeck@globalsolar.com	Tolerance of three-stage CIGS deposition to variations imposed by roll-to-roll processing	242	242
International Solar Electric Technologies Vijay Kapur	Inglewood, CA vkkapur@isetinc.com	Lab to large-scale transition for non-vacuum thin-film CIGS solar cells	297 (plus 200K FY04 for FY06)	60
Iowa State University Vik Dalal	Ames, IA vdalal@iastate.edu	High-efficiency, narrow-gap, and tandem-junction devices	63 (ended during FY)	0
ITN Energy Systems Ingrid Repins	Littleton, CO irepins@itnes.com	Plasma-assisted co-evaporation of S and Se for wide-bandgap chalcopyrite photovoltaics	90 (ended during FY)	10
NanoSolar Chris Eberspacher	Palo Alto, CA chris@nanosolar.com	High productivity annealing for thin film CIS PV	67	3.35
National Institute of Standards and Technology Alan Gallagher	Boulder, CO alang@jila.colorado.edu	Measurement of depositing and bombarding species in the plasma deposition of a-Si:H and a-SiGe:H cells	0 (ended during FY)	0
Pennsylvania State U. Chris Wronski	University Park, PA crwece@engr.psu.edu	Phase-engineered a-Si:H-based multifunction solar cells	169 (ended during FY)	3

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
Pacific Northwest National Laboratory Larry Olsen	Richland, WA Larry.Olsen@pnl.gov	Barrier coatings for thin-film cell protection	61 (FY04 carryover 120)	0
Shell Solar Industries Dale Tarrant	Camarillo, CA Dale.tarrant@shellsolar.com	Process R&D for CIS-based thin-film PV	612	612
Syracuse University Eric Schiff	Syracuse, NY easchiff@syr.edu	Transport, interfaces, and modeling in a-Si:H-based solar cells	41 (plus 100 FY04)	5
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	69	0
U. of Delaware, Institute of Energy Conversion Robert Birkmire	Newark, DE rwb@strauss.udel.edu	Thin Film Center of Excellence	1,067	112
United Solar Ovonic Subhendu Guha	Auburn Hills, MI sguha@uni-solar.com	High-efficiency a-Si-alloy-based solar cells and modules	596	596
University of Florida Tim Anderson	Gainesville, FL tim@nersp.nerdc.ufl.edu	Characterization of the reaction chemistry of CIGS solar cells	5 (ended during FY)	0
University of Illinois Angus Rockett	Urbana, IL arockett@uiuc.edu	Understanding the structural and chemical basis of chalcopyrite solar cells	0 (ended during FY)	0
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	65	0
University of North Carolina, Chapel Hill Daxing Han	Chapel Hill, NC daxing@physics.unc.edu	Micro-structural characterization and identification of Staebler-Wronski mechanism of a-Si:H solar cell materials	0 (ended during FY)	0
University of Oregon Dave Cohen	Eugene, OR dcohen@oregon.uoregon.edu	Electronic properties relevant to improving performance and stability of a-Si PV cells	180	0
University of South Florida Chris Ferekides	Tampa, FL ferekide@eng.usf.edu	High-efficiency CdTe cells by CSS	99	7
University of Toledo Al Compaan	Toledo, OH ADC@physics.utoledo.edu	CdTe cells made by sputtering	267	126
University of Toledo Xunming Deng	Toledo, OH dengx@physics.utoledo.edu	High-efficiency, triple-junction a-Si-H- and nc-Si-based solar cells	227	60
University of Utah Craig Taylor	Salt Lake City, UT craig@physics.utah.edu	Characterization of advanced amorphous silicon materials and PV devices	118	0

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 2005 Budget: $7,922K (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

- Conducted an evaluation of manufacturing progress in crystalline silicon technologies by U.S. industry participants in the PV Manufacturing R&D Project as part of annual Solar Program Review (1st quarter Joule milestone).
- Conducted stage-gate assessment of the need for additional manufacturing R&D as part of annual Solar Program Review—determined "In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up" (IDIP) subcontracted efforts should be continued and "Large-Scale Module and Component Yield, Durability, and Reliability" (YDR) subcontracted efforts should continue awards.
- Completed mid-year conversion and efficiency measurements for crystalline silicon modules with a 12.9% module demonstrating progress toward the annual goal (2nd quarter Joule milestone).
- Analyzed U.S. PV industry cost/capacity data to produce capacity-weighted, industry-average results.
- Achieved a DOE Solar Program milestone with a 13.7%-efficient U.S-made, commercial crystalline silicon PV module (4th quarter Joule milestone).
- Implemented stage-gate processes and a Systems-Driven Approach in managing all PV Manufacturing R&D project activities.
- *BP Solar* – Completed process equipment specifications for sawing, demounting, and handling 100-µm wafers cut on 290-µm centers.
- *Energy Conversion Devices* – Completed testing of on-line PV capacitive diagnostic system to stabilize and optimize a-Si deposition.
- *Evergreen Solar* – Initiated manufacturing of PV modules using new Gemini II-based String Ribbon silicon wafers.
- *ITN Energy Systems* – Implemented improved process controls and fault-tolerance procedures on the production line, resulting in an 85% increase in yield and a 13% increase in cell efficiency.
- *RWE Schott Solar* – Demonstrated the integration of diagnostic equipment and statistical methods for high-speed monitoring of wafers, cells, and processes in 60-MW manufacturing facility, resulting in a 15% increase in wafer and cell operational throughput.
- *Sinton Consulting* – Received an R&D 100 Award for the quasi-steady-state photoconductance Silicon Evaluation System developed under an FY 2004 IDIP subcontract for the measurement of bulk minority-carrier lifetime.
- *Specialized Technology Resources* – Developed flame-retardant encapsulant (passed UL 1703 Class B flammability test); a faster-cure encapsulant; and a new thin-film encapsulant formulation, which is thinner and has improved glass adhesion.
- *Schott Applied Power* – Completed the development of an updated line of wiring junction boxes and the second-generation design of the meter-interconnect device.

- *Spire* – Completed development and testing of large-area Brightfield PV module automated process systems, including a module lay-up process system for large-area modules; a robotic string busing system; an advanced lamination process tool for encapsulating large modules; and a large-area solar simulator for testing large modules or multiple small modules.
- Completed a stage-gate review of remaining proposed subcontracts under the YDR solicitation and determined negotiations and subcontract awards should continue on a delayed schedule.
- Completed the award of 7 out of the 11 proposed subcontracts under the "Large-Scale Module and Component Yield, Durability, and Reliability" solicitation on a delayed schedule.
- *Dow Corning Corporation* – Developed prototype encapsulant materials with fast lamination speed (e.g., 20% greater than typical ethylene vinyl acetate [EVA] lamination times) and the potential for non-laminator assembly methods such as pinch rollers.
- *PowerLight Corporation* – Completed prototype foamless PV roof tile design and implemented production of PowerGuard tiles without the need for added insulation.
- *Shell Solar* – Introduced a thin (125 µm) wafer-cutting wire to pilot-production mode, giving an increase of almost 8% in watts out per kg of silicon input for a significant cost improvement.
- *SunPower* – Developed a new cell interconnect improving long-term field reliability and eliminating Pb in the module, a module with >220 W power and 17.5% total-area efficiency, and identified an automated bonding technique suited to thin, back-contact cells.

Future Directions

- Assess and determine the needs for additional PV Manufacturing R&D and select areas for elimination or support.
- Complete development (achieve manufacturing-line-ready status) for at least three in-line diagnostic processes initiated in FY 2002 awards from IDIP subcontracts.
- Complete stage-gate review of individual progress versus milestones and required redirection for YDR subcontracts.
- Conduct end-of-year measurements to meet the FY 2006 EERE Efficiency Joule Milestone for U.S.-made, commercial crystalline silicon PV modules of 14.0% conversion efficiency.
- Analyze U.S. PV industry cost/capacity data and verify PV industry has reached FY 2006 EERE cost goal of $1.85/Wp.

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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 Multi-Year Technical Plan (MYTP) Tasks 3 and 6 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 2005 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 2005 Budget ($K)
PV Manufacturing R&D Technical Coordination	1,550
In-Line Diagnostics and Intelligent Processing	2,179
Module Yield, Durability, and Reliability	4,193

2.2 In-Line Diagnostics and Intelligent Processing

The IDIP subtask consists of the FY 2005 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 2005 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
Evergreen Solar, Inc.	Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules
ITN Energy Systems	Trajectory-Oriented and Fault-Tolerant-Based Intelligent Process Control for Flexible CIGS PV Module Manufacturing
RWE Schott Solar, Inc.	EFG Technology and Diagnostics R&D for Large-Scale Manufacturing

Table 3. FY 2005 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
Spire Corporation	Development of Automated Production Line Processes for Solar Brightfield Modules

2.3 Yield, Durability, and Reliability

The FY 2005 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
Shell Solar Industries	Photovoltaic Module Manufacturing Technology
SunPower Corporation	Automated Manufacturing of High Efficiency Modules
Xantrex Technology	Advanced, High Reliability, System Integrated 500 kW PV Inverter Development

* 4 subcontracts pending award as of 9/30/2005

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 2005 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 in support of the MYTP Milestone 14, Task 3 (due in FY 2006). Both historical and projected values for manufacturing cost and capacity were compiled in collaboration with PV industry partners. An evaluation of the FY 2004 data, completed in May of 2005, 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 cost/capacity results of the FY 2004 survey of PV module manufacturers. Total PV manufacturing capacity has increased from 14 MW at the project's inception to 240 MW at the close of 2004. This increase in capacity represents a 27% compound average annual growth rate over the 12-year period examined. Direct manufacturing costs, in 2004 constant dollars, declined from $5.70/Wpeak to $2.44/Wpeak over the same time period, a 6.8% compound average annual reduction.

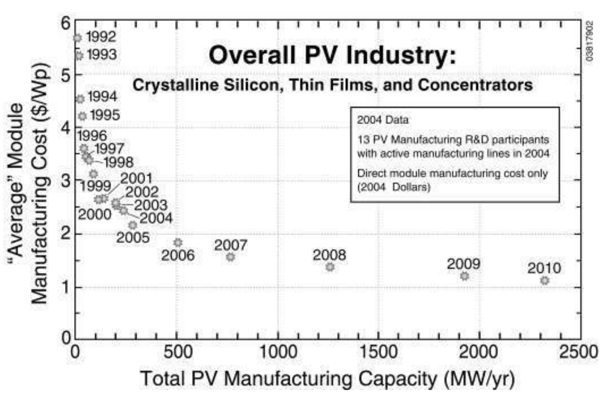

Fig. 1. FY 2004 U.S. PV module manufacturing cost/capacity

In addition, the PVMR&D project tracks the manufacturing cost savings resulting from improvements implemented under project subcontracts (also completed in May 2005). Public recapture of investment (shown in Fig. 2) is calculated based on the amount of measurable cost reductions passed on to the customer, whereas industry recapture of investment (also shown in Fig. 2) is based on the amount of measurable cost reduction retained by the manufacturers. For both the public and private sectors, the estimated recapture exceeded both public and private investments during 1998.

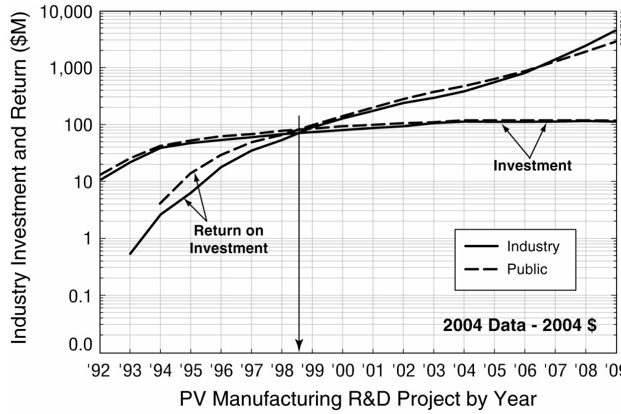

Fig. 2. Recapture of public and industry investment in PVMR&D

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 and addressing the MYTP Milestone 25, Task 6 (due in FY 2005). This milestone was completed in December of 2005.

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

Sinton Consulting

"Development of an In-Line Minority-Carrier Lifetime Monitoring Tool for Process Control during Fabrication of Crystalline Silicon Solar Cells" (Not funded in FY 2005)

- Received an R&D 100 Award for the quasi-steady-state photoconductance Silicon Evaluation System developed under an FY 2004 IDIP subcontract for the measurement of bulk minority-carrier lifetime.

Specialized Technology Resources, Inc.

"Development of New, Low-cost, High-performance PV Module Encapsulant/Packaging Materials"

- Developed a new encapsulant that is a flame retardant.
- Developed a new faster-cure encapsulant.

- Installed a tension-management-system winder to minimize material usage during the manufacture of encapsulant sheets, resulting in enhanced dimensional stability.
- Developed a new thin-film encapsulant formulation, which is thinner and has improved glass adhesion.

ITN Energy Systems
"Trajectory-Oriented and Fault-Tolerant-Based Intelligent Process Control for Flexible CIGS PV Module Manufacturing"

- Implemented improved process controls and fault-tolerance procedures on the production line, resulting in an 85% increase in yield and a 13% increase in cell efficiency.
- Developed Abaqus models to predict thermal behavior with the metal sources.
- Developed robust effusion source, which enabled rapid (non-equilibrium) start-up based on trajectory control, as well as chamber dynamic simulations to optimize system design; and provided model-based diagnosis for fault detection.

BP Solar International, LLC
"Large-Scale PV Module Manufacturing Using Ultra Thin Polycrystalline Silicon Solar Cells"

- Completed process equipment specifications for sawing, demounting, and handling 100-μm wafers cut on 290-μm centers.
- Reduced wafer thickness in production from 250 μm to 220 μm.
- Introduced lead-free interconnects on all BP Solar multicrystalline Si modules.
- Introduced new junction boxes on all commercial products.

Schott Applied Power
"Plug and Play Components for Building-Integrated PV Systems"

- Completed the development of an updated line of wiring junction boxes, or PV Source Circuit Protectors. Improvements include upgrading to superior fused and non-fused terminal blocks and ground lugs and overall cost reduction.
- Completed the second-generation design of the meter interconnect device, a simplified means for interconnecting a residential PV system's AC output to the electrical service at a dwelling. The device has been approved for use by National Grid (Massachusetts Electric) in its service territory, where five demonstration systems will be completed in early FY 2006.
- 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.

RWE Schott Solar
"EFG Technology and Diagnostics R&D for Large-Scale Manufacturing"

- Demonstrated the integration of diagnostic equipment and statistical methods for high-speed monitoring of wafers, cells, and processes in 60-MW manufacturing facility, resulting in a 15% increase in wafer and cell operational throughput.
- Implemented techniques for in-line diagnostics.
- Developed a computer management and maintenance system for remote in-line process monitoring and for application to SPC and monitoring equipment PLC functions. It is fully implemented and being used for process control, maintenance, and performance tracking.
- Raised yield in Edge-defined, Film-fed Growth (EFG) wafer production, demonstrated high-yield processes for 250-μm EFG wafer, and implemented higher-cutting-speed laser (+60%) and cutting-cycle time reduction (~20%).
- Scaled up reflector module prototypes to 50-W module size to demonstrate 25% reduction in cell utilization; identified deficiencies in module materials and reliability using stress analysis and materials and qualification testing.

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

- Built and tested a module lay-up process system for large-area modules.
- Built and tested a robotic string busing system, which automatically connects solar cell strings together and installs bypass diodes in the cell circuit before lamination.
- Demonstrated a method for forming shallow, fine-pitch corrugations in copper ribbon to relieve stress and maintain high yield in the cell string soldering process.
- Designed a large-area solar simulator for testing modules up to 2 m x 4 m in area. Demonstrated a single-flash, long-pulse xenon

light source for this simulator. Developed new electronics that actively controls lamp intensity, significantly improving light intensity during the flash.

Evergreen Solar
"Innovative Approaches to Low-Cost Module Manufacturing of String Ribbon Si PV Modules"

Initiated manufacturing of PV modules using new Gemini II-based String Ribbon silicon wafers, resulting in a 15-MW capacity with significantly reduced wafer and cell costs. The key achievement was a 33% reduction in direct manufacturing costs throughout the factory. Individual accomplishments that contributed to this achievement include:

- 10% improvement in machine uptime by reducing hot zone change time by a factor of 3, simplifying seeding process, and reducing time to steady state by a factor of 2.5.
- 12% improvement in yield, surpassing 10% goal.
- 80% increase in run length (time to crucible change).
- Improved ribbon surface quality by tighter control of the ambient surrounding the solid-liquid interface.
- Developed very reliable conductive adhesive for monolithic module technology.

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

- Completed testing of on-line PV capacitive diagnostic system to stabilize and optimize a-Si deposition, improving both solar cell efficiency and production yield.
- Conducted plasma studies that resulted in the correction of the germane cross-web non-uniformity problem.
- Developed optical reflection spectrometers for online QA/QC and closed-loop control of film thickness and cross-web uniformity of the sputtered ZnO layer in the back reflector, the sputtered ITO top conductive oxide/anti-reflectivity layer, and a-Si layers.

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. PV Manufacturing R&D Project management is currently in the process of awarding these subcontracts. As of September 30, 2005, 7 of these 11 YDR subcontracts have been awarded.

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

SunPower Corporation
"Automated Manufacturing of High Efficiency Modules"

- Introducing an AR-coated cover glass to SunPower's standard module design, and produced an NREL-verified 17.9%-efficient module; tested stability of coating with promising results.
- Studied handling yield and effect on cell efficiency of thin silicon wafers; confirmed an expected 0.25% efficiency increase for 190-µm wafers compared to 240 µm.
- Developed and successfully tested a lead-free interconnect system; found additional benefit of increased resistance to fatigue failure.
- Evaluated six different automated soldering approaches for use on thin, back-contact cells, and down-selected to one for further testing.

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

- Developed prototype encapsulant materials with fast lamination speed (20% greater than typical EVA lamination times) and the potential for non-laminator assembly methods such as pinch rollers.
- Demonstrated samples with dynamic cut resistance at 5–15 micron cut depth (compared to 40 micron for EVA/Tedlar®) and static cut resistance at 130–160 micron cut depth (compared to 100 micron for EVA/Tedlar®).
- Completed initial prototype laminations to determine minimum thickness for the adhesive and encapsulant layers by demonstrating

bubble-free laminates and suitable samples for cut and voltage breakthrough testing.

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

- Designed and bench tested a new in-situ ribbon-cutting apparatus. Based on the success of the tests, company will be moving into pilot production.
- A move to thinner (170 μm) wafers is under development, focusing on process yield improvement in the glass etch, decal application, and tabbing and stringing steps.
- Identified two approaches for high-throughput, high-quality front and back contacts: (1) find an outside vendor as a drop-in replacement for in-house made decals for the front contact; (2) study various pastes for both front and rear contacts, even using direct screen printing instead of decals to form contacts.

Shell Solar Corporation
"Photovoltaic Module Manufacturing Technology"

- Introduced a thin (125 μm) wafer-cutting wire to pilot production mode, giving an increase of almost 8% in watts out per kg of silicon input for a significant cost improvement.
- Effects of light-induced degradation of cells and glass characterized; both effects found to be significant and of comparable magnitude.
- Ran the thinner wire in pilot production mode, demonstrating a production increase of >6% for >500 saw runs.
- Initiated studies of thinner cells; identified boron coat process, the phosphorous diffusion process, and the printing processes as areas of concern for future study.

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

- Completed design of prototype foamless PV roof tile and implemented production of PowerGuard tiles without the need for added insulation.
- Started the first large-scale commercial installation of the RFT-10 product with the improvements accomplished under this contract.
- Implemented modifications in the production of PowerGuard tiles to reduce the cost of the mortar coating of the foam backer-boards, with input from accelerated testing.
- Planned modifications to the PowerGuard manufacturing process to improve quality and reduce labor. Established a team to streamline supply chain logistics and to reduce the cost inventory.

GE Energy
"Solar Cell Design for Manufacturability"
This project started on Aug. 26, 2005, and thus was active for only a month in FY 2005.

Xantrex Technology
"Advanced, High Reliability, System Integrated 500kW Photovoltaic Inverter Development"
This project started on September 29, 2005, and thus was not active during FY 2005.

4. Planned FY 2006 Activities

PVMR&D Project procurements are framed to specifically address milestones under the Solar Program MYTP. 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 2006 EERE cost goal of $1.85/Wp and conduct end-of-year measurements to meet the FY 2006 EERE Joule milestone for U.S.-made, commercial crystalline silicon PV modules of 14.0% 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 2006 EERE milestones mentioned above.

The major task milestones and expected accomplishments of this project during FY 2006 include:

- Analyzing the FY 2005 U.S. PV industry cost/capacity/recapture data to identify the capacity-weighted, industry average. (05/06)
- Assessing and determining the need for additional PV Manufacturing R&D, and selecting areas for elimination or support. (09/06)
- Completing the development of at least three in-line diagnostic processes from research subcontract awards under the FY 2001 IDIP solicitation (achieve manufacturing-line-ready status). (12/05)
- Renewing remaining subcontracts under the "In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up" solicitation. (07/06)
- Completing eligible subcontract awards under the "Large-Scale Module and Component

Yield, Durability, and Reliability" solicitation. (09/06)
- Completing stage-gate reviews for individual YDR subcontracts regarding progress versus milestones, and initiating required redirections and subsequent phased research activities.

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 2005 Publications

K.E. Brown, R.L. Mitchell, W.I. Bower, R. King, "PV Manufacturing R&D Project Status and Accomplishments under 'In-Line Diagnostics and Intelligent Processing,' " *Proc. of the 31st IEEE Photovoltaic Specialists Conference, Lake Buena Vista, Florida, January 3–7, 2005,* NREL/CP-520-37381, February 2005 (www.nrel.gov/docs/fy05osti/37381.pdf).

L. Hargis, J. Botkin, "PowerLight Corporation Lean Manufacturing, PV Manufacturing R&D Phase I Report," 6 December 2001–31 March 2003, NREL/SR-520-35881, June 2005 (www.nrel.gov/docs/fy05osti/35881.pdf).

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," Annual Technical Progress Report, 1 January 2003–30 June 2004, NREL/SR-520-36608, June 2005 (www.nrel.gov/docs/fy05osti/36608.pdf).

J.I. Hanoka, "Innovative Approaches to Low-Cost Module Manufacturing of String Ribbon Si PV Modules," Phase II Annual Technical Progress Report, 1 April 2003–31 May 2004, NREL/SR-520-36908, October 2004 (www.nrel.gov/docs/fy05osti/36908.pdf).

L. Simpson, "Trajectory Oriented and Fault Tolerant Based Intelligent Process Control for Flexible CIGS PV Module Manufacturing Scale-Up," Phase II, Annual Technical Report, March 2004, NREL/SR-520-36983, November 2004 (www.nrel.gov/docs/fy05osti/36983.pdf).

J. Kalejs, P. Aurora, B. Bathey, J. Cao, R. Gonsiorawski, B. Heath, J. Kubasti, B. Mackintosh, M. Ouellette, M. Rosenblum, S. Southimath, G. Xavie, "EFG Technology and Diagnostic R&D for Large-Scale PV Manufacturing," Annual Subcontract Report, 1 July 2003–30 June 2004, NREL/SR-520-37347, January 2005 (www.nrel.gov/docs/fy05osti/37347.pdf).

H. Volltrauer, K. Jansen, "Productivity Enhancement for Manufacturing of Amorphous Silicon PV Modules," Final Technical Progress Report, 1 July 2002–31 October 2004, NREL/SR-520-37659, February 2005 (www.nrel.gov/docs/fy05osti/37659.pdf).

T. Ellison, "Implementation of a Comprehensive On-Line Closed-Loop Diagnostic System for Roll-to-Roll Amorphous Silicon Solar Cell Production," Annual Report-Year 2, 1 September 2003–31 August 2004, NREL/SR-520-37660, February 2005 (www.nrel.gov/docs/fy05osti/37660.pdf).

J. Wohlgemuth, M. Narayanan, "Large-Scale PV Module Manufacturing Using Ultra Thin Polycrystalline Silicon Solar Cells", Annual Technical Progress Report, 1 October 2003–30 September 2004, NREL/SR-520-37738, March 2005 (www.nrel.gov/docs/fy05osti/37738.pdf).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
BP Solar International, LLC John Wohlgemuth	Frederick, MD john.wohlgemuth@bp.com	Large-Scale PV Module Manufacturing Using Ultra Thin Polycrystalline Silicon Solar Cells	50 220*	1,036 304*
RWE SCHOTT Solar, Inc. Miles Russell	Billerica, MA miles.russell@rweschottsolar.us	Plug and Play Components for Building-Integrated Systems	0 70*	0 96 *
ITN Energy Systems, Inc. Lin Simpson	Littleton, CO lsimpson@itnes.com	Trajectory Oriented and Fault Tolerant Based, Intelligent Process Control for Flexible CIGS PV Module Manufacturing	77 119*	95 145*
Evergreen Solar, Inc. Jack Hanoka	Marlboro, MA hanoka@evergreensolar.com	Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules	0 250*	0 250*
Specialized Technology Resources, Inc. Ryan Tucker	Enfield, CT susan.agro@strus.com	Development of New Low-Cost, High-Performance PV Module Encapsulant/Packaging Material	68 260*	68 224*
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	500 417*	500 417*
Spire Corporation Michael Nowlan	Bedford, MA mnowlan@spirecorp.com	Development of Automated Production Line Processes for Solar Brightfield Modules	500 232*	491 222*
RWE SCHOTT Solar, Inc. Juris Kalejs	Billerica, MA juris.kalejs@rweschottsolar.us	EFG Technology and Diagnostics R&D for Large-Scale PV Manufacturing	153 350*	227 519*
Dow Corning Corporation Barry Ketola	Midland, MI barry.ketola@dowcorning.com	High Performance Packaging Solutions for Low Cost, Reliable PV Modules	550 110*	550 110*
Evergreen Solar Jack Hanoka	Marlboro, MA hanoka@evergreensolar.com	Low-Cost Manufacturing of High-Efficiency, High-Reliability String Ribbon Si PV Modules	600 75*	600 75*
GE Energy James Rand	Newark, DE im.rand@ps.ge.com	Solar Cell Design for Manufacturability	350 50*	356 51*
PowerLight Corporation Jonothan Botkin	Berkeley, CA jbotkin@powerlight.com	Accelerating PV Cost Effectiveness Through Systems Design, Engineering, and Quality Assurance	375 326*	1,289 1,121*
Shell Solar Industries Theresa Jester	Camarillo, CA Theresa.jester@shellsolar.com	Photovoltaic Module Manufacturing Technology	400 100*	397 99*
SunPower Corporation Doug Rose	Sunnyvale, CA Doug.Rose@sunpowercorp.com	Automated Manufacturing of High Efficiency Modules	745 85*	746 85*
Xantrex Technology Raymond Hudson	San Luis Obispo, CA Ray.Hudson@xantrex.com	Advanced, High Reliability, System Integrated 500kW Photovoltaic Inverter Development	0 250*	0 250*

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
TBD (four additional awards anticipated) **	TBD	Subcontracts under "PV Module And Component Yield, Durability, And Reliability" solicitation	730** 0*	730** 0*
Shirley Neff, Consultant	Washington, DC shirleyneff@earthlink.net	Inputs and Policy Evaluation for the U.S. PV Industry Roadmap	87 0*	0 0*

* Funded with prior year (FY 2004) funds.
** Awards pending.

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
David King (SNL) 505-844-8220, dlking@sandia.gov

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

FY 2005 Budgets: $2,194K (NREL), $701K (SNL)

Objectives

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

Accomplishments

- Initiated unique high-voltage stress testing experiment that measures module leakage currents to ground on a bipolar array supplied by Shell Solar consisting of CIGSS modules (milestone).
- Initiated cooperative reliability testing program for SunPower's high-efficiency c-Si modules, including light soaking, thermal cycling, and damp heat exposure indoors and real-time outdoor exposure.
- Completed a journal article that documents the implications of using fixed resistive loads for long-term PV module exposure testing; showed that identical degradation rates can be observed with resistive loads compared to maximum-power tracking loads.
- Performed finite element modeling of PV modules to determine the time scales of moisture ingress to PV modules. One conclusion was that using a breathable back sheet can shorten the moisture ingress half-time to 3–30 days, greatly reducing super saturation for most weather environments.
- Experimentally quantified the detrimental effects of localized, non-linear shunt paths on CdTe cell performance. This revealed that a small, stress-induced current shunt path can account for more than half of the cell's efficiency loss during stress testing.
- Developed several module glass priming formulations, self-primed ethylene vinyl acetate (EVA), and non-EVA encapsulants that may provide improved adhesion strengths compared to available commercial products.
- Implemented and documented production line module dark I-V diagnostic procedures with two manufacturers, which motivated their module suppliers to implement similar production line test equipment.

Future Directions

- Research, technical reports, and industry communication on performance of modules under test in environmental chambers and outdoors under normal and stress (e.g., high voltage) conditions.
- Research and technical reports documenting degradation characteristics of commercial PV modules, for distribution to industry collaborators.

- Research, technical reports, and industry collaborations on packaging formulations designed to eliminate module degradation and failure.
- Selected collaborations with manufacturers to help resolve specific issues concerning module performance reliability.

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1. Introduction

This joint NREL/SNL project has existed nearly as long as the National PV Program/Subprogram. Over the years, as PV module technologies have been investigated and developed, the PV Subprogram's module reliability R&D activity has correspondingly changed to address a variety of candidate PV technologies and modules. As advanced, next-generation PV technologies are developed, the module reliability R&D scope and specific activities continue to evolve. The long-term (2020) goal of the *DOE Solar Program Multi-Year Technical Plan* (MYTP) is to commercialize PV modules having at least 30-year service lifetimes and less than 0.5% annual performance degradation rates, at a target cost (e.g., $1.50/Wp) that is consistent with market-required levelized costs of electricity (e.g., $0.06/kWhr$_{AC}$). Achieving these module targets is critical to realizing the success of PV technologies and significant levels of deployment.

2. Technical Approach

For FY 2005 (and beyond), this project's technical approach (hence activities) consists of accelerated indoor environmental (e.g., temperature, humidity, high-voltage, ultraviolet radiation, and solar flux) stress testing of candidate module technologies; accelerated outdoor stress testing (e.g., high solar fluxes, module high-voltage environments); and long-term outdoor environmental analyses, characterization, modeling, failure/degradation analyses, and module packaging R&D to help mitigate failures/degradation and/or reduce module costs and improve performance. To conduct these activities, NREL and SNL develop and apply advanced measurement techniques, diagnostic methods, and instrumentation. A key aspect of the overall approach is close interaction and collaboration with PV module manufacturers. The intent is to optimize the time and funding applied to advancing module technologies from the prototype to the commercial production stage, with respect to meeting acceptable performance, reliability, and costing requirements.

The three tasks comprising this project are:

Task Title	FY 2005 Budget ($K)
Exploratory Reliability & Performance R&D	1,092
Module Packaging Research & Reliability	1,102
Module Reliability Characterization	701

3. Results and Accomplishments

For the three tasks, major results and accomplishments are as follows.

3.1 Exploratory Reliability and Performance R&D

- Assisted a major U.S. thin-film manufacturer with diagnosing a degradation problem that developed in the product line, pinpointing the cause, and recommending a solution.
- Completed a journal article that documents the implications of using fixed resistive loads for long-term PV module exposure testing; showed that identical degradation rates can be observed with resistive loads compared with maximum-power tracking loads, provided the resistance values are chosen correctly (helped to fulfill a milestone 01/05).
- Performed thermal cycling on a prototype CIGS thin-film roofing shingle product for a manufacturer, providing testing to a small manufacturer that would otherwise not be available.
- Initiated a cooperative testing program on SunPower's high-efficiency crystalline-Si modules including light soaking, thermal cycling, and damp heat exposure indoors, and real-time outdoor exposure geared toward helping SunPower improve fabrication of its solar cells.
- Performed indoor stress testing of SBM Solar's prototype crystalline silicon modules, including damp heat, thermal cycling, UV exposure, humidity-freeze, and standard module surface cut tests, helping to advance the company toward full qualification and eventually production.
- Assisted subcontractors in the hot and humid exposure project of the Thin-Film PV Partnership by making site visits and providing

advice on data acquisition, calibrations, and array designs (milestone satisfied for FY 2005).

- Completed a report on CIGS module stability on the Performance & Energy Ratings Testbed and reported to the Thin-Film PV Partnership ahead of schedule.
- Completed installation of Shell CIGSS modules in the High-Voltage Stress Testbed and initiated long-term monitoring of array-level leakage currents and real-time performance (milestone completed 4/05).
- Transferred all available historical data generated by the Performance and Energy Rating Testbed since 1994 from magneto-optical discs to the group file server, which will allow determination of individual module degradation rates in FY 2006 for publication in the open literature.

3.2 Module Packaging Research & Reliability

- Performed finite element modeling of PV modules to determine the time scales of moisture ingress, reported at the IEEE PV Specialists Conference, and submitted to *Progress in Photovoltaics*.
- Published reports covering the evaluations of water vapor ingress rates, peel strengths, and mirror protection for new and existing PV module packing materials; prepared "Testing of Packaging Materials for Improved PV Module Reliability" and "Moisture Transport, Adhesion, and Corrosion Protection of PV Module Packing Materials" (milestone 09/05).
- Developed several glass-priming formulations, self-primed EVA, and non-EVA encapsulants that may provide adhesion strengths greater than the commercial EVA product commonly used for PV module applications. Also prepared "Enhanced Adhesion of EVA Laminates to Primed Glass Substrates Subjected to Damp Heat Exposure" (milestone 09/05).
- Experimentally quantified the detrimental effect of localized, non-linear shunt paths on CdTe cell performance. These less than mm-sized paths were located with the infrared camera, and cell performance was measured before and after their removal. We found that a small, stress-induced shunt path can account for more than half of a cell's efficiency loss during stress studies, and we identified the cell process step causing the shunt path. (Presented at the 31st IEEE PV Specialists Conference, milestone completed.)
- Performed a number of experiments using 800-Angstrom-thick aluminum layers sputtered onto glass substrates and identified accelerated corrosion for areas with an impermeable back sheet that are in direct contact with EVA. This indicates that a volatile decomposition product is increasing the corrosion, of special concern for thin-film PV devices. (Presented at the 31st IEEE PV Specialists Conference, 01/05.)
- The Pernika plasma-enhanced chemical vapor deposition (PECVD) system was revamped, a safe operating plan was approved, a readiness review was conducted, and preliminary moisture-barrier coatings were deposited. An equipment failure interrupted the experiments, and because safety is a top concern in restart of the system before proceeding, the milestone to report on the efficacy of PECVD thin-film moisture barriers was delayed to the first quarter of FY 2006.
- A rheometer acquired last year by NREL is now operational, and samples prepared and acquired are under test, with a summary report being written (milestone 09/05).
- Prepared "Excess Dark Currents and Transients in Thin-Film CdTe Solar Cells" for the IEEE PV Specialists Conference, and "Non-linear Shunt Paths in Thin-Film CdTe Solar Cells" for the *Journal of Applied Physics* (milestone 09/05 on the influence of cell edges on cell performance, etc.).

3.3 Module Reliability Characterization

- SNL's milestone for a comprehensive report summarizing degradation rates for a variety of commercial thin-film and silicon modules was delayed to the first quarter 2006 in response to specific industry requests to address module reliability issues affecting large numbers of production modules, as well as because of an unexpected staff absence for 2 months. The postponement is advantageous because it will be possible to more effectively terminate the initial phase of the module long-term exposure tests by bringing all modules aged since 1997 back to SNL for a final baseline test prior to documenting the long-term test results. At that time, it will be possible to reload the outdoor exposure racks at Florida Solar Energy Center (FSEC) and Southwest Technology Development Institute (SWTDI) with new commercial modules without increasing the associated workload.

- SNLs work with the dark I-V measurement procedure as a lab diagnostic capability and a production line quality-control tool is ongoing with joint efforts with PowerLight and RWE Schott Solar. Success at PowerLight motivated its major module suppliers (Sharp, Sanyo) to implement similar production line test equipment.
- By request, SNL diagnosed field reliability and manufacturing issues for four major c-Si module manufacturers using a combination of dark IV analysis and infrared imaging. Long-term reliability of multi-megawatts of modules was being affected.

4. Planned FY 2006 Activities

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. The plans for FY 2006 are to perform module reliability and packaging research and testing, produce technical reports of results, and interact and collaborate with the PV industry module manufacturers to address the long-term goals of the Solar Program—which are to commercialize PV modules having at least 30-year service lifetimes and less than 0.5% annual performance degradation, at target costs consistent with market-required levelized cost of electricity. Specific activities to support these goals include the following proposed milestones for completion by 9/30/06, subject to funding levels:

- Report analyses of outdoor module performance of ~34 modules under test in the Performance and Energy Ratings Testbed showing effective efficiency and energy production compared to nameplate.
- Report comparisons of module degradation/ failure for 2.5X exposure versus 1X exposure using the Outdoor Accelerated Weathering Tracking System to assess accelerated exposure testing capability.
- Report results of high-voltage stress testing (module leakage currents) using the High-Voltage Stress Testbed for potential high-voltage applications by industry.
- Continue support of data archiving and data analysis of thin-film hot and humid outdoor exposure testing and other in-house and subcontracted module research.
- Enhance accelerated module testing and certification capabilities essential to industry partners.
- Laminate and perform accelerated testing of CdTe-based devices using a variety of encapsulants/processing cycles to determine failures affecting device performance.
- Evaluate the adhesive and cohesive strength of the layers within the thin-film module structures for the principal technologies and report to industry.
- Deposit and measure properties of barrier coatings to protect thin-film module cells from moisture and report results.
- Working with industry, develop new packaging formulations and provide adhesion and water vapor transmission values, water ingress modeling results, and assessment of cracking and shunt problems.
- Prepare a comprehensive summary of degradation rates and diagnostic evaluation of 10 commercial module types using 5–15-year outdoor exposure data at SNL, FSEC, or SWTDI.
- Implement and demonstrate production line module dark I-V diagnostic procedures with two manufacturers.
- Conduct high-reliability cell-ribbon solder-bond experiment.
- Initiate the next generation of long-term exposure testing of the latest high-performance commercial modules from two manufacturers at FSEC and SWTDI, with baseline tests at SNL.
- In support of SNL's System Evaluation and Optimization project, perform baseline performance characterization and modeling of eight new 3–6-kW PV arrays, which will initiate an effort to accurately quantify performance-degradation characteristics of inverters and arrays in continuously operating systems.
- Implement Systems-Driven-Approach and stage-gate processes in project activities, in support of the MYTP.

5. Major FY 2005 Publications

B. Marion, S. Rummel, and A. Anderberg, "Current-Voltage Curve Translation by Bilinear Interpolation," *Prog. Photovolt: Res. Appl.*, 2004, 12:593-607.

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," submitted to *Prog. Photovolt.: Res. Appl.*, July 2005.

J.A. del Cueto and B. von Roedern, "Long-Term Transient and Metastable Effects in Cadmium Telluride Photovoltaic Modules," submitted to *Prog. Photovolt: Res. Appl*., July 2005.

J.A. del Cueto and S.R. Rummel, "Comparison of Diode Quality Plus Other Factors in Polycrystalline Cells and Modules Obtained from Outdoor and Indoor Measurements," 31st IEEE PV Specialists Conference, January 2005.

C.R. Osterwald, J. Pruett, and T. Moriarty, "Crystalline Silicon Short-Circuit Current Degradation Study: Initial Results," *31st IEEE PV Specialists Conference*, January 2005.

J.A. del Cueto, "Closed-Form Solutions and Parameterization of the Problem of Current-Voltage Performance of Polycrystalline Photovoltaic Modules Deployed at Fixed Latitude Tilt," *31st IEEE PV Specialists Conference*, January 2005.

R. Gottschalg, J. del Cueto, T.R. Betts, and D.G. Infield, "Seasonal Performance of a-Si Single and Multi-junction Modules in Two Locations," *31st IEEE PV Specialists Conference,* January 2005.

Ricardo Ruther, G. Tamizh-Mani, J. del Cueto, J. Adelstein, M.M. Dacoregio, and B. von Roedern, "Performance Test of Amorphous Silicon Modules in Different Climates – Year Three: Higher Minimum Operating Temperatures Lead to Higher Performance Levels," *31st IEEE PV Specialists Conference,* January 2005.

Y. Yang, G. Tamish-Mani, L. Ji, and C. Osterwald, "Outdoor Energy Rating of Photovoltaic Modules: Module Temperature Prediction and Spectral Mismatch Analysis," *20th Euro. PV Conf and Exhibition,* June 2005.

J. del Cueto, "Stability of Two CIGS Modules from Outdoor Measurements," NREL Internal Test Report, March 2005.

T.J. McMahon, "Accelerated Testing and Failure of Thin-Film PV Modules," *Prog. In Photovolt*., 12:245, 2004.

G.J. Jorgensen et al., "Testing of Packaging Materials for Improved Module Reliability," *31st IEEE PV Specialists Conference,* January 2005.

M. Kempe, "Control of Moisture Ingress Into Photovoltaic Modules," *31st IEEE PV Specialists Conference,* January 2005.

F.J. Pern and G.J. Jorgensen, "Enhanced Adhesion of EVA Laminates to Primed Glass Substrates Subjected to Damp Heat Exposure," *31st IEEE PV Specialists Conference,* January 2005.

T.J. McMahon et al., "Excess Dark Currents and Transients in Thin-Film CdTe Solar Cells: Implications for Cell Stability and Encapsulation of Scribe Lines and Cell Ends in Modules," *31st IEEE PV Specialists Conference*, January 2005.

T.J. McMahon et al., "Non-liniear Shunt Paths in Thin-Film CdTe Solar Cells," *J. Appl. Phys.,* 97:054503, 2005.

M. Kempe, "Modeling of Rates of Moisture Ingress into Photovoltaic Modules," submitted to *Solar Energy Materials and Solar Cells*.

Additional publications were presented at the DOE Solar Energy Technologies Program Review Meeting, October 2004.

D.L. King, W.E. Boyson, J.A. Kratochvil, "Photovoltaic Array Performance Model," SNL Report, SAND2004-3535, December 2004.

A. Hunter Fanney, D. L. King, et al., "Comparison of Photovoltaic Module Performance Measurements," *Proceedings of ISEC 2005*, ISEC2005-76086, Orlando, Aug. 2005.

D.L. King, W.E. Boyson, and J.A. Kratochvil, "SNL PV Array Performance Model," *ISES 2005 Solar World Conference,* Orlando, August 2005.

6. University and Industry Partners

There were no subcontracts planned in this project during FY 2005. However, the national laboratories work closely with both the Southwest and Southeast Regional Experiment Stations—FSEC and SWTDI—which are funded under the solar energy appropriations.

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 2005 Budget: $1,643K

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 and establish 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 a high-tech R&D strategy with 20-year MTBF inverter/system-integrated inverter and BOS goals.

Accomplishments

- Completed Phase II of the HRII with hardware deliverables from GE and Xantrex.
- Continued the HRII with a Phase II+ no-cost work bridge.
- Continued the HRII Phase III with GE and Xantrex.
- Assessed alpha inverter and controller prototypes for conformity to utility interconnection requirements, performance objectives, and manufacturing objectives.
- Conducted verification and validation of prototypes, through laboratory evaluations, review of highly accelerated life testing (HALT®), environmental testing, and performance.
- Initiated "High-Tech Inverter, Balance-of-System, and Systems R&D" with a FedBizOps announcement and draft of a request for proposal to begin the project.
- Developed an innovative high-reliability micro-inverter topology eliminating short-life components.

Future Directions

- Complete HRII Phase III with GE and Xantrex with focus on commercial-quality inverters.
- Conduct high-tech R&D for inverters, BOS, and systems strategies.
- Focus on inverter and BOS developments and strategies to facilitate building-integrated and vertically integrated systems designs.

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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 very positively, and with a very high level of probability, reduce the levelized cost of energy (LCOE) of installed PV systems, as indicated in new prediction models (such as PV DesignPro and PVSAM) being developed within the Solar Program. This outcome is consistent with the *DOE Solar Program Multi-Year Program Plan* (MYPP) and is critical in achieving its $.06/kWh energy production goal for PV systems. Further, given that today's short-term value-to-the-consumer of installing a PV system is often based 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 match the lifetimes of PV modules (typically 30 years) and other BOS components.

Today's technical barriers associated with inverters involve matching the mean time between failure (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 *National Electrical Code®* (*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 require costs associated with redesign of the BOS and a re-inspection to meet existing code. It will not be like changing a lightbulb. 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 are 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 is 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 tie to the new MYPP. Each of the inverter-related workshops resulted in consensus prioritization that guided the High-Reliability Inverter Initiative and later the drafting of the High-Tech Inverter, Balance-of-System, and Systems R&D: A 5-Year Strategy.

The project objectives are often 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. In addition, the project provides sanity checks that examine the impact on manufacturability of BOS components and integration into complete systems.

Some of the inverter- and BOS-related activities are also applicable to other renewable energy technologies such as fuel cells and micro-turbines. One Inverter and BOS Project goal is to strive to involve U.S. PV inverter manufacturers and key charge-controller manufacturers to examine key products to determine impacts on both the BOS and PV communities. The Inverter and BOS Project seeks to improve system reliability and efficiency, lower life-cycle cost, 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 seeks 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

After many years of nearly no structured R&D support for inverters and BOS, in 2002 the National PV Program, through the DOE Solar

Program, authorized funding for the High-Reliability Inverter Initiative (HRII), to be managed by SNL. The initiative focused on improving the reliability of inverters for PV applications from an average MTBF of 2–3 years to an MTBF of greater than 10 years.

SNL engineers were keenly aware that, in addition to technical advances and innovative thermal management, a key approach to higher reliability was mass production of well-designed hardware. Thus, all HRII bidders for were required to provide detailed marketing and manufacturing plans for high volume (>10,000 units per year). Also, based on today's limited PV module-manufacturing capabilities (slightly less than 100 MW shipments of PV modules in 2001, which translates to ~33,000, 3-kW inverters if every module found its way to that application), it was obvious that inverters with synergistic applications were also a key to mass production and quality control.

In keeping with cross-technology guidelines issued by DOE, the first phase of the HRII was co-funded by the DOE Solar Program, the Energy Storage Program, and the Distributed Energy Resources (DER) Program. Reorganizations at DOE and severe funding shortfalls in Energy Storage and DER resulted in a loss of the cross-technology collaboration for Phases II and III of the HRII.

The technical approach for this work follows the Systems-Driven Approach (SDA), which is a methodical process by which technology development efforts are 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 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. The EERE mission, which follows, was the top priority for all work undertaken under this project.

EERE Mission. *Strengthen America's energy security, environmental quality, and economic vitality through public-private partnerships that: enhance energy efficiency and productivity; bring clean, reliable, and affordable energy production and delivery technologies to the marketplace; and make a difference in the everyday lives of Americans by enhancing their energy choices and quality of life.In addition, the Solar Program goals are mirrored in the goals of the Inverter and BOS Development Project*.

In addition, the Solar Program goals are mirrored in the goals of the Inverter and BOS Development Project.

Solar Program Goal. *To improve performance of solar energy systems and reduce development, production, and installation costs to competitive levels, thereby accelerating large-scale usage across the nation and making a significant contribution to a clean, reliable, and flexible U.S. energy supply.*

A key feature of the SDA is the identification of market-based technical/economic requirements, which is also a focus of the inverter workshops. Rigorous systems analyses are used to assess the impacts of improvements related to targets established for identified markets. This analysis applies to R&D conducted at fundamental levels for devices and applications (longer term) and more applied levels (nearer term).

The analyses are also used to assess the benefits of R&D efforts and related technologies relative to cost and to determine go/no-go (stage-gate) decision points. Data are collected from laboratory and fielded systems to continually reassess goals, targets, progress, and critical technology paths. Coordination with industry and potential users of the technology is a key ingredient in ensuring that the product meets the needs of the market. Ultimately, new technologies will graduate to the commercial marketplace through partnerships with industry.

Task Title	FY 2005 Budget ($K)
High Reliability Inverter Initiative	1643
Inverter Development and Manufacturing R&D	355

3. Results and Accomplishments

General Electric and Xantrex delivered Phase II prototypes of high-reliability inverters to SNL in FY 2005. Benchmark evaluations and validations were completed at SNL's Distributed Energy Technologies Laboratory (DETL) as part of the Inverter Development and Manufacturing R&D Project, and SNL engineers recommended improvements. Each contractor made changes, and the upgraded prototypes were then re-evaluated before contractors moved on to the Phase III (commercialized product). Each contractor provided an overview of its inverter development program for the Phase II report.

Fig. 1. Xantrex high-reliability 5-kW alpha prototype

Results of the upgraded prototype testing at SNL were transferred to each contractor along with suggested engineering changes, which resulted in improved performance and compliance with applicable codes and standards. Figures 1 and 2 show the Xantrex and GE alpha prototypes, respectively. Both prototypes were found to need modifications or upgrades to meet the requirements of the initiative and the contractor's marketing needs. On its 3.6-kW, two-input design, GE used a design for reliability (DFR) process that has been proven accurate on a variety of GE products. The Xantrex design was analyzed using Design Failure Mode Effects and Criticality Analysis (DFMECA) to uncover components and operating modes in which additional work was required to improve long-term reliability. Xantrex established a Highly Accelerated Life Test capability as part of its contract cost share. Beta units are being constructed by each company. Following SNL evaluations and verifications of compliance with the *NEC*, UL standards, performance and operating characteristics, the evolution to commercialized products will begin.

Fig. 2. GE high-reliability 3.6-kW alpha prototype

Advancements in a 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. Figure 3 shows the measured PV array ripple along with simultaneous half-sine waves generated within the inverter. The ripple is measured here at about 60% rated operating level and represents 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. Figure 4 shows the internal components of the micro-inverter as designed for a detailed thermal

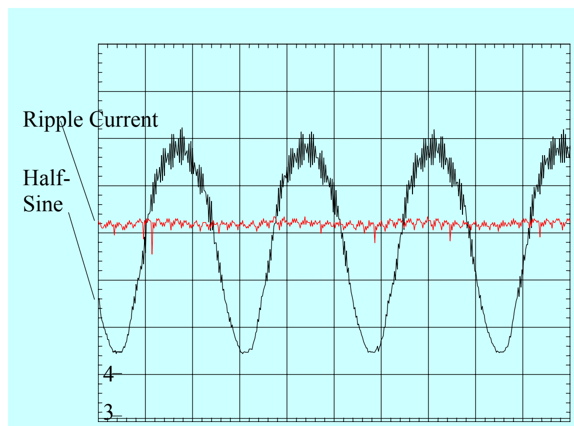

Fig. 3. Inverter half-wave current and ripple current

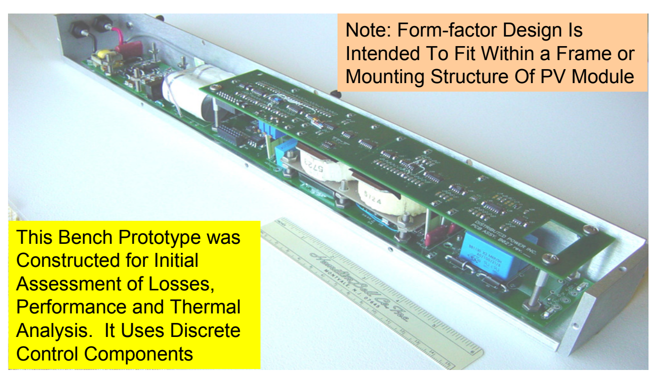

Fig. 4. Micro-inverter thermal analysis prototype

Summary of FY 2005 Results

Milestone or Deliverable	Due Date	Status
Sponsor High-Tech Inverter R&D Workshop.	10/31/04	Completed on time.
Finalize development of new prototype design, with emphasis on switching technologies and switching devices; manufacturing processes and packaging technologies to be developed; cooling technologies and operating temperatures; surge suppression designs; and physical characteristics. Complete Phase II with delivery of prototype inverters and Phase II reports.	12/31/04	Two contractors completed work on time with prototypes delivered.
Report on High-Tech Inverter R&D Workshop.	02/28/05	Completed on time.
Complete no-cost extension of Phase II to bridge contracts and keep R&D teams intact during the Phase II evaluation period and determination of funding resources.	03/31/05	Completed on time.
Validate the prototypes meeting the utility interconnection requirements and compliance with regulating standards (IEEE 1547, IEEE 519, and UL1741).	04/30/05	Completed. Two manufacturers provided prototypes on time.
Deliver commercial quality high-reliability (>10 year) inverters to SNL.	09/30/05	Work delays due to funding delays. New dates extend to 12/06.
Draft document for High-Tech Inverter, BOS and Systems R&D Strategies.	02/28/05	Completed on time.
Assess, test, and validate high-reliability inverter prototypes with characterization and evaluation and determinations of effectiveness of cooling technology at SNL.	02/28/05	Completed on time with two validation iterations for each.
Provide manufacturer feedback and complete summary report to discuss impacts on the PV program and systems.	08/31/05	In process, work delayed due to funding delays.
Draft call for request for proposal for High-Tech Inverter and BOS R&D Strategies.	09/30/05	Announce-ment made on time with request for proposal in process.

Both General Electric and Xantrex are currently active in Phase III of the High-Reliability Inverter Initiative and have extensive and critically timed commercialization plans for the products developed out of this program. Xantrex expects to use the fundamental high-reliability design as a basis for its next-generation family of products. GE is vertically integrating its newly acquired PV module-manufacturing capabilities with the new inverter development into its existing new construction housing market.

4. Planned FY 2006 Activities

Activities planned for FY 2006 follow a natural progression of improving designs to an acceptable reliability level, focusing on further improvement to a required level for inverters and BOS of at least a 20-year MTBF, and then fully integrating components that allow the complete system to have the same lifetime as the PV modules (now typically 30 years) and to optimize the performance of the systems through factory assembled and vertically designed and integrated systems. The "High-Tech Inverter, Balance-of-System, and Systems R&D: A 5-Year Strategy" project will be used to bring U.S. PV technologies to the forefront. The proposed milestones include:

- Completing the HRII Phase III
- Initiating the high-tech R&D strategies with integration into module manufacturing
- Conducting the "conceptual design" (first phase for high-tech R&D)
- Organizing a Systems-Driven Approach workshop for vertically integrated inverters, BOS, systems.

Continuing micro-inverter development with funding and collaboration through PV module manufacturers.

5. Major FY 2005 Publications

High Reliability Photovoltaic Inverter – Phase II Final Report (GE Proprietary), Deliverable D16.1, Proprietary Report to Sandia National Laboratories, SNL Contract Number 55792, General Electric Global, Dec 15, 2004.

High Reliability Photovoltaic Inverter – Phase II Final Technical Progress Report, Releasable Report to Sandia National Laboratories, SNL Contract Number 55792, General Electric Global, Dec 15, 2004.

High Reliability Inverter, Phase II Final Technical Progress Report, Report to Sandia National Laboratories, SNL Contract Number 54110, Xantrex Technologies, Dec 15, 2004.

Draft Final Report Highly Reliable Photovoltaic Inverter (Detailed Proprietary), Prepared by: Dr. Leo Casey, Principal Investigator, SNL Contract Number 54099, SatCon Technology Corporation, Feb 22, 2005.

R. Hudson, M. Edmunds, "Development of a High Reliability Inverter – Phase II," *Proc. DOE Solar Program Review, Denver, CO, Oct. 2004,* DOE/GO-102005-2067 (January 2005).

J. Smolenski, "GE High Reliability Photovoltaic Inverter Program." *Proc. DOE Solar Program Review, Denver, CO, Oct. 2004,* DOE/GO-102005-2067 (January 2005).

B. Borowy, L. Casey, D. Davis, J. Harris, W. Perkinson, W. Valentine, U. Xu, "SatCon's High--Reliability Inverter Initiative," *Proc. DOE Solar Program Review, Denver, CO, Oct. 2004,* DOE/GO-102005-2067 (January 2005).

W. Bower, "The Systems-Driven Approach to Inverter R&D," *Proc. DOE Solar Program Review, Denver, CO, Oct. 2004,* DOE/GO-102005-2067 (January 2005).

W. Bower, R. West, A. Dickerson, "Innovative Micro-Inverter for the AC PV Building Block or AC Modules," *Proceedings of the ISES 2005 World Conference, Orlando, FL, Aug 2005.*

D. Ton, W. Bower, *Summary Report on the DOE High-Tech Inverter Workshop*, Jan 2005.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005.

Organization/Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
General Electric Global Research Joseph Smolenski	Niskayuna, NY smolenski@crd.ge.com	Complete Phase II of the 'High-reliability Inverter Initiative with prototype and Phase II reports deliverables	488	1,158
Xantrex Technologies, Inc. Ray Hudson	Livermore, CA Ray.Hudson@xantrex.com	Complete Phase II of the 'High-reliability Inverter Initiative with prototype and Phase II reports deliverables	279	2,147
SatCon Applied Technologies Leo Casey	Cambridge, MA Leo.Casey@satcon.com	Complete Phase II of the 'High-reliability Inverter Initiative with prototype and Phase II reports deliverables	260	1,015
Xantrex Technologies, Inc. Ray Hudson	Livermore, CA Ray.Hudson@xantrex.com	Conduct Phase III of the 'High-reliability Inverter Initiative with commercial quality prototype and final reports/deliverables	250	1,699

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, the Solar Program helps to develop local and regional markets for all solar technologies by working with communities to identify and encourage new applications. The Solar Decathlon—an intercollegiate competition to design, build, and operate attractive, energy-efficient, and totally solar-powered houses—reaches out to the public in a big way. Between the two Decathlons (held in 2002 and 2005), as many as a quarter of a million people have come to learn about the architectural appeal and myriad benefits of solar energy in the built environment.

FY 2005 accomplishments within this arena follow.

PV Systems Engineering

- Contributed to a number of standards, certification, and test protocols within the Institute of Electrical and Electronics Engineers, Institute of Energy Conversion, Underwriters Laboratories, California Energy Commission, and Florida Solar Energy Center.

PV System Evaluation and Optimization

- Implemented the PV-SOL laboratory at Sandia National Laboratories, which has the capability to perform detailed performance and long-term reliability research on 14 separate nominally 3-kW PV systems with multiple array/inverter combinations.

Domestic PV Applications

- Supported development of program criteria and evaluation of proposals for U.S. Department of Agriculture Farm Bill Solar Program.

Building-Integrated Photovoltatics

- Continued the implementation of the 2005 Solar Decathlon university competition, releasing the final regulations, solidifying sponsors, and supporting teams.
- Convened a workshop on BIPV for big-box retailers, chain hoteliers, and BIPV industry leaders.

Million Solar Roofs Initiative

- Added five new MSR State and Local Partnerships, bringing the total to 94. In addition, 104 businesses, electricity providers, organizations, and agencies joined Partnerships, bringing the national total of participants to 926.

PV Systems Analysis

- Expanded work on PV value analysis to include both identifying best practices and information sharing, aimed at helping to inform state-level policymaking.
- Provided technical and analytical support to the Western Governors' Association Solar Energy Task Force.

Regional Experiment Stations

- Completed 2005 benchmarking of residential, utility-scale, and large commercial PV systems for inclusion in the *2007–2011 DOE Solar Program Multi-Year Program Plan.*

PV Systems Engineering

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL) DOE Golden Field Office (DOE/GO)
Key Technical Contacts:	Carol Riordan (NREL, Primary Contact), 303-384-6780, carol_riordan@nrel.gov Ward Bower (SNL), 505-844-5206, wibower@sandia.gov Glenn Doyle (DOE/GO), 303-275-4706, glenn.doyle@go.doe.gov
DOE HQ Technology Manager:	Dan Ton, 202-586-4618, dan.ton@ee.doe.gov
FY 2005 Budgets:	$1,375K (NREL), $122K (SNL), $160K (DOE/GO)

Objectives

- 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 and reliable installations that perform as expected.
- Provide the DOE Solar Program with world-class and traceable solar irradiance capabilities, measurements, and standards.

Accomplishments

- Generated 24 performance reports for the PV systems monitored at the NREL Outdoor Test Facility (OTF). These reports were archived and circulated internally at NREL, and distributed to the respective module manufacturers (milestone completed).
- Improved the PVWATTS software. The PV system specification size was changed from an AC power rating to a nameplate DC power rating; an input for an overall DC-to-AC derate factor was added for calculating a reference AC power rating, and residential electric rates were updated with the latest available data (milestone completed).
- Completed the technical and logistical preparations for the World Meteorological Organization International Pyrheliometer Intercomparison set for October 2005 (milestone 8/05).
- Completed and published the 2005 National Electrical Code (NEC) with “Industry Forum.” consensus changes, simplifying installs, allowing ungrounded PV circuits to reduce costs and improve system performance.
- Continued North American Board of Certified Energy Practitioners (NABCEP) practitioner certifications with updated tests, study guide, and task analysis.
- Contributed to a number of standards, certification, and test protocols within Institute of Electrical and Electronics Engineers (IEEE), Institute of Energy Conversion (IEC), Underwriters Laboratories (UL), California Energy Commission (CEC), and Florida Solar Energy Center (FSEC).

Future Directions

- Issue quarterly engineering test reports on small PV system performance at the NREL OTF to provide module manufacturers and the DOE Solar Program with independent analyses of energy performance ratings and long-term degradation rates at the system level.
- Upgrade the on-line PVWATTS software program/model to provide decision makers, the public, and the industry with credible estimates of PV system electric generation and costs for specific geographical locations nationally and internationally.

- Continue world-class solar radiometric, and therefore PV system performance, measurements and instrumentation.
- Provide PV system performance and reliability data and analysis required by the DOE Solar Program Systems-Driven Approach activities (i.e., benchmarking) and analyses.
- Provide robust technical support of important national and International standards, codes, and testing and certification activities, which are needed to assure safe installations that perform as expected, i.e.,
    - Maintain U.S. industry influence on international PV standards.
    - Continue proactive advances in codes, standards, and certification for PV.
    - Evolve the Inverter Certification Test Protocol to include economical maximum power point tracking (MPPT) procedures
    - Work with Industry Forum to have proposed changes accepted for the 2008 National Electrical Code.
    - Collaborate with UL on impacts on standards of ungrounded PV arrays.
    - Continue evolving NABCEP tests, study guides, and procedural requirements.
    - Develop protocol procedures for PV module performance certification.

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1. Introduction

Central to this project is the near-term and long-term performance monitoring, characterization, and modeling of emerging-technology, small (<5 kWp), grid-connected, prototype PV systems installed and operating at the NREL 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. This project is integral to the *DOE Solar Program Multi-year Technical Plan* 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 to R&D management.

This project provides leadership and support in creating and implementing codes and standards for safe, high-quality, cost-effective systems. It addresses and reduces technical and institutional barriers to all applications of PV technologies through the collaborative development of codes, standards, and certification procedures—paving the way for a wide variety of PV installations and insuring that interconnect issues with utilities are resolved.

2. Technical Approach

The three tasks comprising this project are:

Task Title	FY 2005 Budget ($K)
PV System Performance and Standards	750
Solar Radiometry and Metrology	625
Codes, Standards, and Certification	282

2.1 PV System Performance and Standards
This task provides PV emerging-technology, small grid-connected system performance and reliability data, analyses, and characterizations to the Solar Program and to the participating industry partners. The approach includes producing small PV system performance reports (e.g., electric power produced versus time) on a quarterly basis, delivered to industry partners and internal project managers, providing annual system outputs and degradation rates for each of the technologies/systems. Also, the very popular PVWATTS software (which provides the public with estimates of PV system electrical output and levelized electricity costs for locations in the United States) was slated for upgrade.

2.2 Solar Radiometry and Metrology
This task provides world-class and traceable solar radiometric measurements, instrumentation, and metrology required by the PV Subprogram projects. In FY 2005, an important activity included making technical and logistical preparations for participating in the next WMO International Pyrheliometer Intercomparison in October 2005, to maintain traceability to world radiometric standards.

2.1 Codes, Standards, and Certification
Under this task, we provide leadership and support in creating and implementing domestic and international certification, codes, and standards for high-quality, safe, cost-effective PV systems applications. SNL, in close collaboration with Southwest Technology Development Institute (SWTDI), leads an industry forum of up to 90 members of the PV industry, utilities, academia, and government agencies to review the existing electrical codes for installation requirements, and proposes improvements and changes for the next code cycle. Certification, to improve the likelihood of safe and properly designed PV installations has been improved through establishment of NABCEP, and certification of components is addressed through the Certification Test Protocol for Inverters.

Additional subcontract support for codes, standards, and certification is shown in Section 6 below.

3. Results and Accomplishments

Highlights of results and accomplishments in the three tasks of this project include the following.

3.1 PV System Performance and Standards
- 24 performance reports were generated for the PV systems monitored at the OTF. These reports were archived and circulated internally at NREL and distributed to the respective module manufacturers (milestone completed).
- Formal designs were made for two new grid-tied PV systems planned for installation in the OTF array; these will feature SunPower high-efficiency c-Si modules and Shell Solar's new CIGSS modules. (Planning completed; one system installed before the end of FY 2005.)
- Improvements to the PVWATTS software were completed. The PV system specification size was changed from an AC power rating to a nameplate DC power rating; an input for an overall DC-to-AC derate factor was added for calculating a reference AC power rating, and residential electric rates were updated with the latest available data (milestone completed).
- The Siemens (now Shell) Solar CIGSS array was taken down for performance measurements and reassembled. Results were discussed with Shell Solar. As a result of discussions with Shell Solar, this array will be replaced with a new system using the latest 80-W modules.
- Results of collaborations with Arizona Public Service and PowerLight Corporation on systems data analysis were reported at the 31st IEEE PV Specialists Conference (milestone completed early).

3.2 Solar Radiometry and Metrology
- A summary report of National Institute of Standards and Technology (NIST) traceable/ ISO17025-compliant optical calibrations of NREL and PV industry radiometers and task activities was published as an NREL technical report (milestone 3/05). A second report is in publication (milestone 9/05).
- Completed the technical and logistical preparations for the WMO International Pyrheliometer Intercomparison set for October 2005 (milestone 8/05).
- After developing specifications, in concert with the Measurements and Characterization task, a purchase order is in place for a new spectroradiometer for the PV Reference Cell Calibration procedures (milestone 8/05).
- Completed redesign of the Pulse Spectral Analysis System, reducing the measurement time for pulse solar simulator classification from 1–2 hours to 15 minutes.
- Performed 15 characterizations of NREL and industry flash solar simulators on request.
- Implemented an automated system for collecting, filtering, and reporting broadband calibration; a process that formerly required 1-2 weeks of manual data analysis now produces results 2–4 hours after completion. New low-noise custom data acquisition system reduces "zero-offset" error signals by a factor of 9. Calibration results are automatically printed and transmitted to a database for archiving and user access. Evaluated indoor calibration system for pyranometers.

3.3 Codes, Standards, and Certification
- Completed and published the 2005 NEC with Industry Forum consensus changes simplifying installs, allowing ungrounded PV circuits to reduce costs and improve system performance. Proposed 42 changes for the 2008 NEC through the SNL/SWTDI Industry Forum.
- Acceptance and adoption of IEEE 1547.1 for interconnecting distributed generation to the utility.
- Completion of technical input revisions of UL 1741 for listing inverters for PV and other

distributed generation systems, which now adopts the IEEE 1547.1

- Development of a test protocol with BEW Engineering for certification of inverters at SNL, subsequently adopted in part for the CEC "Emerging Renewables Program."
- Continuation of NABCEP practitioner certifications with updated tests, study guide, and task analysis.
- Correlated with international standards to assure that U.S. industry can compete in the world with major advances in the IEC standard for PV system interconnects and made major steps to remove unneeded testing requirements using rotating equipment.
- Advancements and concurrence on critical anti-islanding requirements in the IEC interconnect draft standard.
- Initiated a PV Module Certification project to be led by SNL and FSEC to provide more accurate performance characteristics for PV modules.

4. Planned FY 2006 Activities

The goals of this project will be continued into FY 2006. Specific activities to support these goals include the following proposed milestones for completion by 9/30/06, subject to funding levels:

- Continue reporting small PV system performance results, including degradation rates, to manufacturers and program contacts. Install one or two new technology small PV systems at the OTF and initiate long-term testing (as expense funding permits).
- Verify and implement a new in-situ pyranometer calibration procedure for instruments attached to the OTF PV systems.
- Implement improvements to PVWATTS systems analysis software by adding international sites.
- Report results of collaborations between NREL and SNL and industry to evaluate performance-based assessment of system performance.
- Transfer World Radiometric Reference to NREL Reference Absolute Cavity Radiometers through results of the Intercomparison.
- Submit revised American Society for Testing and Materials (ASTM) pyrheliometer and pyranometer calibration standard documents for final ASTM ballot approval.
- Publish a journal article on environmental influences on solar radiometer calibration errors.
- Support Practitioner Certification through small contracts for NABCEP committee work.
- Support international and domestic safety standards, including UL, IEEE, IEC, and ASTM.
- Evolve the Test Protocol for Certification of Inverters to address MPTT/array utilization.
- Collaborate with UL to address ungrounded systems issues related to standards, codes, and safety.
- Continue support of Industry Forum proposals for changes to the 2008 NEC.

5. Major FY 2005 Publications

B. Marion, J. Adelstein, K. Boyle, H. Hayden, T. Fletcher, S. Canada, D. Narang, A. Kimber, L. Mitchell, G. Rich, and T. Townsend, "Performance Parameters for Grid-Connected PV Systems," *31st IEEE PV Specialists Conference*, January 2005.

J. Adelstein and B. Sekulic, "Performance and Reliability of a 1 kW Amorphous Silicon Photovoltaic Roofing System," *31st IEEE PV Specialists Conference,* January 2005.

A. Lester and D.R. Myers, "A Method for Improving Global Pyranometer Measurements by Modeling Responsivity Functions," submitted to *Solar Energy*, 2005.

D.R. Myers, "Solar Radiation Modeling and Measurements for Renewable Energy Applications: Data and Model Quality, Energy, Vol. 30(9), 1517-1531 (2005).

D.R. Myers et al., "An Update on Reducing the Uncertainty in Solar Radiometric Measurements," *SOLARIS 2005, 2nd International Conference on Advancements in Solar Radiation Measurements and Models,* Kormos Publications, Athens, Greece.

I. Reda et al., "Using a Blackbody to Calculate Net-Longwave Responsivity of Shortwave Solar Phyrnometers to Correct for their Thermal Offset Error during Outdoor Calibration Using the Component Sum Method," *J. of Atmospheric and Oceanic Technology,* Vol 20, 1531-1540, 2005.

D.R. Myers et al. "Analysis of Broadband Model Performance for an Updated National Solar Radiation Database in the United States of

America," 2005 Joint ASES/ISES Meeting, Orlando, FL, American Solar Energy Society, 2005.

Additional papers presented at the DOE Solar Energy Technologies Program Review Meeting, October 2004 (see proceedings).

National Electrical Code®: 2005, NFPA70, Published by the National Fire Protection Association, Quincy, MA, 2005.

NEC2005 Handbook, NFPA70, Published by the National Fire Protection Association, Quincy, MA 2005.

UL Standard for Safety for Static Converters and Charge Controllers for Use in Photovoltaic Power Systems; UL 1741, Underwriters Laboratories, Updates for the Second Edition, Oct. 2005.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
PowerMark Corp. Steve Chalmers	Phoenix, AZ Chalmers@powermark.org	U.S. PV module and system certification program support	40* 35
Sunset Technologies Howard Barikmo	Scottsdale, AZ hbarkimo@aol.com	IEC-TC Secretariat support	40* 34
BEW Engineering (formerly Endecon Engineering), Chuck Whitaker	San Ramon, CA Chuck.whitaker@bewengineering.com	PTC system rating standard development	30*
BEW Engineering Chuck Whitaker	San Ramon, CA Chuck.whitaker@bewengineering.com	Work on IEC, IEEE, NABCEP PV and systems standards	50
NABCEP, Pete Sheehan	Malta, NY psheehan@napcep.org	Complete SNL support for establishment of the national practitioner certification program	0
BEW Engineering Chuck Whitaker	San Ramon, CA Chuck.whitaker@bewengineering.com	Continuation of work on IEC, IEEE, and NABCEP standards	25
NABCEP Pete Sheehan	Malta, NY psheehan@nabcep.org	Support for establishment of the national practitioner certification program	160**

* Funded with prior year (FY 2004) funds; allocated
** Funded by DOE/GO

PV System Evaluation and Optimization

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contact: David King, 505-844-8220, dlking@sandia.gov

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

FY 2005 Budget: $966K

Objectives

- Design, implement, and operate a versatile fully instrumented PV System Optimization Laboratory (PV-SOL) for system and inverter performance and aging research.
- Develop, validate, and apply new testing and analysis procedures, based on energy production, 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 inverters, in collaboration with inverter manufacturers and the Florida Solar Energy Center (FSEC), Southwest Technology Development Institute (SWTDI), and BEW Engineering.
- Collect and analyze system installation and operating information in collaboration with established system integrators to establish performance and cost baselines.
- Investigate advanced PV system concepts, manufacturing methods, and deployment strategies that improve performance, reliability, and cost, and accelerate deployment.

Accomplishments

- Implemented the PV-SOL laboratory, which has the capability to perform detailed performance and long-term reliability research on 14 separate nominally 3-kW PV systems with multiple array/inverter combinations.
- Completed baseline performance characterization on 14 inverters from 5 manufacturers as part of a coordinated long-term, inverter-aging project at FSEC, SWTDI, and SNL.
- Provided comprehensive inverter testing in support of DOE high-reliability inverter development contracts with General Electric (GE) and Xantrex.
- Conceived and promoted the concept of fully integrated “PV system manufacturing” as a logical approach to lowering cost, improving reliability, and accelerating system deployment. Initiated investigation of 3-kW system structural design concepts at New Mexico State University (NMSU).
- Investigated new PV market sectors (~200 MW/yr) for pre-manufactured PV systems through discussions with a major metal building manufacturer (Star Buildings) and major auto parking companies (Central Parking Corporation, Parking Company of America Airports).
- Characterized additional modules and arrays. SNL’s “module database,” used by integrators and in commercial PV system design software, now includes 180 commercial modules and 12 arrays.
- SNL’s module/array outdoor testing and data analysis procedures are being implemented at the Arizona State University (ASU) Photovoltaic Testing Lab (PTL), enabling staff to generate coefficients for the “module database.”
- Completed final effort to validate SNL’s module-characterization procedures and array-performance model in cooperation with the National Institute of Standards and Testing (NIST) via a Work for Others agreement. Presented at a special forum on modeling and received American Society for Testing and Materials (ASME) “best paper” award at the International Solar Energy Society (ISES) 2005 conference.

Future Directions

- Continue the concerted effort to enhance and document PV system and inverter performance and reliability research through coordinated efforts in the PV-SOL with module/inverter manufacturers, integrators, FSEC, SWTDI, and BEW Engineering.

- Continue to investigate turnkey PV system manufacturing concepts, including electrical and structural design, installation cost, commercialization plans, and prototype system demonstration.
- Emphasize technical publications, including: tech transfer of module procedures to ASU/PTL, performance characterization/modeling of new technology PV arrays, energy analysis for multiple systems, inverter aging capabilities/procedures, inverter performance modeling, advantages of PV system manufacturing concepts.
- Develop improved field data acquisition and analysis procedures for monitoring PV system performance that provide more meaningful system performance indices.

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1. Introduction

The System Evaluation and Optimization Project activities at SNL are closely linked to the needs of manufacturers and system integrators. The effort provides the laboratory and field-test information needed to establish the performance and reliability status of current PV systems and also identifies opportunities for improved system design and component integration in next-generation systems. These activities are key to meeting the *DOE Solar Program Multi-Year Program Plan* (MYPP) targets, as well as the goals of the *U.S. PV Industry Roadmap*. As such, the System Evaluation and Optimization Project is the focal point within the DOE Solar Program where the technical issues of PV component manufacturers, system integrators, and users converge.

2. Technical Approach

Major research activities for FY 2005 included detailed module, array, inverter, and system research aimed at understanding and improving the performance, reliability, and cost of fully integrated PV systems. This research was conducted using the capabilities and expertise associated with SNL's newly implemented laboratory, PV-SOL.

The PV-SOL is now equipped to accurately evaluate the energy production from 14 separate 3-kW grid-tied systems using different combinations of the latest vintage modules and inverters. Energy flow in and out of all system components is continuously recorded, providing detailed performance characteristics, as well as long-term aging characteristics for both inverters and arrays under all weather conditions. The performance of the PV array associated with each inverter has been fully characterized and modeled, providing real-time calculation of the expected DC energy from the array for comparison with measured DC input to the inverter.

Specific technical goals and output from the PV-SOL will include the following:

- Validation of PV system performance models and development of better performance indices
- Testbed for new "system manufacturing" concepts and structural designs,
- Characterization of balance-of-system components supporting product development
- Improved performance or diagnostic field tests
- Investigation of array utilization, inverter maximum power point tracking (MPPT), and efficiency based on energy production
- Improved start-up, shut-down, MPPT, and performance-monitoring algorithms for inverters
- Thermal model (operating temperature) for inverters versus meteorological conditions
- Investigation of array shading and orientation
- Optimization of design, components, setpoints, and controls for off-grid and hybrid systems
- Evaluation of PV system monitoring and control hardware and software
- Development of wireless, low-cost, accurate data acquisition (DAS) hardware.
- Characterization of prototype components supporting industry product development.

Budget allocations by task for the System Evaluation and Optimization Project are provided in the following table.

Task Title	FY 2005 Budget ($K)
System Performance Testing and Modeling	430
Inverter Performance Characterization	259
Advanced System Concepts	277

Fig. 1. PV-SOL: Six new PV array technologies

Fig. 2. PVSOL: Fully instrumented inverters in continuous system performance test

For FY 2005, the project had three separate sub-tasks: System Performance Testing and Modeling, Inverter Performance Characterization, and Advanced System Concepts.

2.1 *System Performance Testing and Modeling*
This task was focused on developing, validating, and documenting improved system and PV array testing, modeling, and monitoring techniques in direct collaboration with industry, the National Renewable Energy Laboratory (NREL), and also this year with NIST.

Specific objectives of the task are to:

- Develop array testing, data analysis, and performance-modeling procedures that are accurate and able to be practically implemented for c-Si, thin-film, and concentrator PV.
- Assist industry in developing improved performance indices and low-cost monitoring methods for systems.
- Apply testing/modeling methods, providing integrators and manufacturers with detailed inverter and array performance data for current technology systems.
- Evaluate the field-aging characteristics of arrays and inverters that affect performance, reliability, and safety.

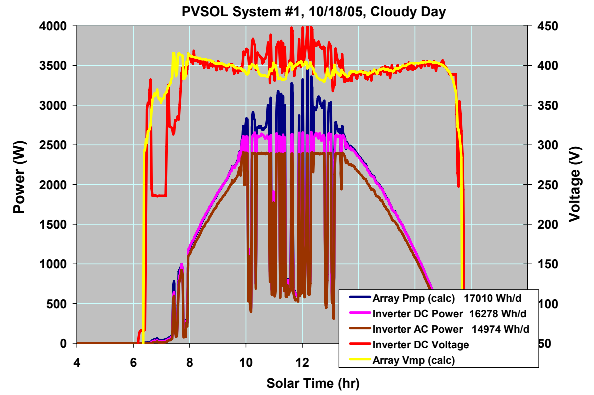

Fig. 3. Typical system performance on cloudy day

2.2 *Inverter Performance Characterization*
Under this task, we conducted comprehensive inverter testing to aid inverter development, benchmark performance and utility compatibility of commercial inverters, identify degradation/failure mechanisms during long-term field aging, and provide performance parameters needed for system energy modeling. Extensive laboratory equipment and expertise shared with SNL's Distributed Energy Technology Laboratory (DETL) are used to support this effort. This activity addresses the "Inverter Testing and Industry Support" section of the MYPP.

For the inverter long-term aging activity, multiple sites (SNL, FSEC, and SWTDI) were established and instrumented to obtain consistent sets of performance data under different environmental conditions. A test protocol was developed for the comprehensive initial baseline tests conducted at SNL. After field aging, the baseline tests will be repeated at SNL on nominally an annual basis to identify failures and degradation rates.

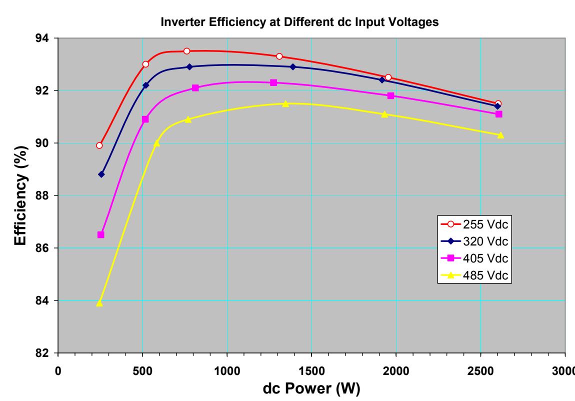

Fig. 4. Typical inverter efficiency characterization

2.3 Advanced System Concepts
This task was initiated to pursue novel PV system manufacturing methods with the specific objectives of lowering system installation costs, improving system reliability, and accelerating system deployment. This effort directly addresses DOE Solar Program targets described in the MYPP for 2007–2011.

Fig. 5. Manufacturing concept for turnkey systems

Development of manufacturing technology for complete PV systems will reduce PV system assembly and installation costs, indirectly cut component costs, and significantly improve system reliability. Although this approach is valid for multiple market sectors, the focus this fiscal year was to examine the potential impact on the commercial sector. Specific research activities included:

- Investigation of technical barriers to large-scale PV adoption and deployment
- Development of accurate information related to individual cost elements in overall system cost
- Identification of technological improvements that reduce costs and improve system reliability
- Identification and promotion of markets obviously suited to pre-manufactured PV systems.

3. Results and Accomplishments

The FY 2005 technical milestones and related accomplishments for the System Evaluation and Optimization Project are listed below by project subtask.

3.1 System Performance Testing and Modeling

- Transfer of SNL outdoor module/array performance characterization methods and module database to ASU/PTL was initiated. Milestone delayed until FY 2006 due to personnel changes at ASU/PTL.
- Completed comprehensive effort with NIST to compare and validate SNL module testing and modeling methods for building-integrated photovoltaic systems (BIPV). Documented completion of milestone at ISES-2005 conference in August 2005.
- Characterized additional modules and arrays. SNL's module database, which is used by integrators, research labs, and in commercial PV system design software, now includes 180 commercial modules and 12 arrays.
- Completed performance characterization of eight new PV arrays at SNL's PV-SOL for long-term system performance and reliability research.

3.2 Inverter Performance Characterization

- Coordinated implementation of long-term inverter-aging capabilities at SNL, FSEC, and SWTDI for milestone completion.
- Developed and experimentally verified an initial multi-factor inverter performance model for the PV Advisor model used to benchmark PV system performance as part of the DOE Solar Program prioritization using the Systems-Driven Approach.
- Completed comprehensive baseline performance characterization of 14 separate inverters from 5 manufacturers for use in the field-aging project.
- Provided detailed inverter characterization for GE and Xantrex in support of their high-reliability inverter development contracts with SNL.
- Developed and implemented inverter testing protocol in cooperation with BEW Engineering and the California Energy Commission, addressing both performance and utility compatibility.

3.3 Advanced System Concepts

- Initiated and documented initial effort with manufacturers, integrators, and users to define new manufacturing, certification, installation, and deployment strategies for next generation PV system-manufacturing concepts. Milestone.
- Conceived prototype designs for manufactured PV systems and conducted

initial structural design as part of Senior Design Projects at NMSU.

- Investigated new PV market sectors (~200 MW/yr) for manufactured PV systems used in manufactured metal building (Star Buildings) and for covered parking structures (Central Parking Corporation, Parking Company of America Airports).

Fig. 6. Markets for manufactured PV systems

4. Planned FY 2006 Activities

In FY 2006, the System Evaluation and Optimization Project will consist of the following three subtasks: System Performance Testing, Modeling, and Aging; Inverter Performance Characterization and R&D Support; and Advanced PV System Manufacturing and Deployment Concepts.

The major expected results for FY 2006 include:

- Completing and documenting tech transfer of SNL outdoor PV module/array testing and analysis procedure to ASU/PTL for module database work.
- Characterizing, modeling, and documenting baseline performance of eight new PV arrays used for inverter-aging and system energy analyses at SNL.
- Demonstrating and documenting new benchmark for accuracy in energy-based performance assessment of systems and components.
- Completing and documenting baseline performance of five inverter types used for initial phase of long-term inverter performance evaluation at SNL, FSEC, and SWTDI.
- Generating joint report with FSEC and SWTDI describing capabilities and procedures used for long-term field aging of inverters.
- Continue effort to improve general performance model for inverters, including characteristics associated with DC/AC efficiency, MPPT effectiveness, start-up, shut-down, thermal foldback, and power factor.
- Generating report describing cost, reliability, safety, installation, and marketing advantages of factory-integrated and certified PV systems, (i.e., system manufacturing).
- Designing, fabricating, and demonstrating an optimized 3-kW PV system intended for complete factory assembly and testing and simplified field installation.
- Generating a report describing the development status of the high-reliability "AC Building Block" PV system concept for plug-and-play residential applications.

5. Major FY 2005 Publications

D.L. King et al., "Array Performance Characterization and Modeling Method for Real-Time PV System Performance Analysis," *DOE Solar Program Review Meeting*, Nov. 2005.

J.W. Ginn et al., "Photovoltaic Inverter Baseline Characterization for Field Aging Research," ibid.

M.A. Quintana et al., "Development of New System Manufacturing, Integration, Deployment Concepts," ibid.

A. Hunter Fanney, D.L. King, et al., "Comparison of Photovoltaic Module Performance Measurements," *ISES-2005 World Solar Congress*, Orlando, Aug. 2005.

M.A. Quintana, "Photovoltaic Systems Engineering and Reliability; Overview," DOE Solar Program Review Meeting, Oct. 2004.

D.L. King, W.E. Boyson, J.A. Kratochvil, "Photovoltaic Array Performance Model," *SNL Report*, SAND2004-3535, Aug. 2004.

Domestic PV Applications

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL)
Key Technical Contacts:	John Thornton (NREL), 303-384-6469, john_thornton@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 2005 Budgets:	$776K (NREL), $50K (SNL)

Objectives

- Support development of DOE Systems-Driven Approach (NREL and SNL).
- 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).
- 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).
- Support U.S. Department of Agriculture (USDA) Farm Bill Solar Program (NREL and SNL).

Accomplishments

- Supported development of program criteria and evaluation of proposals for USDA Farm Bill Solar Program (NREL and SNL).
- Conducted three consumer workshops at the Denver Western Stock Show with public attendance of approximately 450 (NREL).
- Conducted solar applications workshops for farmers in Nebraska and Kansas.
- Performed rooftop surveys for Department of State headquarters building, Washington, D.C., and the U.S. Federal Building, Raleigh, North Carolina (NREL).
- Provided technical support to the City of Palo Alto per DOE request.
- Developed partnership with DOE Rocky Mountain Oilfields Testing Center to test use of PV in oilfields (NREL).
- Provided technical support to U.S. Environmental Protection Agency Supplemental Environmental Projects (NREL).
- Assisted the USDA/Rural Utility Service in the development of a pre-approved packaged systems and standardized acceptance criteria and systems specifications appropriate for bulk system procurements and/or financing (SNL).
- Provided technical assistance to priority Native American renewable energy programs (SNL).

Future Directions

- Continue to assist the USDA/Rural Utility Service in the development of pre-approved packaged systems and standardized acceptance criteria and systems specifications appropriate for bulk system procurements and/or financing (SNL).
- Continue to provide technical assistance to priority Native American renewable energy programs (SNL).
- Support development of program criteria and evaluation of proposals for USDA Farm Bill (NREL and SNL).
- Conduct consumer workshops at the Denver Western Stock Show (NREL).
- Provide logistical support for Solar Decathlon 2007 (NREL).

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1. Introduction

The Domestic PV Applications Project supports 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 is to provide a focal point for DOE activities through project development, dissemination of information, increasing public awareness, subcontract management, and technical assistance. Our work is carried out both in-house at NREL and SNL, as well as externally with and/or through a wide range of federal, state, and local groups.

2. Technical Approach

During FY 2005, 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 products that will effectively convey the potential of PV (and other solar technologies) to both technical and non-technical audiences, and providing support to organizations, such as the USDA/Rural Utility Service, to develop standardized system specifications and acceptance criteria. We also supported several DOE-requested activities, as well.

Task Title	FY 2005 Budget ($K)
Training, Education, and Technical Assistance (NREL)	776
Domestic Technical Support (SNL)	50

3. Results and Accomplishments

3.1 National Renewable Energy Laboratory

During FY 2005, our highest priority was to support the Solar Decathlon, although we also found time to contribute in other ways (see below).

Solar Decathlon 2005. For FY 2005, our major objective was to support Solar Decathlon, which took place on the National Mall in Washington, D.C., during September and October 2005. This intercollegiate competition required students to design, build, and operate the most attractive and energy-efficient solar-powered home. Our project was responsible for installing, operating, and removing the Decathlon village and returning the Mall to its original condition. We worked closely with the National Park Service, Smithsonian Institution, and the private sector to make the competition a success.

Solar Decathlon 2007. Our efforts on Solar Decathlon were not just directed toward the 2005 event. We also started planning for the third Solar Decathlon in 2007. The short lead time mandated that the request for proposal be sent to universities in FY 2005.

National Western Stock Show. In January, we conducted workshops and hosted an exhibit at the National Western Stock Show in Denver, Colorado. According to Stock Show staff, more than 650,000 visitors attended the 16-day event.

Telecommunications Study. Our acknowledged expertise in both PV technology and project management led to our receiving $50,000 from the Million Solar Roofs Initiative to study the potential of PV as a power source for advanced telecommunications applications. We worked with Sprint to provide technical advice to their engineers, who are developing PV power sources for wireless communications. The effort will continue into FY 2006.

Fossil and Renewable Energy Partnership. Increasing the efficiency and robustness of our nation's current energy infrastructure has become a high priority since the events of September 11, 2001. Because of our earlier involvement in energy security, we were asked to participate in a special task force convened by the DOE Denver Regional Office. The goal of this task force, called the Fossil and Renewable Energy Partnership, is to pursue a highly beneficial, integrated development of energy resources in the Rocky Mountain region that combines the individual advantages of both fossil and renewable resources. The Partnership consists of representatives from national laboratories, universities, and industry. Our specific interest is to foster applications of PV in the production and distribution of coal, oil, and gas.

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 effort will continue into FY 2006.

DOE Special Requests. We supported special requests from DOE. We installed a PV-powered water pump and a small wind turbine in the lobby of the Forrestal Building as part of an NREL-produced EERE exhibit.

Boy Scout Jamboree. We worked with EERE and Fossil Energy to provide staffing and exhibits for the 2005 Boy Scout Jamboree held in July 2005 at Fort A.P. Hill, near Fredericksburg, Virginia. DOE is responsible for teaching the Energy Merit Badge and had requested our assistance to cover renewable energy. We joined a team of DOE volunteers from various DOE program offices who taught the young people from all over the country about various aspects of energy. More than 40,000 boys and girls (ages 14 to 21), some 30,000 adults, and more than 100,000 visitors attended this event.

Channel 7 Meteorological Tower and Radar. The TV weatherman at Denver's Channel 7, Mike Nelson, requested NREL's help to evaluate the possibility of powering a new weather radar and meteorological tower using PV. We installed a 2-kW PV array to power Channel 7's weather radar in a rural location near Watkins, Colorado, a few miles east of Denver International Airport. The new meteorological tower will be located on the roof of Channel 7 headquarters in downtown Denver.

Solar Secure Schools. Under contract to NREL, En-Strat Associates developed strategies and design specifications for low-cost, prepackaged PV systems for schools to enable the schools to be used as emergency community centers. The report will be published in FY 2006.

3.2 Sandia National Laboratories

SNL has active partnerships with several state and federal agencies, including the USDA Forest Service, National Park Service, Bureau of Land Management, and the USDA, as well as with several tribal utilities and other tribal organizations. These partnerships have focused on leveraging SNL technical assistance with large procurement activities to expand the use of PV in viable applications. Key to these partnerships is the use of PV systems with reliable components, approved designs, and quality installations using SNL's expertise and support. Through these partnerships and related field activities, valuable insight is gained regarding the technical functioning of installed systems, aspects of installed and lifetime costs, and feedback for benchmarking and advanced systems engineering activities. Activities in FY 2005 focused on assisting the USDA Rural Utility Service (RUS) in the development of a pre-approved packaged systems and standardized acceptance criteria and systems specifications appropriate for bulk system procurements and/or financing, and technical assistance to priority Native American renewable energy programs.

This information is considered important for RUS to insure that its loans are for acceptable technology and that they will in fact be repaid. SNL addressed the complementary needs of both DOE and USDA RUS with the life-cycle cost information obtained in this work.

4. Planned FY 2006 Activities

4.1 Training, Education, and Technical Assistance (NREL)

During FY 2006, our highest priority will be to plan the logistics and support proposal evaluation for Solar Decathlon 2007. Other activities will address 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 and developing information products that will effectively convey the potential of PV (and other solar technologies) to both technical and non-technical audiences. We will conduct three consumer workshops in January 2006 at the Denver Western Stock Show, where 400 to 500 public attendees are expected to come to learn about PV. We will continue to provide technical support to federal, state, and local organizations, such as the Rocky Mountain Oilfields Testing Center in Casper, Wyoming, and the Federal Aviation Administration for the installation of PV systems. DOE Headquarters activities will be supported on request.

4.2 Domestic Technical Support (SNL)

Activities in FY 2006 will focus on developing a paper on PV residential systems with Tucson Electric Power.

5. Major FY 2005 Publications

5.1 National Renewable Energy Laboratory

G.W. Braun, P.F. Varadi, and J. Thornton, "Energy Secure Schools: Technology, Economic, and Policy Considerations." Presented at the

International Solar Energy Society 2005 Solar World Congress, Orlando, FL, 2005.

J.P. Thornton, “Renewables—America’s Well-Kept Secret,” *EnergyBiz Magazine*, pp. 60–61, November/December 2004.

W. Larsen, “Outreach is Serious Fun,” *2004 Solar Program Review Meeting*, Denver, CO, October 25–28, 2004.

C. Hanley and J.P. Thornton, “The Role of Technology Adoption within the Department of Energy’s Solar Energy Technologies Program,” *2004 Solar Program Review Meeting*, Denver, CO, October 25–28, 2004.

5.2 Sandia National Laboratories

"Operation and Maintenance Field Experience with Photovoltaics Water Pumping Systems." Presented at the ASME conference in Orlando, August 2005.

"Operation and Maintenance Field Experience for Off-Grid Residential Photovoltaic Systems," published in PIP, January 2005.

"Multi-Year Performance Assessment of Two PV Installation Cluster." A joint effort published and presented at the ASME conference in Orlando in August 2005.

"Photovoltaic Power Plant Experience at Arizona Public Service: A 5-Year Assessment," published in PIP, June 2005.

6. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share
En-Strat Associates Gerry Braun	Darnstown, MD Gbraun12@comcast.net	Develop strategies and design specifications for low-cost, prepackaged PV systems for schools (to enable the schools’ use as emergency community centers).	50	0
Carolynne Harris Knox	Washington, D.C. carolynnehknox@mindspring.com	Provide logistical support for Solar Decathlon 2005	30	0
Sustainable Buildings Industry Council Helen English	Washington, D.C. SBIC@SBICouncil.org	Conduct strategy session with “big box” architects and facility managers to expedite building-integrated PV adoption.	50	10

Building-Integrated Photovoltaics

Performing Organizations:	National Renewable Energy Laboratory (NREL) DOE Golden Field Office (DOE/GO)
Key Technical Contac):	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 2005 Budgets:	$1,370K (NREL), $166 (DOE-GO)

Objectives

- Support deployment of building-integrated photovoltaic (BIPV) technologies with tools for modeling performance, and by supporting a forum for potential users of BIPV.
- Engage homebuilding industry in evaluation of long-term potential of net zero energy homes (ZEH), a key BIPV market.
- Accelerate adoption of BIPV in new residential and commercial construction through successful collaborative industry partnerships among PV manufacturers, installers, builders, designers, and the trades.
- Conduct the next Solar Decathlon university competition of 100% solar-powered homes, which demonstrate BIPV and solar technologies in marketable residential applications.

Accomplishments

- Continued the implementation of the 2005 Solar Decathlon university competition, releasing the final regulations, solidifying sponsors, and supporting teams.
- Completed a releasable Version 1.8 of the building energy tool Energy-10.
- Convened a workshop on BIPV for big-box retailers, chain hoteliers, and BIPV industry leaders (January 2005).
- Concluded the ZEH potential study and reported with the National Association of Home Builders (NAHB) to the satisfaction of all contributors.

Future Directions

- Conduct the 2005 Solar Decathlon in the first quarter, FY 2006, and release a solicitation for the 2007 event.
- Select teams for the 2007 Solar Decathlon and launch the activities leading toward execution of the 2007 event.
- Monitor and guide the development of BIPV through the subcontracted university programs.

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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 several distinct, interrelated activities within this overall effort.

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 are competing. Teams were selected through a competitive procurement in 2003, and have been working on their projects over the intervening 2 years, under our supervision and guidance. They will transport their houses to the National Mall in Washington, D.C., where they build a “solar village” and open their homes to the visiting public from October 7 to October 16, 2005. They compete against one another in ten contests. The contests will test 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 must also provide the power for an electric car. In addition to the energy-related contests, each team will be judged on its home's architecture and livability. And expert homebuilders will evaluate each home’s “build-ability” (ease of construction and replication of design). The teams must provide documentation about their homes’ designs and communicate about their homes to the public.

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 comprise the activities of this project for the NREL organizers and its subcontractors. Some contests will be scored by measuring performance, and some will be 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 Solar Decathlon are 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, NAHB, and private-sector sponsors BP, the DIY Network, and Sprint-Nextel.

2.2 Complete a Releasable E-10 Version 1.8

ENERGY-10, an award-winning PC-based design tool, helps architects and building designers quickly identify the most cost-effective, energy-saving measures for residential and small commercial buildings. *ENERGY-10* can quickly identify the best combination of energy-efficient strategies, including daylighting, passive solar heating, and high-efficiency mechanical systems.

The significant new addition and goal for FY 2005 in Version 1.8, supported by the BIPV Project, is the integration of grid-tied PV systems (using EnergyPlus as the simulation engine) and simple modeling of solar domestic hot water (SDHW) as new strategies that can be applied either manually or automatically.

2.3 Hold a BIPV Workshop for Big-Box Retailers

Attract major retailers and others to a workshop on commercial applications of PV in buildings.

2.4 Conclude the ZEH Potential Study

This goal of this study is to present a far-reaching outlook into the possibilities for net zero energy home (ZEH) technologies in the new home market and their potential impact on U.S. energy consumption through 2050. Zero energy homes, which are connected to the utility grid, combine highly energy efficient design and technology with solar electric and thermal systems to produce as much energy as they use on an annual basis.

This study examines four scenarios for the adoption of ZEH into the single-family home market and the effect of each scenario on residential energy consumption through 2050. A reference case, where household energy use remains constant, serves as a basis for comparison.

Zero energy homes are technically feasible today. If cost trends continue and research milestones are accomplished in solar energy and efficiency technologies, ZEH will become economically competitive with conventional construction when utility costs are included in the cost of homeownership. Market penetration of highly efficient homes with solar energy systems has already begun and will continue in selected markets. Solar electric (photovoltaic) system costs have continued to decline while production continues to increase by about 30% annually. New, low-cost solar water heating designs are under development that will reduce costs and improve efficiency. At the same time, a portfolio of energy efficiency improvements in appliances, building envelopes, windows, and mechanical systems is moving into the market. Combined, all of these elements suggest a potential to build practical ZEH with a significant market potential. But critical questions remain, including the following key questions to be investigated in this study:

- Will homebuyers value the features and benefits of ZEH?
- How much are homebuyers willing to pay for ZEH?
- What level of impact would further investment into R&D and public policies have on hastening the adoption of ZEH and the resultant energy savings by 2050?

To answer these questions, the study will aim to:

- Evaluate homeowner attitudes and opinions about the features and benefits of ZEH and their willingness to pay more for a home that has increased comfort and environmental performance and fixed monthly costs (accounting for a higher mortgage to pay for ZEH features, but no utility bill).
- Determine at what year a ZEH becomes cost effective under various incentive scenarios.
- Using technology diffusion curves, determine the projected rate of market adoption of ZEH and the final impact on energy consumption of the single-family housing stock to 2050.

To achieve these goals, a combination of techniques was employed including: focus group and Internet-based market research; computer optimization techniques to calculate the optimal combination of today's state-of-the-art energy efficiency and solar technologies to achieve ZEH; and calculations to project market diffusion of ZEH using market adoption curves and solar technology cost projections.

The study was directed and conducted by independent sources, and its findings were endorsed by experts in the building industry, represented by the NAHB. The work at the NAHB Research Center was conducted through an NREL subcontract to McNeil Technologies.

Task Title	FY 2005 Budget ($K)
Solar Decathlon (NREL)	1,270
Solar Decathlon (DOE/GO)	166
PV in Buildings R&D	100
ZEH Potential	180*

*FY 2004 funding

3. Results and Accomplishments

3.1 Major Accomplishment: Solar Decathlon 2005

During FY 2005, we prepared for successfully carrying out the 2005 Solar Decathlon, to be held September 29–October 19, 2005 on the National Mall in Washington, D.C. Activities include scoring algorithm development for the 10 contests; selection of expert judges for dwelling, architecture, engineering, Web sites, and house tours; review of team designs for code and regulation compliance; instrumentation system development, acquisition, and shakedown, as well as some installations of equipment; development of communications materials (brochures, media kits, official program, Web site materials, and graphics); review of educational exhibit designs; coordination of teams (including a face-to-face workshop in January with all teams and organizers and monthly conference calls); coordination of sponsors (including organizing and convening two sponsor meetings in Washington, D.C.); coordination of volunteers (including a procurement for management of volunteers); procurement of stagecraft and assembly of the solar village; and development of procedures for safe conduct of the entire event. These activities comprise the project thus far carried out by the NREL organizers and its subcontractors. We have prepared for crowds of more than 200,000 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. For more information, see the Solar Decathlon Web site (www.solardecathlon.org).

3.2 Major Accomplishment: Adding Solar Analysis Capability to ENERGY-10

On May 5, 2005, ENERGY-10 Version 1.8 (a beta test version of this software) was released to a select community of building energy analysts via the NREL FTP site. ENERGY-10 E10 Online HELP has been updated for these new features. A new feature in Version 1.8 of ENERGY-10 is the ability to model and simulate the performance of a PV system that is either stand-alone or integrated with the building. This is an energy-efficient strategy, appearing as one of 14 strategies in the APPLY dialog box. This adds a powerful and unique capability to the program, allowing the user to study the hourly interaction between the building load and the PV array. The PV option contains 120 actual modules for user selection.

The new PV capability in Version 1.8 will help ENERGY-10 users evaluate how a PV system will offset realistic building electrical loads, whereas very stylized loads have been used in other programs. If the PV system is integrated into the building skin, there will be thermal effects that are accounted for by changes in the building description, which is passed to the ENERGY-10 thermal simulation engine. Thus, results produced by this tool show the overall consequences of building electrical load requirements (before and after the PV system contribution), PV system output, and when and how much of the PV output is available to be sold back to the utility. These results are available as annual summaries, typical monthly plots, and hourly plots.

Building designers can take advantage of this capability to easily perform preliminary investigations of PV. Although the PV capability in ENERGY-10 is not intended to replace detailed PV system design, the analysis that is performed is an integrated accounting for 8,760 hours, including, for example, hourly schedules for lights, plug loads, time-variable HVAC loads, and time-variable dimming of lights due to daylighting. The approach can accommodate future technologies, such as new PV products integrated into building elements (e.g., thin-film coatings on windows).

The program distinguishes between building-integrated (wall-, roof-, or window-integrated) and stand-alone systems, as defined by up to four building-integrated arrays and one stand-alone array, all fed through a single inverter. Only grid-connected systems are modeled in this version.

ENERGY-10 Version 1.8 also includes a new solar domestic/service hot water modeling capability. A straightforward collector efficiency, storage tank accounting type model has been embedded in this version and integrated with the APPLY and RANK features of the program. Selection of this strategy launches an hourly simulation of the SDHW system, which is then used to adjust the service hot water load in the main whole-building simulation.

3.3 Major Accomplishment: Held BIPV Big-Box Workshop

We held a workshop in January 2005 in Washington, D.C., on commercial applications of PV in buildings (organized by the Sustainable Building Industry Council). Representatives from Target, Wal-Mart, Marriott, and others attended.

3.4 Major Accomplishment: ZEH Potential

A draft report of a zero energy home "due diligence" study was completed by NREL analysts working together with DOE, the NAHB Research Center, and McNeil Technologies. The study demonstrates that R&D supporting ZEH in conjunction with state and federal tax incentives can accelerate and significantly improve the energy performance of the residential sector in the United States. By 2050, ZEH, with a tax incentive for solar technologies, can reduce the energy consumption of all single-family homes by 19% while, at the same time, the stock of single-family homes increases by 39%.

With continued federal R&D programs to lower the cost of solar electric, solar thermal, and advanced building energy efficiency technologies—coupled with providing tax credits to homeowners for renewable energy systems—the ZEH concept will begin to diffuse into the market as early as 2012 and result in annual energy savings in 2050 of 3.4 quads (19%) in single-family homes. In contrast, without tax incentives or the advantages of ZEH bundling (defined as the portfolio of energy efficiency and solar technologies necessary to make ZEH), but with continued federally supported R&D to reduce solar prices and develop advanced energy efficient technologies, residential solar electric systems do not begin to diffuse into the marketplace until 2027 at the earliest and only realize a reduction of 0.5 quad (3%) in the energy use of single-family homes by 2050.

The results illustrate how the potential market for ZEH could be accelerated with government investment in a robust ZEH R&D effort and consumer tax incentives. Market penetration of ZEH has benefits to consumers, homebuilders, electric utilities, and the environment. Consumers benefit from more stable, predictable home energy costs in the near term and savings on combined mortgage and utility bills in the longer term (as utility bills rise for non-ZEH). Builders benefit from having a new product to offer consumers that enhances profit due to a higher sales price (but that does not affect affordability to the consumer). Electric utilities benefit from reductions in peak electric demand that help avoid expensive investments in new peak generating capacity. Lastly, society benefits from reduced air emissions and distributed generation that reduces the vulnerability of our energy infrastructure.

Milestones Supported by DOE Funding

Milestone or Deliverable	Due Date	Status
Convene Solar Decathlon Teams Workshop during IEEE PV conference in Orlando, FL.	01/31/05	Complete
Competition electric vehicles purchased and	04/30/05	Complete

Milestone or Deliverable	Due Date	Status
delivered to Solar Decathlon teams.		
Initiate Solar Decathlon 2005 event on the National Mall in Washington, DC, beginning September 29, 2005.	09/30/05	Complete
Complete releasable version of ENERGY 10, Version 1.8 building modeling software, including new features of SDHW and BIPV components.	04/30/05	Complete

4. Planned FY 2006 Activities

- Conduct the 2005 Solar Decathlon in the first quarter, FY 2006.
- Release a solicitation for the 2007 Solar Decathlon event.
- Select teams for the 2007 Solar Decathlon and launch the activities leading toward execution of the 2007 event.
- Monitor and guide the development of BIPV through the subcontracted university programs.
- Develop a solicitation for subcontracting production of the 2007 Solar Decathlon.

5. Major FY 2005 Publications

M.R. Wassmer, C.L. Warner, "Building-Energy Simulation and Monitoring Research Activities for Solar Decathlon Houses." *Proc. 31st IEEE PV Specialists Conference, January 3–7, 2005, Lake Buena Vista, FL*, pp. 1714-1717 (2005).

E. Hancock, G. Barker, C. Warner, R. King, R. Nahan, *2005 Solar Decathlon Rules and Regulations*, NREL Report No. MP-520-34627 (2005).

U.S. DOE, *2005 Solar Decathlon Web Site,* www.solardecathlon.org.

U.S. DOE, *Solar Decathlon: Powered by the Sun,* 5 pp., DOE/GO-102005-2154 (2005).

U.S. DOE, *2005 Solar Decathlon Competition Program*, 36 pp., DOE/GO-102005-2184 (2005).

6. University and Industry Partners

The following organizations partnered in the project's activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
Hargrove, Inc. Kate Graffeo	Washington, D.C. kgraffeo@hargroveinc.com	Multiple awards for event management, including tents, venue, instrumentation, judging and infrastructure, for the Solar Decathlon competition	300
Consultant C.E. Hancock	Boulder, CO cehancock3@aol.com	Solar Decathlon instrumentation installation, data acquisition, and monitoring, and real-time scoring for the event	100
New Resources Group Dan Eberle	Freeman, MO daneberle@mac.com	Award to support site operations for Solar Decathlon	50
Interweaver Norman Weaver	Steamboat Springs, CO norm_weaver@interweaver.com	ENERGY-10 revision with PV and Solar	90
SENTECH, Inc Jonathan Hurwitch	Bethesda, MD jwitch@sentech.org	Special events organization for key audiences (students, builders, observers) and volunteer coordination at Solar Decathlon	40
Formula Sun Dan Eberle	Freeman, MO deberle@formulasun.org	Purchase of electric cars for 19 Solar Decathlon teams.	166*
McNeil Technologies Kevin deGroat	Springfield, VA Kdegroat@mcneiltech.com	Assessment of U.S. ZEH potential by the U.S. home-building Industry (NAHB Research Center) and DOE.	180

* DOE-GO award

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:	Heather Mulligan (DOE Headquarters, Project Manager), 206-553-7693, heather.mulligan@ee.doe.gov Carol Tombari (NREL, Primary Contact), 303-275-3821, 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 2005 Budgets:	$250K (NREL), $70K (SNL), $100K (DOE/ROs), $1,325K (DOE/NETL)

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

- Added five new MSR State and Local Partnerships during FY 2005, bringing the total to 94. In addition, 104 businesses, electricity providers, organizations, and agencies joined Partnerships, bringing the national total of participants to 926.
- Awarded $1.325 million in State and Local Partnership grants, with an average cost share of well over 20%.
- Provided engineering support, economic analysis, and directed market studies for Partnerships. Segue Consulting, NREL's subcontractor, responded to 920 technical assistance e-mail requests from the Partnerships and prepared 64 pieces of analysis ranging from 2–20 pages.
- NREL/Segue developed an analytical approach that captures the value (versus cost) of solar technology. The tool is titled the Analysis of State Energy Tradeoffs Databank (ASSET).
- Created a link between the on-the-ground experience of MSR Partnerships and the ongoing solar systems research at SNL and NREL by promoting the collection of data from Partnerships for the reliability database. In addition, the Florida Solar Energy Center (FSEC) is using data collected as part of MSR metrics work to identify the best states and utilities to partner with to collect high-quality performance data.
- Produced *Become One in a Million Annual Report*, plus an Executive Summary, which was distributed at the MSR/IREC Joint Annual Meeting.
- Prepared the *Million Solar Roofs: Metrics* report, which examined inputs, outputs, and outcomes of the initiative between 1997 and 2003/4.
- Held five telephone seminars, which are 1-1/2 hour interactive seminars on a single subject. Subjects included: PV Industry Roadmap; Inspector Guidelines for PV Systems; Zero Energy Homes; Advanced Interconnection and Net Metering and Solar in the Energy Bill. Attendance was more than 100 for the most recent call.
- Held peer-to-peer meetings of MSR Partners in each DOE region to exchange ideas and share valuable informational resources. In addition, held an Annual Meeting of MSR participants in conjunction with the American Solar Energy Society (ASES) Conference.

- A paper titled “Urban Scale Solar” was drafted last November. As a result, a new program—Solar Powers America—was announced and introduced to the MSR participants at the Annual Meeting on October 8, 2005.

Future Directions

- Million Solar Roofs will transition into the Solar Powers America Program in FY 2006.
- Solar Powers America will focus on incorporation of solar technologies into local infrastructure-planning exercises, and will allow for more than just building applications.
- Solar Powers America expects to make fewer grant awards for larger sums of money.

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1. Introduction

The objective of the Million Solar Roofs Initiative is 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 supports the development of local and regional markets for solar technologies by working with states and local communities to address and remove institutional barriers.

MSR activities are essential components of the DOE Solar Program Systems-Driven Approach, which considers deployment an integral part of the sequence from basic research through market conditioning. In addition to helping create markets, MSR has provided the R&D program with critical feedback on performance and consumer preferences.

2. Technical Approach

To achieve its objective, MSR works 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 must commit to facilitating the installation of a specified number of “solar roofs” by 2010. These Partnerships use 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.

The hallmarks of MSR’s technical approach in FY 2005 involved: (1) providing Partnerships with access to small grants to support market development in their communities; (2) providing individualized technical assistance (TA) to Partners on request by their participating members; (3) directing market studies based on needs identified by multiple participants; (4) sharing information on a regular, routine basis through a host of forums and communication media; and (5) functioning as a feedback link between the Solar Program’s laboratory-based R&D and the real-world experiences of solar technology owners.

2.1 Technical Assistance to MSR Participants

MSR, with support from NREL and SNL, offers all Partnerships access to individualized TA, along with directed market studies. The assistance is often delivered on site in the field and represents the “Cadillac” of service delivery. To amortize the costs, and consistent with its information sharing approach, MSR posts the written TA reports on its Web site for all participants to use.

Most economic analysis is subcontracted by NREL to Segue Consulting, the principal of which developed an analytical tool that captures the value (versus cost) of solar technology, known as the ASSET Databank.

2.2 Information Sharing

With support from IREC, MSR provided opportunities for information sharing by: (1) hosting at least one peer exchange (per DOE region) among Partners, selected MSR Team members, and guest experts, as requested by the Partners; (2) arranging conference call seminars on subjects of interest to MSR Partners; (3) hosting an annual meeting, held in conjunction with the ASES Conference; and (4) managing a dynamic Web site that posts valuable information for use by the Partnerships (postings include TA reports, analytical briefs, and [with permission] papers on topics of interest to MSR Partners and affiliates); and (5) preparing the MSR Metrics report to examine inputs, outputs, and outcomes from 1997–2003/4.

Web site maintenance, meetings and conference call seminars’ development, and metrics are subcontracted to IREC, an organization comprising the renewable energy program managers in State Energy Offices.

2.3 Providing Feedback to the R&D Efforts

MSR has made, and continues to make, concerted efforts to link with researchers at SNL and NREL to provide customer-level feedback on market drivers, issues, and real-world system performance. During FY 2005, MSR provided data that was collected as part of the MSR metrics work to FSEC staff to help them identify the best states and utilities to partner with to collect high-quality performance data. The data allowed FSEC to build on existing information to more easily identify those programs that are already monitoring system performance.

Task Title	FY 2005 Budget ($K)
State and Local Partnership Grants	1325
Technical Assistance through NREL	250
Performance Coordination with SNL	70
Communication and Outreach Support through IREC	360

3. Results and Accomplishments

During FY 2005, the MSR network continued to grow. Five new Partnerships joined the effort, bringing the total to 94. In addition, a total of 886 businesses, electricity providers, organizations, and agencies make up the Partnerships. Also in FY 2005, the six DOE regional offices awarded 35 grants, worth more than $1.325 million. Each grant was between $10–$50K, with an average cost share well over 20%.

Below are a few examples of the varied efforts Partnerships have undertaken in the past year, based on their own unique set of needs and circumstances.

- Montana and Chicago are using PV for energy-emergency planning purposes. Montana is placing 2-kW PV systems on fire stations for uninterruptible power. Chicago will host a meeting of 250 regional mayors regarding the role of solar energy in emergency planning and operations.
- Delaware has partnered with the state's poultry industry to incorporate solar thermal energy in its operations.
- San Diego partnered with Kyocera Solar to give homeowners affected by recent wildfires larger financial incentives for PV than otherwise are available.
- The primary focus of the Brockton (MA) Partnership is its proposed 500-kW solar "Brightfield," proposed for creation on a brownfields site. Iowa also is working on converting a brownfield to a brightfield.
- Arizona and Nevada are collaborating to explore the potential of solar thermal energy to meet some of their states' substantial air-conditioning needs.
- New York State Energy Research and Development Authority (NYSERDA) reports that it is making industry capacity-building its number one priority.
- Maine is reaching out to the faith community.
- New Hampshire partners with the Low-Income Weatherization Program to provide solar water heating for program-eligible residences and to conduct training for installers.
- Maryland leverages the resources of BP Solar, which recently expanded its manufacturing plant in Frederick and donated more than $100,000 of PV modules to local schools.
- Efforts in San Diego and Marin County (CA) have an important geographical information system (GIS) element. The City of San Diego GIS Department identified 15,157 buildings with more than 194 million square feet of roof space that are good candidates for solar energy systems. Marin County uses GIS tools to identify commercial roofs with promising potential for rooftop PV. It parlays the information into a targeted consumer awareness program, extending site assessments and training to those who respond to a direct-mail offer.

Other significant outputs include:

- Technical Assistance: In FY 2005, Segue responded to more than 900 e-mail inquiries from Partnerships. Assistance, which ranges from analysis of hardware problems to analysis of the benefits provided by specific technologies, is typically provided directly to the Partnerships. The results of any assistance and analysis are typically reported back to the research community.
- Regional Peer-to-Peer Workshops: Since 2002, MSR has conducted 26 peer-to-peer workshops (at least one per year, per region) attended by more than 650 people. Seventy-nine percent of the MSR Partners have participated in at least one workshop. Workshops provided an information-exchange opportunity among Partnerships, offered skills

training, and included briefings on important issues.
- Telephone Seminars: From 2003–2005, ten seminars were held with a total of 910 people calling in. The seminars are intensive 1- to 1-1/2-hour interactive seminars on a single subject. They inform Partners on model programs that Partners can use to positively affect the widespread adoption of solar energy.
- Annual Meeting: The FY 2005 Annual Meeting was held in Portland, Oregon, in conjunction with the ASES Conference. More than 100 participants attended the one-day meeting, which focused on relevant activities/actions taking place nationally or regionally. In addition, DOE took the opportunity to recognize outstanding Partnerships for their successes.

Milestones for Million Solar Roofs in FY 2005:
- A paper titled "Urban Scale Solar" was drafted in November 2004 and revised later that year (completed 11/30/04).
- A new program—Solar Powers America—was introduced to MSR Partners at the Annual Meeting held October 8, 2005.
- Awarded $300K/yr, multiyear grant (depending on funding) for outreach and communication by competitive process (completed 8/05).
- Awarded $1.12 million in competitively selected State and Local Partnership grants to support local MSR efforts (completed 9/30/05).
- Provided technical assistance (i.e., engineering, economic) to Partnerships and their members and made information widely available to other Partners and members through dissemination mechanisms (completed throughout the year).
- Provided FSEC with data collected as part of MSR metrics work to identify the best states and utilities to partner with to collect high-quality performance data. The data allowed them to build on existing information to more easily identify those programs that are already monitoring system performance (completed 9/30/05).

4. Planned FY 2006 Activities

- Begin transition from Million Solar Roofs to Solar Powers America (10/05).
- Launch the Solar Powers America Web site (03/06).
- Complete transition (09/06).

5. Major FY 2005 Publications

Larry Sherwood, Interstate Renewable Energy Council, "Million Solar Roofs Initiative: Metrics," September 2005

National Renewable Energy Laboratory et al., "Million Solar Roofs Initiative: Building Capacity in American Markets," October 2005.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
Segue Consulting Christy Herig	Redington Shores, FL cherig@tampabay.rr.com	Economic, regulatory, financial and value analysis (individualized response to TA requests; generic analysis and document production)	110	0
Interstate Renewable Energy Council Jane Weissman	Latham, NY jane@irecusa.org	Communication and outreach activities aimed at the 89 MSR Partnerships and their participating members	260	0
Appalachia Science for the Public Interest Andy McDonald	Mt. Vernon, KY solar@kyisolar.org	State and Local Partnership Grant	49.2	0
Georgia's Southface Energy Institute Laura Uhde	Atlanta, GA laura@southface.org	State and Local Partnership Grant	49	0

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
North Carolina State University Solar Center Valerie Everette	Raleigh, NC Valerie_everette@ncsu.edu	State and Local Partnership Grant	50	0
South Carolina Energy Office Janet Lockhark	Columbia, SC jlockhart@gs.sc.gov	State and Local Partnership Grant	40	0
Foundation for Environmental Education Glen Kizer	Columbus, OH gkizer@columbus.rr.com	State and Local Partnership Grant	30	200
Minnesota Department of Commerce Mike Taylor	St. Paul, MN mike.taylor@state.mn.us	State and Local Partnership Grant	30	28
Wisconsin Energy Conservation Corp. Don Wichert	Madison, WI donw@weccusa.org	State and Local Partnership Grant	25.5	26
Illinois Solar Energy Association Mark Burger	Chicago, IL Mark.burger@illinoissolar.org	State and Local Partnership Grant	15	10
City University of New York Ron Spalter	New York, NY Ron.Spalter@mail.cuny.edu	State and Local Partnership Grant	30	0
The Vineyard Energy Project, Inc. Kate Warner	West Tisbury, MA Kate@vineyard.net	State and Local Partnership Grant	50	0
Long Island Solar Roofs Initiative Gordian Raacke	Long Island, NY reli@optonline.net	State and Local Partnership Grant	50	0
Vermont Energy Investment Center David Hill	Burlington, VT dhill@veic.org	State and Local Partnership Grant	40	0
Rhode Island State Energy Office Julie Capabianco	Providence, RI JulieC@gw.doa.state.ri.us	State and Local Partnership Grant	35	0
Cape and Island Self Reliance Megan Amsler	Cape Cod, MA meganams@reliance.org	State and Local Partnership Grant	15	0
Maine State Energy Program, Maine Public Utilities Commission Shirley Bartlett	Augusta, ME Shirley.Bartlett@maine.gov	State and Local Partnership Grant	15	0
Solar Boston Larry Chretien	Boston, MA larry@massenergy.com	State and Local Partnership Grant	15	0
Boulder Energy Conservation Center Amy Ellsworth	Boulder, CO aellsworth@conservationcenter.org	State and Local Partnership Grant	50	0
Sunsense Scott Ely	Carbondale, CO sunsense@sopris.net	State and Local Partnership Grant	50	0
Solar Austin Anne Marie Johnson	Austin, TX annejohnsonpc@yahoo.com	State and Local Partnership Grant	45	0
Salt Lake City Corp. Lisa Romney	Salt Lake City, UT lisa.romney@slcgov.com	State and Local Partnership Grant	40	0
Colorado Renewable Energy Patrick Keegan	Golden, CO pkeegan@energyscience.org	State and Local Partnership Grant	40	0
The New Center Tom Potter	Denver, CO tpotter@allamericanenergy.com	State and Local Partnership Grant	30	0

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
San Luis Valley Resource James Mietz	Alamosa, CO james.mietz@co.usda.gov	State and Local Partnership Grant	32	0
Greater Tucson Coalition for Solar Valerie Rauluk	Tucson, AZ vajra@vecat-inc.com	State and Local Partnership Grant	50	132
Marin County Community Development Agency Gwen Johnson	Marin, CA gjohnson@co.marin.ca.us	State and Local Partnership Grant	50	37
Oregon Office of Energy Christopher Dymond	Salem, OR christopher.s.dymond@state.or.us	State and Local Partnership Grant	50	28
San Diego Regional Energy Office Ashley Watkins	San Diego, CA awa@sdenergy.org	State and Local Partnership Grant	50	50
Washington State University, Energy Program Mike Nelson	Olympia, WA miknel@seanet.com	State and Local Partnership Grant	50	25
Great Valley Center, Inc. Manuel Alvarado	Modesto, CA manuel@greatvalleycenter.org	State and Local Partnership Grant	50	61
Community Environmental Council Tamlyn Hunt	Santa Barbara, CA thunt@cecmail.org	State and Local Partnership Grant	49	43
Renewable Energy Leadership Group Phil Key	Phoenix, AZ KeyTAIC@aol.com	State and Local Partnership Grant	30	30
Delaware Energy Office Charlie Smisson	Dover, DE Charlie.Smisson@state.de.us	State and Local Partnership Grant	34	11
Commission on Economic Opportunity Eugene Brady	Wilkes-Barre, PA ceo@sunlink.net	State and Local Partnership Grant	33	8
Greenfaith Fletcher Harper	Trenton, NY revfharper@greenfaith.org	State and Local Partnership Grant	31	31
Energy Coordinating Agency David McVeigh Schultz	Philadelphia, PA dennisw@ecasavesenergy.org	State and Local Partnership Grant	30	50

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 2005 Budgets:	$711K (NREL), $357K (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 Multi-Year Program Planning process.
- Expanded partnered activities on commercial and utility-scale systems to further refine determinations of life-cycle cost, system reliability, and system availability.
- Developed working version of the SolarDS model with an initial set of scenarios.
- Expanded work on PV value analysis to include both identifying best practices and information sharing, aimed at helping to inform state-level policymaking.
- Provided technical and analytical support to the Western Governors' Association (WGA) 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 program planning
- Benchmark activities
- Work on technology-policy tradeoff studies and value analysis
- Provide technical and analytical support to the WGA Solar Energy Task Force.

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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.

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 2005.

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 EIA'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 2005 a key emphasis of the analysis team has been to identify best practices for estimating both the benefits and cost of distributed PV technology and to document the methodologies and data sources used to carry out value analysis of distributed PV technology. This area of work is aimed at informing state-level policymaking.

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 2005 Budget ($K)
PV Advisor Modeling	275
PV Market, Value, and Policy Analysis	436
System Reliability and Cost Analysis	357

3. Results and Accomplishments

The primary objective of the modeling and benchmarking activities during FY 2005 has been 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 using the Solar Advisor Model, and to apply projections of technology improvements to determine future-year costs and overall targets. The results of this process have served as the foundation for the *Solar Program's Multi-Year Program Plan*.

Within the PV Subprogram, the program management team has identified several Technology Improvement Opportunities (TIOs) within a PV system. These are: modules; inverters and balance of systems (BOS); systems engineering and integration; and deployment facilitation. By assessing the impacts of technology improvements in each TIO area and then modeling the system performance and cost in the Solar Advisor Model, trade-off studies in overall LCOE were conducted. The technology improvements were determined using a combination of expert consensus and reference to published projections.

Figure 1 shows the difference between installed cost, a commonly used metric, and LCOE for a residential PV system. Because the PV industry is increasingly focused on grid-tied applications, the more important measure of system value is the cost of energy delivered during the lifetime of the system, rather than its initial cost. As Fig. 1 shows, the non-module components are a larger part of LCOE than installed cost, highlighting the importance of system-level technology improvements.

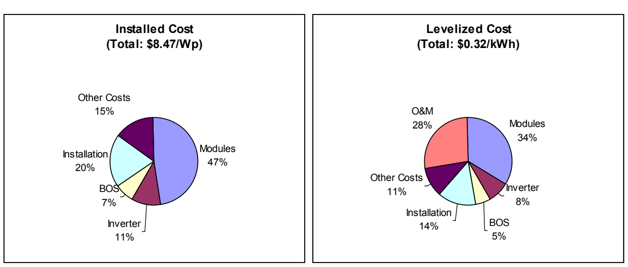

Fig. 1. Difference between installed and levelized cost of a residential PV system, using FY 2005 benchmark parameters.

Table 1 lists some key characteristics of the reference systems that were identified for each market sector. All of these "baseline" system configurations use crystalline silicon modules with an efficiency of 13.5% and are located in Phoenix, Arizona. These characteristics and numbers were selected from the range of benchmark data to represent typical "best practices" installations—meaning these are neither the best nor the worst values available.

Table 1. Characteristics of PV Systems in Reference Applications

	Res.	Comm.	Util.	Util. CPV[a]	Off-grid
Sys Power (kW)	4	150	10 MW	10 MW	1.2
Module Power (W)	100	150	150	40 kW	100
Mounting	Roof retrofit	Roof top	Ground, 1-axis	2-axis	Sled
Tilt (°)	18	15	Horiz.	N/A	33
Inverter Power (kW)	4	150	150	150	2.4
Installed Price ($/Wdc)	8.47	6.29	5.55	5.95	12.71
O&M[b] (%)	0.5	0.45	0.15	0.85	3.6

[a]Concentrating Photovoltaics
[b]O&M is listed as percent of initial capital cost per annum.

Figure 2 shows the results of the TIO systems analysis for residential PV systems. Similar analyses have been performed for systems in the other reference applications, as well.

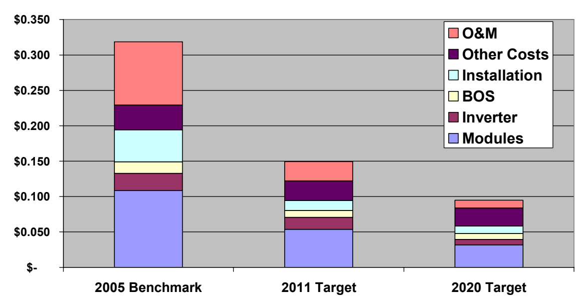

Fig. 2. Residential PV reference system total energy price ($/kWh) for current and future years.

"Other costs" include design and other engineering, site preparation, permitting and interconnection, inspection, and related costs. This part of the bar graph does not change much over time because this analysis assumes increased investment in systems engineering and integration, whereas the rest of the "other" category is reduced through resultant innovations. Thus, while "other" does not decrease much as a part of the cost, it leads to decreases across the rest of the system.

The main improvements that drive reductions in LCOE for these systems are:

- Improvements in PV module cost and efficiency
- Reductions in installation costs through improved systems engineering
- Improved inverter reliability and performance and associated reductions in O&M costs.

Table 2 shows the current benchmarks and out-year projections of PV systems in all market sectors studied.

Table 2. Current Benchmarks and Future Projections of PV System LCOE (cents/kWh)

	2005	2011	2020
Residential	32	15	10
Commercial	18	10	6
Utility Flat Plate	16-22	10-15	7-10
Utility CPV	15-28	10-15	7-11
Off-grid	79	46	31

Each of the systems shown in Table 2 includes some form of financing. For the utility cases, the numbers indicate the range between cash financing at the low end and Independent Power Producer financing, which includes an internalized profit and is thus more expensive. The *Multi-Year Program Plan* discusses these financing scenarios and associated assumptions in detail.

4. Planned FY 2006 Activities

- Perform PV component- and system-level studies, using the Solar Advisor Model, necessary to conduct a PV Subprogram portfolio analysis.
- Complete detailed PV BOS cost model for the Solar Advisor Model.
- Gather detailed data on installed and operational costs of PV systems, including non-hardware aspects.
- Complete benchmark and analysis report on residential PV systems
- Complete functional version of Web-based distributed PV cost-benefits clearinghouse and calculator.
- Complete update to solar 2050 scenarios, using NEMS, MARKAL and/or SolarDS.
- Provide technical and analytical support to the WGA Solar Energy Task Force.

5. Major FY 2005 Publications

K. Comer et al. "Characteristics and Feedback from Residential PV Early Adopters," *ASES Solar 2005 Conference,* Orlando, FL, August 6-12, 2005.

T. Hoff, R. Perez, and R. Margolis, "Maximizing the Value of Customer-Sited PV Systems Using Storage and Controls," *ASES Solar 2005 Conference,* Orlando, FL, August 6-12, 2005.

J. Levene et al. "Analysis of Hydrogen Production from Renewable Electricity Sources," *ASES Solar 2005 Conference,* Orlando, FL, August 6-12, 2005.

L. Moore et al. "Photovoltaic Power Plant Experience at Arizona Public Service: A 5-Year Assessment," *Progress in Photovoltaics* (in press).

R. Perez et al. "Solution to the Summer Blackouts? How Dispersed Solar Power-Generating Systems Can Help Prevent the Next Major Outage," *Solar Today*, Vol. 19, No. 4, pp. 32-35, July/August 2005.

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. September, 2005 (Draft).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share
SUNY Albany Richard Perez	Albany, NY perez@asrc.cestm.albany.edu	Value Analysis of PV Technologies	70	10
Clean Power Research Thomas Hoff	Napa, CA tomhoff@clean-power.com	Developing a Framework to Evaluate the Benefits and Costs of Distributed PV	50	0
SENTECH, Inc. Jonathan Hurwitch	Bethesda, MD jwitch@sentech.org	Case Study of a PV-Covered Parking Installation	5	0
Massachusetts Institute of Technology David Marks	Cambridge, MA dhmarks@mit.edu	Regional Assessment of the Impact of Grid-Connected Photovoltaic Power Systems on Wholesale Power Prices	25	0
MRG & Associates Marshall Goldberg	Nevada City, CA mrgassociates@earthlink.net	Development of Jobs and Economic Development Impact Models	12	0

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 2005 Budget:	$2,000K (DOE/GO)

Objectives

- Team with the national laboratories to meet Solar Program Annual Operating Plan objectives and milestones.
- Conduct R&D activities to develop resources, standards, and information necessary to address cost, performance, reliability, and market barriers as stated in the *DOE Solar Program Multi-Year Program Plan.*
- Structure work and set priorities to reflect a commitment to applying the Systems-Driven Approach.
- 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.

Accomplishments

- Four inverters (Fronius, PV Powered, SMA, and Xantrex) have been placed in service for long-term performance testing at each Regional Experiment Station (RES).
- Transitioned RES contract administration from the DOE Albuquerque Field Office to the DOE Golden Field Office (DOE/GO) as requested by DOE headquarters.
- Southeast Regional Experiment Station (SERES): In late March 2005, DOE/GO requested SERES assistance for the Mark Twain Home and Museum in Hartford, Connecticut, to install a PV system funded by a Congressionally directed project. As a result of SERES consultation with the recipient regarding system requirements, the museum's board of directors decided to cancel this project and requested their Congressional delegation accept forfeiture of the award.
- Southwest Regional Experiment Station (SWRES) and SERES: Completed 2005 benchmarking of residential, utility-scale, and large commercial PV systems for inclusion in the *2007–2011 DOE Solar Program Multi-Year Program Plan* (MYPP).
- SWRES: As requested by DOE/GO, provided technical and economic modeling and recommendations for town of Yucca Valley, California, to assist in optimizing a $500K Congressionally directed project for a PV system.
- SERES and SWRES: Worked with eight countries through the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) Task 2 to develop a comprehensive PV database containing performance and economic data for selected countries, including the United States, Germany, and Japan.
- SWRES: Developed, edited, and revised 24 pages of draft proposal for the 2008 *National Electric Code (NEC)* covering PV and issues of cabling, grounding, and interconnection.
- SWRES: Completed the Sacramento Utility District (SMUD) Program Index software used monthly to evaluate the performance of more than 1,000 PV systems in the Sacramento area.
- SWRES and SERES: Provided expertise to the $35 million California Energy Commission PIER Commonwealth Program as working members of the Technical Advisory Panel.
- SERES: Florida Solar Energy Center (FSEC) staff conducted PV installer workshops in New Jersey on behalf of Villanova University, at Cornell University in New York on behalf of the

National Joint Apprenticeship and Training Committee (NJATC), at FSEC, and at the NJATC/International Brotherhood of Electrical Workers National Training Institute in Knoxville, Tennessee.

Future Directions

- Support DOE/GO administration of the RES cooperative agreements by adjusting technical activities to meet R&D emphases, assuring that milestones align with program priorities and that deliverables are met on time.
- Support benchmarking activities to assist with the overall Solar Program goals.
- Resume the PV Design Assistance Center function that was a hallmark of the SNL/RES programs of the 1990s.
- Develop advanced PV designs for integrated manufacturing and deployment.
- Conduct a continuous review of activities to improve alignment with the Systems-Driven Approach.
- Prepare documentation necessary to renew the DOE/RES cooperative agreements.

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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) International Solar Technologies
5) Domestic PV Applications
6) System Evaluation and Optimization
7) PV System Analysis.

Collaborations with SNL, NREL, 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 the *U.S. PV Industry Roadmap*, 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 Testing and Analysis of Fielded PV Systems

Data gathered from fielded systems provide a powerful opportunity to perform analysis of system costs, performance, and reliability. Data also provide a basis for addressing infrastructure issues inherent to PV applications in different markets. This activity examines systems in residential, commercial, utility, and off-grid applications to provide benchmarking information for validation of codes and in pursuit of solving issues that prevent widespread adoption. Information is provided to industry-wide counterparts and is applied to analysis conducted by the DOE Solar Program participants. This activity recognizes the positive role the government can play by adopting PV and consequently provides agencies (e.g., National Park Service, U.S. Department of Agriculture Rural Utilities Service, U.S. Department of Defense, Bureau of Land Management) and various states the technical assistance needed to successfully demonstrate the value of PV.

2.2 Infrastructure Development

This activity consists of multiple 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 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.

2.2 Long-Term Component Testing

The RES 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 200 code officials in one-day workshops in New York, California, Colorado, and Wisconsin.
- Taught a North American Board of Certified Energy Practitioners (NABCEP) Preparatory Course for more than 100 people from throughout the United States.
- Performed complete assessment of utility-scale PV power plants in Arizona and California for performance, reliability, and cost benchmarks.
- John Wiles (SWRES) served as Secretary of the PV Industry Forum; drafted 24 pages of recommended changes to the 2008 *National Electrical Code.*
- SERES: Terminated outdoor-exposure and performance tests of Global Solar Energy's P3 55 Power Packs (CIGS) after 120 days. The ~20% degradation in power output prevented FSEC from assigning a power rating to the modules.
- SWRES: Participated in development of the Solar Program's International Strategic Plan; conducted survey of U.S. vendors.
- SWRES: Provided design reviews to dozens of major PV system developers (e.g., PowerLight, RWE Schott Solar) and purchasers (e.g., utilities, Million Solar Roofs communities) for code compliance and proper design.
- SWRES: Installed and placed under test 2.5-kW CIS thin-film array for long-term exposure and evaluation.
- SWRES: Provided system acceptance testing for a 35-kW PV system for the City of Tucson.
- SWRES and SERES: Provided testing and analysis of c-Si and thin-film modules in support of the Module Long-Term Exposure Program.
- SWRES: Provided a system rating and current field evaluation of the SMUD PV-2, 1-MW array with recommendations for remediation of parts of the plant.

- SWRES: Performed thin-film performance testing on U.S.-manufactured CdTe modules in service in hot/humid climate of Morelos, Mexico.
- SERES: A meeting of the IEA Photovoltaic Power Systems Program Task 2 was held at FSEC with representatives from DOE, SWRES, SERES, and several of the participating countries.
- SERES: In January, FSEC welcomed its new director, Dr. James Fenton, formerly with the University of Connecticut.
- SERES: About 100 people participated in a PV dealer's conference sponsored by SunWize Technologies and hosted by FSEC.
- SERES: Performance of a monitored system in Homestead, Florida, using a Kyocera KC120 PV array and two SMA 2500U inverters, underwent significant performance degradation of >25% during a 4-month period, ultimately causing inverters to drop off-line for extended periods. An investigation found array voltage problems, and the manufacturer was involved in corrective actions. Other instances of the same problem have been identified.
- SERES: FSEC staff conducted acceptance testing on a number of PV and solar thermal installations in the U.S. Virgin Islands under a separate contract to the Virgin Islands Energy Office.
- SERES: SERES and SNL staff participated in the National Rural Electric Cooperative Association's New and Emerging Technologies Conference in Tampa, Florida.
- SERES: FSEC's PV installer and code-official training programs were recognized by the Florida Department of Business and Professional Regulation for continuing education units required for contractors and code officials.
- SERES: Major construction activities were completed on a new facility at FSEC for PV inverter and systems testing, and PV and distributed-generation applications training.
- SERES: FSEC staff conducted two PV installer workshops: May 2–6 at FSEC and May 23–27 at the Portland Electrical JATC, Lewiston, Maine.
- SERES: Jim Dunlop agreed to serve as technical committee chair for the North American Board of Certified Energy Practitioners, having previously served in this capacity through September 2003. The position became vacant as a result of the death of Mark Fitzgerald.
- SERES: Jim Dunlop assisted a Florida contractor in inspecting a residential PV system suspected of underperforming. Investigations showed that the Photowatt modules, rated at 165 watts, were 20 watts lower (which was indicated by a small notation on the back surface of the modules, not on the nameplate). This single relatively trivial example demonstrates the need for module-performance rating standards to protect consumers, especially for residential markets.
- SERES: GE Solar contacted FSEC about field-testing its new interactive inverter, which is still under development and has undergone significant testing at SNL. Funding the cost of this testing is an unresolved issue.
- SERES: FSEC hosted a meeting at the American Solar Energy Society (ASES)/ International Solar Energy Society (ISES) Conference to address PV product certification in the United States. Twenty-four individuals attended this meeting, including representatives from laboratories, states, and other groups involved in developing standards and evaluating and certifying PV systems and equipment
- SWRES: Performed PV system field tests of on-grid and off-grid PV systems: Tucson, Arizona; Albuquerque, Las Cruces, and Farmington New Mexico; Sacramento, California; Yellowstone National Park, Wyoming; Phoenix, Arizona; Amarillo, Texas; and Morelos, Mexico.
- SERES: American Association of Laboratory Accreditation (A2LA) staff completed a surveillance audit of FSEC PV and solar thermal testing laboratories in accordance with ISO 17025.
- SWRES: Participated in the UL 1741 (inverters) and 1703 (modules) Standards Technical Panels; participated in the NABCEP Exam Committee.
- SERES: FSEC staff met with Sharp Solar staff regarding a planned PV project involving 500 homes in Naples, Florida, with Centex homes.
- SERES: FSEC staff met with Mark Dougherty, Solar Program manager for Long Island Power Authority (LIPA). The discussion involved areas of joint interest to LIPA, FSEC, and SERES, including an upcoming LIPA solicitation for PV system evaluation and monitoring services.

4. Planned FY 2006 Activities

RES projects will focus on the following tasks:

- Benchmarking
- PV systems analysis and engineering
- Codes and standards development
- Restoring and staffing the Solar Program PV Design Assistance Center
- R&D of advanced system concepts.

Expected results for FY 2006 include the following:

- Comprehensive update of 2006 benchmarking, including evaluation of first-year Technical Improvement Opportunities for 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.
- Introduction of the PV Design Assistance Center to the U.S. PV community. The RES will work together 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.
- Develop novel component, control, and communications that support new manufactured system concepts.

5. Major FY 2005 Publications

A. Rosenthal, *Benchmarking Plan for Utility and Large Commercial PV Systems*, Submitted to SNL, December 2004.

A. Rosenthal, *Benchmarking Results for Utility-Scale Flat Plate PV Systems*, Submitted to SNL, February 2005.

A. Rosenthal, *Benchmarking the California Energy Commission Self-Generation Incentive Program*, Submitted to SNL, May 2005.

J. Wiles, *Proposed Submissions to the 2008 National Electrical Code*, Submitted to SNL and the PV Industry Forum, August 2005.

A. Rosenthal and G. Cisneros, *Recommendations for Yucca Valley PV Parking Structures: Performance and Economic Results*, Submitted to DOE/GO, May 2005.

R. Foster, *Field Test Results for First Solar PV Modules in Morelos, MX*, Submitted to SNL, June 2005.

B. Young, "Basics of Solar Energy for Disasters," 2005 ASME/ISEC, Orlando, FL, Aug. 6, 2005.

B. Young, "Renewable Energy and Disaster Resistant Buildings and Disasters: PV for Special Needs," International Disaster Assistance Group Conference, 2005.

K. Lynn, "Procedures for Photovoltaic System Design and Approval," *31st IEEE PV Specialists Conference, Orlando, FL, Jan. 3–7, 2005.*

G. Atmaram, "Photovoltaic Module Performance Certification," *31st IEEE PV Specialists Conference, Orlando, FL, Jan. 3–7, 2005.*

ASES/ISES 2005 Solar World Congress, Orlando, FL, Aug. 6–12, 2005:

G. Nelson, A. Rosenthal, "One Megawatt Photovoltaic Plant Completes Twenty One Years of Successful Operation."

R. Foster, W. Amos, S. Eby, "Ten Years of Solar Distillation Applications."

R. Foster, A. Cota, "Two Decades of PV Lessons Learned in Latin America."

J. Wiles, "Are PV Systems Getting Better?"

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
Florida Solar Energy Center Jim Dunlop	Cocoa, FL Dunlop@fsec.ucf.edu	PV System Research	1,000
Southwest Technology Development Institute Andrew Rosenthal	Las Cruces, NM arosenth@nmsu.edu	PV System Research	1,000

Solar Thermal R&D Subprogram Overview

Frank W. Wilkins, Team Leader, Solar Thermal R&D

The Solar Thermal Subprogram comprises two key activities: Concentrating Solar Power (CSP) and Solar Heating and Lighting (SH&L). CSP technologies use mirrors to concentrate the sun's energy up to 10,000 times sunlight to power conventional turbines, heat engines, or other converters to generate electricity. Energy from CSP systems is high-value renewable power, because energy storage and hybrid designs allow it to be provided when most needed. This is particularly important to utilities that need to increase the amount of power available to them during periods of peak demand. The SH&L research activity develops solar technologies that provide hot water for residential and commercial buildings as well as hybrid solar lighting for commercial buildings. Reducing the cost of these two technologies is important to the goal of a reasonably priced zero energy building. R&D sponsored by the Solar Thermal Subprogram is done in collaboration with industry and university partners.

Goals and Objectives

Concentrating Solar Power

CSP systems currently offer the least-expensive source of solar electricity (12¢–14¢/kWh) with systems ranging in size from kilowatt-scale distributed systems to multi-megawatt power plants. A recent study by the Western Governors' Association Solar Task Force projected that large CSP systems will be able to produce power at about 5.5¢/kWh with continued R&D and the deployment of 4,000 MW. The 2012 goal is to reduce the cost of energy from CSP technology to 8¢–10¢/kWh. This will be done through R&D carried out by the national laboratories and industry combined with the establishment of CSP plants deployed by the states and their industry partners.

Solar Heating and Lighting

SH&L research emphasizes the development of low-cost, polymer-based solar water heaters, which have the potential to cut the cost of today's solar water heating (8¢/kWh) to 4.5¢/kWh. The objective for FY 2005 was to install and evaluate prototype units at locations throughout the nonfreezing regions of the country. Both industrial partners, however, decided to make significant changes to their designs. This resulted in the year's efforts being focused on design modifications and evaluation. One partner though submitted a prototype system to the Solar Rating and Certification Corp., and it is likely to be certified in early FY 2006. Budget issues precluded work on systems applicable to freezing climates. The objective of hybrid solar lighting development was to improve the design of the system to the point where prototypes could be installed and evaluated at commercial locations during FY 2006.

Results and Accomplishments

Concentrating Solar Power

During FY 2005, Stirling Energy Systems (SES) built, entirely with its own funding, a six-dish mini-power plant at the National Solar Thermal Test Facility at Sandia National Laboratories (SNL). SES also moved a sizable portion of its technical staff to Albuquerque to make the best use of the facilities and engineers at SNL. President Bush toured the dish power plant following his signing of the 2005 Energy Bill at SNL. Operation of the dishes provided valuable data, enabling improvement in engine reliability and system operation. This effort was made more important by SES's signing power purchase agreements with Southern California Edison and San Diego Gas & Electric, which could lead to projects totaling 800 to 1,750 MW.

Solargenix Energy built a 1-MW trough plant in Arizona for Arizona Public Service. Its operation is expected to begin in early FY 2006. This is the first trough plant to be built anywhere in the world in nearly 15 years. Solargenix also plans on beginning construction of a 64-MW project in Nevada in early FY 2006. Evaluation of a new trough concentrator was completed and may be used in the 64-MW project.

The Western Governors' Association established a Solar Task Force to determine the potential of solar energy in the West and identify the incentives required to establish projects. The National Renewable Energy Laboratory provided much of the analysis required by the WGA. The Task Force recommended that CSP be allotted 4 GW of the WGA's *30 GW Clean and Diversified Energy Initiative*. The Task Force concluded that continued R&D improvements, along with the 4 GW of deployment, would result in a 5.5¢/kWh cost of CSP power.

Solar Heating and Lighting
Both industrial partners working on development of a low-cost solar water heater made significant changes in their design during the year. The new designs were meant to reduce cost below that of the Program's goal, albeit at reduced efficiency. The primary effort was in design and evaluation of the new designs, not evaluation of demonstration systems as originally planned. This required additional resources from a lower-than-planned-for budget. As a consequence, a planned solicitation for systems applicable to freezing climates has been postponed.

Oak Ridge National Laboratory (ORNL) made several design improvements to the hybrid solar lighting (HSL) system and incorporated them into a new solar collector/tracker system called *HSL 3000*. One of these units was installed at the American Museum of Science and Energy in Oak Ridge and another was scheduled for installation at the Sacramento Municipal Utility District's Customer Service Center in early FY 2006. A contract was initiated that is designed to estimate the market potential of HSL. This study is expected to be completed in FY 2006.

The Solar Program sponsored a study by the National Association of Home Builders Research Center to estimate the long-term energy impact that could result from the widespread adoption of the net zero energy homes (ZEH). This study, completed during FY 2005, estimated that ZEH could result in energy savings of 2 to 3 quads by 2050 and lead to a decrease in the energy consumption of the entire U.S. housing stock.

New Directions

The CSP Subprogram has developed a strategy that emphasizes deployment of the technology. It has established partnerships with the Western Governors' Association and several states that have expressed an interest in having concentrating solar power plants built in their state. The CSP projects now being developed, ranging in size from 64 to 900 MW, show the potential for CSP to provide energy in large blocks. Activities have been established to support the trough and dish/engine industry as it readies for projects. This burst of activity after years of inactivity provides encouragement that CSP technology will soon become competitive in the intermediate power market.

Analysis shows the polymer water heaters being evaluated will meet the 4.5¢/kWh goal. The next steps are to complete certification by the Solar Rating and Certification Corp. of the first team's system and initiate the testing and certification of the second team's system. Evaluation of the hybrid solar lighting system has entered a new phase. The new HSL 3000 is providing data from its location on the American Museum of Science and Energy. Another will soon be providing data from Sacramento. Field tests such as these will provide valuable data that will lead to improvements in the efficiency and reliability of the system.

Concentrating Solar Power

Concentrating solar power (CSP) systems use the heat generated by concentrating and absorbing the sun's energy to drive a conventional turbine or heat engine/generator and produce electric power. Three types of CSP systems—power tower, trough, and dish—are all capable of producing power using the sun's energy.

Trough systems, the most commercially mature of the three systems, use linear parabolic concentrators to focus sunlight along the focal lines of the collectors. In a power tower system, a field of two-axis tracking mirrors, called heliostats, reflects the solar energy onto a receiver that is mounted on top of a centrally located tower. Dish/engine systems comprise a parabolic dish concentrator, a thermal receiver, and a heat engine/generator located at the focus of the dish to generate power. A variation of the dish/engine system, concentrating photovoltaics or CPV, would replace the thermal receiver and heat engine with an array of high-efficiency photovoltaic cells.

With the advent of renewable friendly policies within the United States and abroad there is a renewed interest in CSP technologies based on their potential for low cost and ease of large-scale implementation. The Western Governors' Association (WGA) established a Solar Task Force to determine the potential of solar energy in the West and identify the incentives required to establish projects. The National Renewable Energy Laboratory (NREL) provided much of the analysis required by the WGA. In the U.S. southwestern states, CSP projects are under way in Nevada and Arizona; New Mexico and California are investigating the possibilities of developing CSP plants. R&D priorities of the CSP Subprogram are determined, in part, by projects being developed under the state programs.

Among the accomplishments of the DOE Solar Program's CSP activity in FY 2005 are:

Dish/Engine System R&D

- Installed and started operation of a six-dish, 150-kW mini power plant at Sandia National Laboratories' National Solar Thermal Test Facility.

Parabolic Trough R&D

- Construction of the first commercial parabolic trough plant in nearly 15 years neared completion at the end of FY 2005. The plant is being developed for Arizona Public Service by Solargenix Energy. It is a 1-MWe solar power plant using an organic Rankine power cycle provided by Ormat Technologies. The plant, whose start-up is expected in early FY 2006, uses parabolic trough collector technology developed by Solargenix under a cost-shared R&D contract with DOE/NREL.

Advanced Concepts

- Continued to perform durability testing of optical materials and published results of durability testing of several mirror types.
- Provided significant industry support about reflectors to the concentrating photovoltaic industry.

CSP Systems Analysis

- Developed detailed maps and performed analysis of CSP in the Southwestern WGA region in support of the *30 GW Clean Energy Initiative*.
- Developed recommendations on the most promising locations for CSP plants in the WGA region based on resources, transmission constraints, and access to major load centers.

Dish/Engine System R&D

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contact: Charles Andraka, 505-844-8573, ceandra@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2005 Budget: $950K

Objectives

- Perform R&D on dish/engine system components and systems.
- Improve the reliability and reduce the cost of dish/engine components and systems.
- Support industry in the commercialization of the technology.
- Test, evaluate, and improve the performance of dish/engine components and systems.

Accomplishments

- Installed and started operation of a six-dish, 150-kW mini power plant at SNL's National Solar Thermal Test Facility.
- Identified and began addressing gas-management system valve issues.
- Began developing an operational database.

Future Directions

Primary activities in FY 2006 will support Stirling Energy Systems' efforts toward commercialization by:

- Continuing to evaluate the reliability of the six-dish mini power plant
- Identifying and resolving operational and reliability issues
- Defining initial, baseline system performance and reliability
- Supporting SES as it starts to deploy a 1-MW power plant.

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1. Introduction

Stirling Energy Systems (SES) is pursuing an aggressive deployment of 25-kW dish-Stirling systems for bulk power generation. SES hardware is based on the tried-and-true McDonnell Douglas Corporation (MDC) design, with refinements for reducing manufacturing costs. SES is working closely with an SNL engineering team to maximize the possibility of success.

This year, SES deployed five upgraded systems at SNL, completing the six-dish Model Power Plant (MPP). SNL engineers provided critical development support to resolve structural issues during assembly. SNL also developed a new alignment strategy to improve system performance and began work on solving known reliability issues. The success of the MPP has, in part, led to SES signing agreements with Southern California Edison for up to 850 MW of power and San Diego Gas and Electric for up to 900 MW of power. Operation and improvement of the MPP is critical in the design process for these deployments.

The DOE dish-Stirling program works closely with SES to improve system performance and reliability and to support deployment by industry in the near term, both explicit goals of the *DOE Solar Program Multi-Year Program Plan*, section 4.2.5.3. This year, our primary goal was to install, test, and begin to baseline the performance (reliability, availability, and efficiency) of six SES 25-kW dish-Stirling systems operating as a plant. The system is derived from the successful MDC system, but was redesigned to improve cost. SES's objective is to put this system into production within a few years, with a target market of bulk power production in the southwestern United States. This corporate goal drives the DOE goal of determining the baseline performance of the system, so that follow-on work can address performance improvement.

2. Technical Approach

SES plans to achieve cost reduction by rapidly moving to high production rates in support of bulk power production. This approach, when compared to smaller prototype installations spread out at many locations, has the advantage of lower cost through production automation early in the product design cycle and lower O&M cost through consolidation of O&M resources.

SES has co-located its engineering team at the SNL National Solar Thermal Test Facility, which provides direct access to technology transfer and expertise and allows the engineers daily hands-on access to the dish systems. This is critical to accelerating the development and deployment path and rapidly training new solar engineers.

Last year, SES and SNL installed and began operating the first SES-built dish system at SNL. This system is designated “serial 0.” This fiscal year, SES installed the remaining five systems, heavily utilizing its steel fabrication partner Schuff Steel in the erection process. This experience is critical to developing rapid-deployment tools for the large deployments. All of the dish system hardware is funded through SES investor financing, while SNL, through the DOE Concentrating Solar Power Subprogram, provides in-kind engineering support, technology transfer, training, and facilities.

3. Results and Accomplishments

Initial installation of the five new units was scheduled for completion in December. However, late in the installation process two structural issues arose. The elevation jackscrew failed on two units. Extensive gravity and wind-load modeling by SNL led to specification of a slightly larger diameter jackscrew. During dish assembly, a bolted joint on the boom failed. Extensive SNL analysis evaluated the design of every bolted joint in the new boom design and led to field rework to replace most of the structural bolts with welds. Subsequent detailed analysis by SES contractors has agreed with SNL’s initial analysis. The field-rework and drive upgrades were completed by May.

The power conversion units (PCUs) include engines under various stages of development, from fully Kockums-built PCUs to SES-built PCUs. The Kockums engines are fully refurbished by SES. SNL designed and prototyped a new engine package system that utilizes commercial-off-the-shelf (COTS) radiators, a robust cavity, and better access to the engine for maintenance. This package is the subject of another paper [1]. SNL developed a capability to operate the engines in a test cell at about half power, a critical function to ensure safe operation of the engine prior to solar testing. The facility uses a quartz lamp array salvaged from prior heat pipe receiver work. The engines were operated and controls calibrated in this facility.

To support rapid manufacturing with the existing mandrel choices, SNL performed CIRCE2 modeling of the flux on the receiver for a variety of facet focal length combinations. We determined a 2-focal-length arrangement, with two-thirds of the facets at a long focal length, provided the best blend of performance and manufacturing speed. SNL, with cooperation from NREL, performed flux mapping of one new dish to ensure that the key design changes did not add flexibility to the structure. Flux mapping was performed from the horizon to over 60 degrees elevation, and no substantial changes were noted in the flux pattern. This verifies the analytical work performed to redesign the main beam assembly, as well as the CIRCE2 [2] predictions of flux profiles with the new facet distribution.

SNL spent considerable effort on understanding and improving the alignment scheme of the systems. This aspect has the potential for a substantial payoff, as the scheme selection can substantially affect the aperture size, and therefore thermal losses and efficiency, with no change in cost. The alignment scheme must balance the flux distribution to avoid hot spots locally, but must also balance the power between cylinders for maximum engine performance. The original MDC alignment scheme “dithers” some facets out of “perfect” single-point alignment in order to balance the power, filling in the slot caused by the pedestal. However, this scheme requires an aperture that is 2 inches larger in diameter, a substantial thermal loss when compared to a single-point alignment. Initial efforts with a single-point alignment were promising, but the power imbalance proved greater than desirable.

SNL developed an approach that considers the flux distribution not only at the receiver, but also at the aperture. Through use of a code similar to molecular dynamics modeling, and applying constraints at both the aperture and the receiver, we proposed, modeled, and implemented a new aimpoint strategy. CIRCE2 modeling indicates a flux and power distribution at the receiver equivalent to the MDC strategy, but an aperture diameter equal to the single-point alignment. Initial on-sun testing indicates a very uniform cylinder-to-cylinder power distribution.

Initial routine operation was hampered by recurring incidences of known issues, particularly failure of the compressor short-circuit valve. This valve bypasses the gas compressor, allowing it to “idle” when not needed. The valve is an internally piloted valve providing a large flow area. The fluctuating flow field of the compressor appears to accelerate wear in the valve. SNL has begun testing several valve options, with great initial success. We have also begun characterizing the pressure drop through the valve, helping to determine suitable COTS valves available for mass production and substantial cost savings. It appears the large flow area on the original valve is oversized by several orders of magnitude. Initial operation with several valve options has been trouble free, and all six dishes are now operational. Other reliability issues have centered on the PCU control system, which is an old design. We have helped design and install short-term fixes to improve the noise rejection. SES is building a team to modernize the controller, which will reduce the parts count, provide programming flexibility, and greatly improve reliability.

The systems have accumulated 1,734 dish-hours of operation so far, which is expected to increase rapidly in the next fiscal year. To reduce risk to limited assets, most dish operation is limited to attended operation. The systems have performed well, with indicated efficiencies similar to the record of 29.4% net. We are installing and calibrating NIST-traceable instruments for power and solar resource to accurately determine system and field performance. We fully expect improved performance versus the MDC systems, based on the improved alignment strategy and improved glass reflectivity (low-iron glass).

SNL has worked closely with SES to develop improved data, information, and control handling and systems. SES is leading a program to update the Supervisory Control and Data Acquisition system to provide graphical interfaces, historical online data, and efficient field communications. This system is database-driven and will provide views suitable for operators (simple), managers (summary), and engineers (highly detailed). In addition, SNL has continued to develop procedures and tools for capturing human interactions (electronic logbook) and documenting safe operational procedures. The larger number of systems requires diligent efforts to capture and catalog issue areas that will lead to product improvement.

4. Planned FY 2006 Activities

SES and SNL have successfully installed and begun operating a six-dish MPP to demonstrate the technology, develop new components and methods, and improve reliability in preparation for larger deployments. SES has developed agreements with California utilities for up to nearly 2 GW of installed capacity. The systems have brought unprecedented publicity to both the CSP Subprogram and SES, culminating in a visit by President Bush in August 2005.

SES is continuing an aggressive schedule for product improvement and deployment. The company will next install a 1-MW (40-dish) system, followed by high-rate production. The involvement of high-production suppliers and the national laboratories in the deployment of the MPP and the 1-MW plant is key to transitioning to production.

The systems are performing at expected efficiency and power production levels, which helps firm up predictions for large plant production. Initial reliability has been impacted by several known problems. SNL and SES have applied engineering resources to these problems, implemented short-term fixes to the MPP, and outlined development paths for the production version.

The partnership between SNL and SES is a new way of doing business that maximizes the benefit to SES while continuing to leverage the expertise developed at the national laboratories. During FY 2006, we will:

- Continue to operate the six-dish system, and evaluate performance and identify reliability issues
- Start to resolve known issues (e.g., gas-management valve)
- Define initial, baseline system performance and reliability
- Support SES as it starts to deploy a 1-MW power plant.

REFERENCES

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[2] Romero V.J., "*CIRCE2/DEKGEN2: A Software Package for Facilitated Optical Analysis of 3-D Distributed Solar Energy Concentrators – Theory and User Manual,"* SAND91-2238, Feb 1,1994.

Parabolic Trough R&D

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

Key Technical Contacts: Henry Price (NREL, Primary Contact), 303-384-7437, henry_price@nrel.gov
Doug Brosseau (SNL), 505-844-5218, dabross@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2005 Budgets: $1,645K (NREL), $580K (SNL)

Objectives

- Support development of near-term parabolic trough technology for central station power generation.
- Support development of advanced technologies for next-generation parabolic trough solar fields, thermal energy storage, and power plant technologies to meet long-term goals of the *DOE Solar Program Multi-Year Technical Plan*.
- Support the expansion of U.S. industry to supply parabolic trough technology.
- Support development of SunLab to support parabolic trough technology development and testing.

Accomplishments

- Construction of the first commercial parabolic trough plant in nearly 15 years neared completion at the end of FY 2005. The plant is being developed for Arizona Public Service (APS) by Solargenix Energy of Raleigh, North Carolina. It is a 1-MWe solar power plant using an organic Rankine power cycle provided by Ormat Technologies of Sparks, Nevada. The plant uses parabolic trough collector technology developed by Solargenix under a cost-shared R&D contract with DOE/NREL. Start-up of the plant is expected in early FY 2006.
- Solargenix installed and optically tested its first full collector at its new Nevada test site. The collector design was further refined to reduce cost and simplify field assembly for the first commercial deployment at the APS parabolic trough power plant.
- Two contracts were placed during FY 2005 from the FY 2004 USA Trough Initiative request for letters of interest (LOI). The first was to Solargenix for further optimization of its new parabolic trough concentrator. The second was to Industrial Solar Technology for the development of an advanced low-cost parabolic trough concentrator.
- NREL continued development of a new selective coating that appears to meet the long-term selective property goals for parabolic trough receivers. The coating was simplified by further modeling and initial test samples of the new coating were produced on the NREL vacuum deposition system.
- SNL completed testing of the new Schott receiver on an LS-2 collector installed on the National Solar Thermal Test Facility's rotating platform. The receiver demonstrated about 30% lower thermal losses and a 5% improvement in optical efficiency versus the Luz cermet receiver tested in 1993.
- The Video Scanning Hartmann Optical Test (VSHOT) instrument, used for measuring the slope error of a concentrator surface, was modified to improve the speed of field-testing trough concentrators. The VSHOT was used to test the Solargenix parabolic trough concentrator at the company's Nevada collector test facility.
- SNL completed concept development and feasibility assessment of a new field-deployable concentrator optical alignment tool.
- NREL developed a new technique for evaluating receiver thermal performance in operating solar fields. This technique was used to help FPL Energy evaluate the condition of its solar fields, including a receiver hydrogen build-up phenomenon.

- Nexant developed a detailed design and cost estimate for a thermocline thermal energy storage system for the APS 1-MWe trough plant, which will allow evaluation of the interaction among the solar field, thermal energy storage system, and the power plant.
- SNL developed TRNSYS models of the APS plant to support decisions relative to the eventual implementation of thermal storage.

Future Directions

- Continue development of advanced receiver and concentrator technologies to meet long-term MYTP goals.
- Support development of advanced thermal energy storage technologies.
- Continue building laboratory capability to support trough testing and analysis.

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1. Introduction

Parabolic trough technology is currently the lowest cost central station solar power option and has the potential to become directly competitive with conventional power sources. As a result, there is growing interest in the U.S. Southwest to deploy more of these types of plants. In the near term, the objective of the parabolic trough R&D program is to advance technologies that have an opportunity to be deployed in these early projects. A second objective is to encourage expanded U.S. supply in these early plants. The longer-term objective is to encourage the development of advanced technologies that will help improve the competitiveness of future parabolic trough plants with conventional fossil power plants. Although a number of technical approaches could be undertaken to support these objectives, the focus of the DOE program is to encourage U.S. supply of the solar collector technology, improve the parabolic trough receiver, and to support the development of advanced thermal storage technologies. In addition, the program is working to develop improved tools, testing capabilities, and the technology knowledge base necessary to support the needs of a growing U.S. parabolic trough industry.

2. Technical Approach

The parabolic trough R&D effort is broken into four areas in the *DOE Solar Program Multi-Year Technical Plan* (MYTP): (1) solar field technology, (2) thermal energy storage technology, (3) solar power plant technology, and (4) systems integration.

2.1 Solar Field Technology

The primary solar field technology activity was the continuation of the Solargenix Energy parabolic trough collector development under the USA Trough Initiative and DOE Nevada renewable energy funds. This effort focused on field-testing two full size collectors at a new test facility in Nevada and completing the design for the first commercial deployment of these collectors in the 1-MWe parabolic trough plant built for Arizona Public Service near Tucson, Arizona.

During FY 2005, two proposals were awarded contracts from the FY 2004 USA Trough Initiative near-term component manufacturing solicitation:

- Solargenix Energy: optimization of concentrator and receiver sizes, alternative concentrator design, and drive system cost optimization.
- Industrial Solar Technology: advanced concentrator design for power plant application.

During FY 2005, SunLab support focused on:

- Performance testing of the new Schott receiver at the SNL National Solar Thermal Testing Facility's (NSTTF) rotating platform
- Continued development of advanced selective coating technologies for receivers, with the focus on developing coatings with improved thermo/optic properties and that are thermally stable in air up to 500ºC
- Developing approaches for assessment of receiver performance at operating plants and understanding potential hydrogen build-up in receivers.

2.2 Thermal Energy Storage (TES) Technology

The SunLab TES program is responsible for the development of the indirect 2-tank molten-salt TES system that will be used in several parabolic trough solar plants under development in southern Spain. Unfortunately, this TES technology is still more expensive than the U.S. power market will tolerate (approximately $30/kWht). The objective of the TES R&D effort is to develop the next generation of TES technology, which will cost substantially less ($10–$15/kWht). To achieve this goal, the DOE R&D effort focuses on developing single-tank (thermocline) TES systems, application of TES systems in which inorganic molten salt is used directly in the solar field, and on the development of advanced new heat transfer fluids that will lower the cost of the TES system (using either indirect or direct TES designs). Specific activities during FY 2005 included:

- Completion of a detailed design and cost estimate for a thermocline TES system for the APS 1-MWe parabolic trough plant. This system would be used to understand operational characteristics of a thermocline storage system in a commercial solar plant.
- Use of TRNSYS software to develop models of the APS Saguaro plant, both without and with storage. The models without storage compared favorably with independent estimates by Solargenix. The model with storage is in close agreement with the Solar One power tower storage system. The TRNSYS model will be instrumental in determining the technical/economic feasibility of the APS plant with storage.
- Developing advanced heat transfer fluids that would help reduce the cost of thermal energy storage and/or allow operation of trough plants at temperatures above 390ºC. Two approaches are being pursued. The first looks at possible chemical modifications of the VP-1 components, i.e., biphenyl and diphenyl oxide, that would reduce the vapor pressure. The second approach looks at higher polyaromatic compounds and aromatic esters as potential high-temperature heat transfer fluids.

2.3 Solar Power Plant Technology

During FY 2005, activities focused on supporting the development of the 1-MWe parabolic trough/Organic Rankine cycle power plant under development by APS and Solargenix, specifically development of a specialized database for tracking O&M costs and the detailed design and cost estimate of the TES. In addition, a contract was placed with Nexant to evaluate the cost penalty for dry cooling and to evaluate issues with scaling up the size of parabolic trough power plants to sizes larger than 100 MW.

2.4 Systems Integration

This activity focuses on the development of systems-integration tools for evaluation of trough technologies and assessment of program activities. Specific FY 2005 activities included:

- Upgrades to the VSHOT tool to increase the speed of field measurement of parabolic trough concentrators
- Concept development, scoping, and feasibility for a new concentrator optical alignment tool
- Installation of the two-axis tracker at the NREL mesa top facility
- Installation of two Solargenix parabolic trough collector modules at the NREL optical testing laboratory and on the new two-axis tracker for development of a VSHOT optical testing tool.

Budget allocations by task are provided below.

Task Title	FY 2005 /CO* Budget ($K)
Solar Field Technology	1,070/475
Thermal Storage Technology	535/0
Solar Power Plant Technology	140/0
Trough Systems Integration	480/0

*Carryover from FY 2004

3. Results and Accomplishments

3.1 Solar Field Technology

During FY 2005, Solargenix continued the development and testing of its new parabolic trough concentrator. The final pre-commercial design was optically and operationally tested. Based on results from testing, the final design was completed and used in the 1-MWe parabolic trough plant built by Solargenix for APS near Tucson, Arizona (see Fig. 1). The new structure was optimized to further reduce cost and to improve field assembly. The design optimization resulted in a 16% weight reduction and an 11% reduction in the cost to manufacture the collector. The new design also resulted in a 41% reduction in the time required to assemble the space frames.

Fig. 1. New APS solar power plant using Solargenix parabolic trough concentrator and Schott receiver

Solargenix also initiated full-scale wind load testing at the SEGS II plant owned by Sunray Energy. The data acquisition system and sensors were installed and calibrated during FY 2005. Wind testing will continue into FY 2006 because no high wind conditions were observed before the end of FY 2005. The field-scale testing is expected to validate the wind tunnel testing completed several years ago.

New competitive contracts were awarded to Solargenix and Industrial Solar Technology (IST). The Solargenix contract includes activities to look at ways to further reduce the cost of the company's current parabolic trough concentrator. They are conducting a design for manufacturing and assembly (DFMA) on the drive to reduce the part count and cost. They will develop a new design that increases the number of receivers on each collector module from two to three. They will look at increasing the length of the receivers by about 10% to 20%. They are also evaluating a separate concentrator design using a new hub structure, which could substantially reduce the number of pieces in their collector design. The IST contract develops a new parabolic trough concentrator design for electric applications that uses a structural design concept similar to the company's solar process heat collector. The IST collector will use a concept where the mirrors rotate around a fixed receiver. The IST design appears to offer the potential for substantial cost savings while minimizing the need for flex hoses or ball joint assemblies. The key is whether they can develop a drive system and bearing design that works. Both of these contracts are structured as phased efforts under which the initial phase must demonstrate proof of concept before moving on to the second phase in FY 2006 (which includes field testing of prototypes).

During FY 2005, SNL completed testing of the new Schott Glass parabolic trough receiver (see Fig 2). The Schott receiver represents a next-generation receiver design intended to improve the optical and thermal performance and reliability and lifetime of the receiver. The receiver demonstrated about a 30% lower thermal losses and a 5% improvement in optical efficiency over the Luz cermet receiver tested in 1993. In addition, in field-testing at SEGS, several hundred receivers have shown no failures after more than a year of operational service.

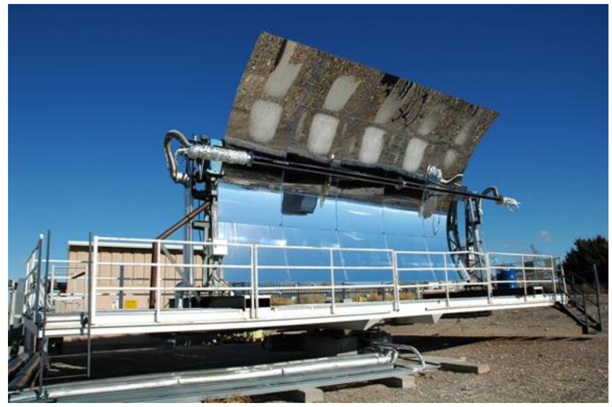

Fig. 2. Schott receiver on test at the NSTTF

NREL continued development of a new selective coating that appears to meet the long-term selective property goals for parabolic trough receivers ($\alpha \geq 0.96$ and $\varepsilon \leq 0.07$ @ 400ºC). During FY 2005, the coating was simplified by further modeling to reduce the number of materials required in the coating and to reduce the number of layers. Several test samples of the new coating were produced with the NREL vacuum deposition system. Initial deposition results were encouraging, but were not fully successful at accurately producing the modeled coating. Modifications to the vacuum deposition system have been initiated that will allow more accurate deposition of multi-layered cermet coating.

During FY 2005, NREL developed a new technique for evaluating receiver thermal performance in operating solar fields using an infrared (IR) camera. The IR camera was used to survey approximately 12,000 receivers to help FPL Energy, the operator of seven of the SEGS plants, evaluate the condition of the receivers in the company's solar fields. This effort helped FPL understand the extent of hydrogen build-up in the receivers in its solar fields, which can have a significant impact on overall plant performance.

FY 2005 Milestones:

- Complete testing of thermal receiver technology for next-generation CSP trough system. (12/04)
- Placement of LOI trough solar field technology development subcontracts. (03/05)
- Complete design of trough concentrator for next-generation CSP trough system. (06/05)
- Prepare samples of new selective coating. (06/05).

3.2 Thermal Energy Storage Technology

A SunLab and industry team has developed a preliminary design and cost estimate for a thermocline storage system for the APS 1-MWe-trough plant currently under construction. The plant has been constructed without TES, but in a way that it can be added later. The APS plant provides an opportunity for testing a full-scale thermocline storage system to understand the interactions between TES and the power plant. In a thermocline TES system, the thermocline is the zone between the hot and cold fluid. If the TES is not operated properly, the thermocline zone can expand to fill the entire volume of the tank. Thus the plant must be designed and operated in a way that minimizes the volume of the tank occupied by the thermocline zone. Some penalty in performance and operational flexibility results from using a thermocline storage system. The test of a thermocline TES system is intended to resolve whether the operational and performance penalties are manageable in a commercial plant and can still provide cost-effective TES. SNL developed a TRNSYS model of the plant and the TES to evaluate the operational impact on plant performance. The FY 2005 work set the stage for a possible demonstration project beginning in FY 2006.

The advanced heat transfer fluid (HTF) efforts have not been able to identify salts variants of the current Therminol VP-1 HTF that are liquid at ambient temperatures, but did succeed in preparing several esters that behave as oil-like fluids with very high boiling points under vacuum, and that remain liquid below 0ºC. They were "oily" liquids at 0ºC, and differential scanning calorimetry (DSC) showed that these esters did not have clear freezing points above –40ºC, but rather underwent supercooling. Boiling points were extrapolated to 760 mm Hg using a nomograph. Although the combination of a very high boiling point with a low freezing point fits the requirements for thermal storage fluids, it is not clear that these materials can withstand temperatures above 400ºC for an extended period of time. Further studies are under way.

FY 2005 Milestones:

- Complete design and economic assessment of thermocline storage for APS power plant. (8/05)
- Complete annual progress report on advanced fluids. (9/05)

3.3 Solar Power Plant Technology

During FY 2005, SunLab supported the development of an O&M database for the APS parabolic trough power plant. Delays in construction of the plant and the decision to switch the database to the Maximo computerized maintenance management database that APS uses has delayed expected completion of this activity until the summer of 2006.

Nexant completed a study to evaluate the cost and performance impact of using dry cooling with a parabolic trough power plant. Dry cooling is a conventional cooling option for trough-type power plants that can reduce water consumption by 90%. The study estimated that dry cooling would result in an 8% increase in the levelized cost of energy based on increased capital cost, increased fan parasitic electric, and a drop in plant efficiency and output during hot summer periods.

FY 2005 Milestones:

- O&M database program development for APS 1-MWe trough plant. (Delayed until 6/06)
- Complete assessment of dry cooling. (9/05)

3.4 Systems Integration

NREL completed upgrades to the VSHOT system for measuring concentrator curvature (see Fig. 3). The system hardware and software were upgraded to speed field setup and data acquisition for field-testing applications. The new system was used to field test the new Solargenix concentrator that was installed at their Nevada test site. Field test results verified that the Solargenix concentrator met the optical accuracy target required for commercial deployment.

Fig. 3. Optical testing of IST concentrator with VSHOT

NREL completed installation of the APS two-axis tracker at the NREL mesa top facility. A Solargenix space frame and mirrors were installed on the tracker to test the operation of the system and to use for development and testing of the VSHOT system. Initial plans included installation of a low-temperature thermal loop to allow optical efficiency testing of the Solargenix collector and new Schott receivers. During the year, the implementation of the fluid loop was put on hold to develop a laboratory receiver-testing capability that would allow more accurate measurement of receiver thermal losses. A new receiver thermal loss experiment was developed based on the approach that the German DLR has begun using to test receiver thermal losses. The approach uses the electric resistance heaters to determine thermal losses. This approach offers the potential for higher measurement precision and should be much quicker than the more conventional fluid loop measurement. The system will be installed and initial tests will be conducted during FY 2006.

FY 2005 Milestones:

- Complete installation of two-axis test bed. (12/04)
- Complete optical testing of next-generation trough concentrator. (09/05)
- Develop initial concept of new optical alignment tool. (09/05)

4. Planned FY 2006 Activities

Key activities planned for FY 2006 include:

- Funding of phase II of USA Trough Initiative near-term component manufacturing contracts with IST and Solargenix.
- Complete field receiver survey to evaluate performance of receivers at existing plants. (12/05)
- Field test of new instrument to measure gas pressure in receiver annulus.
- Complete receiver testing of new and used receivers with new receiver thermal loss test rig. (06/06)
- Complete second-generation prototype sample and property testing of new high-temperature selective coating. (09/06)
- Complete VSHOT testing to baseline Luz LS-2 and LS-3 concentrators at SEGS plants and new Solargenix concentrators at APS plant. (08/06)
- Field validation of new concentrator optical alignment tool. (06/06)
- Continue development of advanced thermal energy storage technologies.
- Provide technical support to Nevada and Arizona parabolic trough projects.

5. Major FY 2005 Publications

D. Brosseau et al., “Testing of Thermocline Filler Materials and Molten-Salt Heat Transfer Fluids for Thermal Energy Storage Systems in Parabolic Trough Power Plants,” *Journal of Solar Energy Engineering,* American Society of Mechanical Engineers, Vol. 127, February 2005.

C. Kennedy, H. Price, 2005, “Progress In Development Of High-Temperature Solar-Selective Coating,” ISEC Solar 2005, August 6-12, 2005, Orlando, Florida, ISEC2005-76039.

D. Kearney, H. Price, 2005, “Recent Advances In Parabolic Trough Solar Power Plant Technology,” *Advances in Solar Energy*, Vol. 13, ASES, Boulder, CO.

L. Moens, B. Blake, 2005, “Task 2.3.1.2 Progress Report FY 2005, Advanced Heat Transfer and Thermal Storage Fluids,” Milestone Report, NREL September 2005.

T. Moss, D. Brosseau, 2005, “Final Test Results for the Schott HCE on a LS-2 Collector,” Sandia Report, SAND2005-4034, Albuquerque, New Mexico, July 2005.

Nexant, 2005, “Comparison of Wet and Dry Rankine Cycle Heat Rejection,” Task 2 Report NREL Subcontract LDC-5-55014-01, June 2005.

Nexant, 2005, “Cost Estimate for Thermal Storage System, APS Solar Power Plant Project, Saguaro Power Plant, Arizona,” Task 4 Report NREL Subcontract LDC-5-55014-01, Mod 1, May 2005.

San Diego Regional Renewable Energy Study Group, 2005, “Potential for Renewable Energy in the San Diego Region, August 2005. http://www.renewablesg.org/.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
Solargenix Energy Randy Gee	Raleigh, NC randycgee@comcast.net	USA Trough: Near-Term Component/ Subsystem Development – Advanced Parabolic Trough Concentrator Components and Subsystems, Phase I	170* 37	52
Industrial Solar Technology Ken May	Golden, CO industrialsolar@qwest.net	USA Trough: Near-Term Component/ Subsystem Development – Advanced Parabolic Trough Concentrator, Phase I	30* 220	63
Nexant Bruce Kelly	San Francisco, CA bdkelly@nexant.com	Dry cooling analysis, power plant size optimization study, APS thermocline TES engineering design and cost.	94	0
Latent Structures, LLC Dr. Robert Meglen	Boulder, CO bmeglen@comcast.net	Development of field instrument non-intrusive measurement of hydrogen in trough receiver annulus.	27	0
TBD **	TBD	USA Trough: Near-Term Component/ Subsystem Development, Phase II	120	20%

* Funded with prior year (FY 2004) funds.
** Award pending phase I completion and will be spent in FY 2006.

Advanced Concepts

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Cheryl Kennedy, 303-384-6272, cheryl_kennedy@nrel.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2005 Budget: $130K

Objectives

- Develop advanced reflector materials that are low in cost (less that $\$1/ft^2$ or $\$10.76/m^2$) and maintain high specular reflectance (90%–95% into a 4-mrad cone angle) for long lifetimes (10 to 30 years) under severe outdoor environments.
- Test the durability of optical materials to determine lifetime of solar reflector materials.

Accomplishments

- Continued to perform durability testing of optical materials and published results of durability testing of several mirror types.
- Provided significant industry support about reflectors to the concentrating photovoltaic industry.

Future Directions

- Continue durability testing of optical materials to determine lifetime of solar reflector materials.
- Analyze and publish results of advanced reflector durability testing.

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1. Introduction

Commercialization of concentrating solar power (CSP) technologies requires the development of advanced reflector materials that are low in cost and maintain high specular reflectance for lifetimes of 10 to 30 years under severe outdoor environments. The *DOE Solar Program Multi-Year Technical Plan* targets cost reductions of up to 50% for the solar concentrator. These goals should be achieved through technology advances to the lightweight front-surface reflectors, including anti-soiling coatings. The objective of this research is to identify new, cost-effective advanced reflector materials that are durable with weathering.

2. Technical Approach

Candidate reflector materials are identified based on their potential for low cost and high optical performance and durability. All candidate materials are optically characterized prior to exposure testing and as a function of exposure time to assess optical durability. These mirrors are subjected to accelerated or outdoor weathering at a variety of geographically diverse exposure sites.

3. Results and Accomplishments

- Published cost analysis results of advanced solar reflective mirror (ASRM). (04/05)
- Published results of durability testing of thin glass mirror matrix. (08/05)
- Provided status of test results of candidate solar mirror samples and identify promising candidates. (09/05)
- Provided significant industry support about reflectors to concentrating photovoltaics (CPV) industry.

3.1 Glass Mirrors

Glass mirrors have excellent durability in terms of corrosion of reflective layer, are readily available, have the confidence of the solar manufacturing industry, and are commercially deployed. However, they are heavy and fragile and require slumped glass for curved shapes, which is expensive. Two significant changes in mirror manufacturing have recently occurred in the classical wet-chemistry process because of environmental concerns. The first is the method of forming a copper-free reflective mirror, and the second is the use of lead-free paints.

Trough mirrors (used in commercial solar plants) manufactured by Flabeg, which use silvered, thick, slumped glass with a proprietary multilayer paint system designed for outdoor exposure, have been very durable. Flabeg recently converted its mirror line to the copper-free process and a new lead-free paint system. The manufacturer reports durability is expected to be equivalent. Side-by-side exposure testing began in FY 2004. After 1 year of accelerated and outdoor exposure, new mirrors are performing slightly better than the original mirrors.

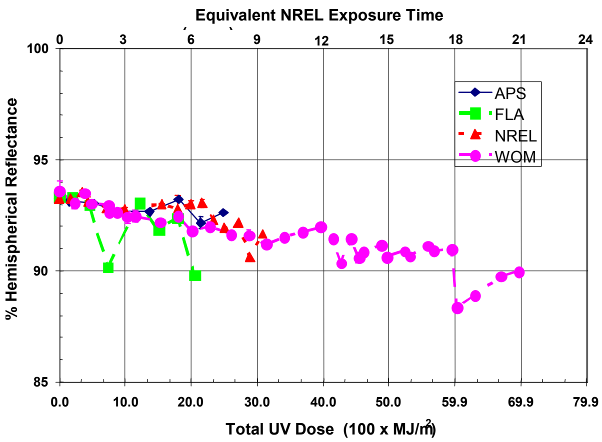

Fig. 1. Loss of solar-weighted reflectance of original Flabeg thick-glass mirrors as function of accelerated WOM and outdoor exposure at Phoenix, AZ (APS), Miami, FL (FLA), and Golden, CO (NREL) in total UV dosage.

Testing of samples of Pilkington (4-mm copper-free) mirrors and "Spanish" (Cristaleria Espanola S.A) glass mirrors (3 mm, copper-free, and lead-free paint), bonded to steel with four different candidate adhesives, was initiated in FY 2001 for possible use at Solar Tres. Neither Pilkington nor Spanish mirrors exposed outdoors show degradation after 60 months, but in accelerated testing using the Altas Ci5000 WeatherOmeter (WOM), the Pilkington mirrors exhibit better optical durability, and adhesive-related degradation is more prevalent with Spanish glass mirrors. Spanish mirrors degraded 19.0%, whereas Pilkington mirrors degraded 6.8% after 40 months of accelerated WOM exposure. Depending on the adhesive used to bond the mirror, Spanish mirrors degraded 5.3% to 12.0%, whereas Pilkington mirrors degraded 2.5% to 2.9% after 34 months of accelerated WOM exposure.

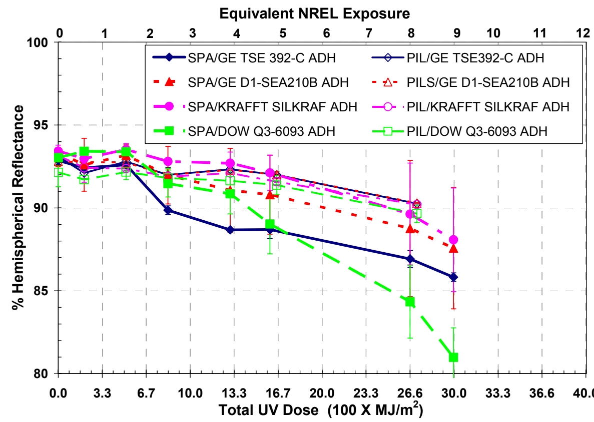

Fig. 2. Loss of solar-weighted reflectance of thick Pilkington and Spanish reflectors with copper-free back layer, Pb-free paint, and four adhesives as a function of WOM exposure.

Thin-glass mirrors also use traditional wet-silvered processes on thin (<1 mm), relatively lightweight glass. Choice of adhesive has been observed to affect the performance of weathered thin-glass mirrors, and corrosion has been observed in deployed mirrors. A matrix of sample constructions has been prepared to identify the most promising combinations of paints and adhesives for use with solar reflectors. After almost two years of exposure in the WOM and in damp heat, data indicate that the mirror performance strongly depends on the back protection. For the copper-free constructions, the addition of epoxy and polyurethane back protection appears to be a poor choice because when these constructions failed, they typically failed catastrophically (e.g., delaminated). Between the mirrors incorporating the new copper-free process, the Glaverbel mirror tended to outperform the Naugatuck mirror. However, this could be because at the time the mirrors were acquired Glaverbel had more experience than Naugatuck in manufacturing mirrors with the copper-free technique. In this experiment, adhesives and substrates were less significant than the choice of back protection. The 3M 504 adhesive and aluminum steel showed slight advantages versus other adhesive/substrates. Edge protection and substrate and glass back-cleaning had no effect. Degradation of the samples exposed to date in the damp-heat chamber is similar, but at a rate ten times faster than observed for samples in the WOM. CPV manufacturers have expressed significant concern regarding the durability of thin-glass mirrors made with copper-free and lead-free paint systems.

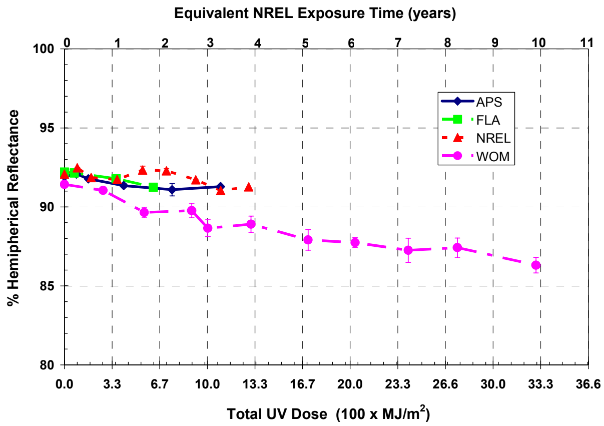

Fig. 3. Loss of solar-weighted reflectance of Naugatuck thin-glass mirrors with Cu back layer and Pb-free paint as a function of APS, FLA, NREL, and WOM exposure.

Although glass mirrors with copper back layers and heavily leaded paints have been considered robust for outdoor use, the new copper-free back-layer and lead-free paint systems were designed for interior mirror applications. Their outdoor durability must be determined.

3.2 Aluminized Mirrors

Aluminized reflectors use a polished aluminum substrate, an enhanced aluminum reflective layer, and a protective oxidized topcoat. The major concern has been poor durability of such materials in urban and industrialized (polluted) locations. An improved anodized aluminum mirror incorporated a protective polymeric overcoat onto aluminized aluminum. However, specularity degraded with outdoor exposure at Arizona, Florida, and Colorado (NREL) and with accelerated exposure in the WOM. Alanod stopped selling this material in FY 2004 for outdoor use because of problems associated with the delamination of the overcoat. Alanod worked to solve the problem and improve outdoor durability; new samples received in the fourth quarter of FY 2005 are undergoing testing. The company will commercially reintroduce the reflector in early FY 2006.

3.3 Silvered Polymer Reflectors

A polymeric solar reflector was developed through collaborative research with ReflecTech. In FY 2001, a small pilot run demonstrated that production could be achieved using standard commercial film converter equipment. This initial pilot-run material shows no significant loss in solar-weighted reflectance after 2.5 years of real-time outdoor exposure in Golden, Colorado. In addition, samples exposed in accelerated outdoor weathering tests (natural sunlight in Phoenix, Arizona, concentrated 7 to 8 times with a Fresnel-reflector while samples are cooled with a fan to near-ambient conditions and sprayed with deionized water 8 min per natural sun hour) are near a 10-year equivalent time period, and show no significant loss in solar-weighted reflectance. However, WOM results showed significant reflectance loss earlier than anticipated. Prototype materials to test modifications to the baseline construction were produced. These tests were successful in identifying changes to the baseline construction that dramatically improved the WOM durability of the reflective film. These improvements were then incorporated into a new pilot plant production run delivered late FY 2004; durability testing is ongoing and the material is being deployed. We expect the new reflector to considerably outperform the original material (which has maintained durability after 10 equivalent years of accelerated outdoor exposure), however testing has only recently been initiated, and further real time exposure will be needed to determine its actual lifetime.

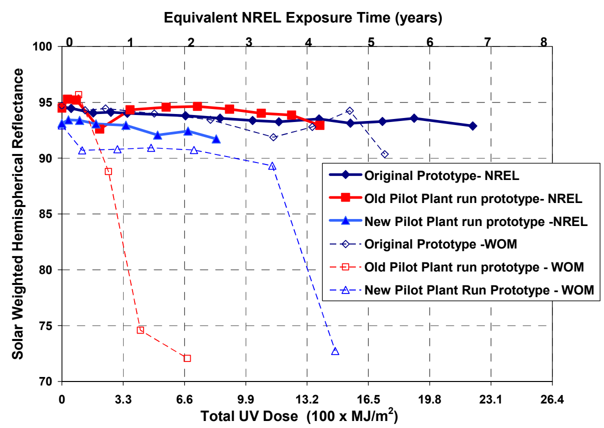

Fig. 4. Loss of reflectance of initial pilot run and most promising new variation as a function of NREL and WOM exposure.

3.4 Advanced Solar Reflective Mirror (ASRM)

The ASRM developed under a subcontract with SAIC (which ended 9/30/04), has a silvered specular substrate protected by an alumina coating several microns thick. The alumina hard coat is deposited by ion-beam-assisted deposition (IBAD). Samples of this “super thin glass technology” have been deposited at 20 nm/s both by batch and a laboratory roll-coater. Many samples prepared have maintained 95% hemispherical reflectance after more than 4 years of accelerated and outdoor exposure; testing is continuing. A cost analysis showed the ASRM has the potential for a manufacturing cost lower than $10.76/m^2$, but the deposition rate must be increased to 30–50 nm/s. Although thin oxide coatings are routinely deposited at deposition rates greater than 100 nm/s, increasing the deposition rate while maintaining the optimized IBAD deposition conditions could be difficult. For long-term durability, edge protection will be necessary and the addition of adhesion-promoting layer should also improve durability. A short subcontract to evaluate different web materials, adhesion-promotion and anti-soiling layers, and use of a lower-purity alumina is warranted. To increase the deposition rate, the ASRM will need to be transitioned to a commercial roll-coating company (with SAIC's consultation). However, NREL will need to establish this relationship.

Progress has been made on advanced solar reflector research, but development work has been severely limited due to a lack of funding. Durability testing of reflectors supplied by industry is ongoing. Glass, ReflecTech, and Alanod mirrors are commercially available and, based on accelerated exposure testing, should meet the 10-year lifetime goals. However, predicting an outdoor lifetime based on accelerated exposure testing is risky. Recently, the construction of all of the solar reflectors has significantly changed. Because of this, all of the solar reflectors commercially available have been in outdoor real-time exposure testing for less than 3 years.

4. Planned FY 2006 Activities

Continue durability testing of optical materials to determine lifetime of solar reflector materials.

- Complete upgrade of optical material durability database. (06/06)
- Analyze and publish results of advanced reflector durability testing. (07/06)
- Provide status of test results of candidate solar mirror samples and identify promising candidates. (09/06)
- Contingent on funding, develop with mirror paint manufacturers a mirror-backing paint system suitable for outdoor applications, to be applied during mirror manufacturing.

5. Major FY 2005 Publications

Kennedy, C.E.; Smilgys, R.V.; and Swisher, R.L., 2005, "Durability and Cost Analysis of Solar Reflective Hardcoat Materials Deposited by IBAD," *2005 Society of Vacuum Coaters 48th Annual Technical Conference Proceedings.*

Kennedy, C.E.; and Terwilliger, K., 2005, "Optical Durability of Candidate Solar Reflectors," *J Sol Energy Eng Trans ASME*, **127**, May 2005, pp. 262-269.

Kennedy, C.E.; and Swisher, R., 2005, "Cost Analysis of Solar Reflective Hard-Coat Materials Deposited by Ion-Beam-Assisted Deposition," *J Sol Energy Eng Trans ASME,* **127**, May 2005, pp. 270-276.

Kennedy, C.E.; Terwilliger, K.; and Jorgensen, G.J., 2005, "Analysis of Accelerated Exposure Testing of Thin-Glass Mirror Matrix," In publication, ISEC2005-76040, *Proc. 2005 Solar Conf.* and *J Sol Energy Eng Trans ASME*, Aug. 2005.

Kennedy, C.E.; Terwilliger, K.; and Lundquist, C., 2005, "Summary of Status of Most Promising Candidate Advanced Solar Mirrors," *CSP FY 2005 Milestone Report*.

CSP Systems Analysis

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

Key Technical Contacts: Mark Mehos (NREL), 303-384-7458, mark_mehos@nrel.gov
Tom Mancini (SNL), 505-844-8643, trmanci@sandia.gov

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2005 Budgets: $546K (NREL), $255K (SNL)

Objectives

- Provide support for the Concentrating Solar Power (CSP) Subprogram analysis efforts related to implementation of 1000 MW of concentrating solar power in the Southwestern United States through the Western Governors' Association (WGA).
- Support CSP-specific analysis related to implementation of the Systems-Driven Approach within the DOE Solar Program.
- Support DOE and Energy Information Administration analysis requests on as-needed basis.

Accomplishments

- Developed detailed maps and performed analysis of CSP in the Southwestern WGA region in support of the *30 GW Clean Energy Initiative*.
- Developed recommendations on the most promising locations for CSP plants in the WGA region based on resources, transmission constraints, and access to major load centers.
- Provided significant technical support to the State of New Mexico in response to Governor Richardson's implementation of a New Mexico Concentrating Solar Power Task Force.
- Performed a study of the potential economic impact of CSP plants in California.

Future Directions

The primary activity for the systems analysis task in FY 2006 will be to continue support of the Southwest 1000 MW Initiative through the Western Governors' Initiative. Specific directions will include:

- Providing support to WGA with coordination of Task Force and stakeholder meetings and completing the Solar Task Force Report.
- Providing support to California Solar Task Force and exploring ways to implement CSP.
- Continuing support of the New Mexico CSP Task Force to develop recommendations for 2006 legislature.
- Continuing interactions in the West with Nevada, Arizona, Texas, and Colorado in support of developing further CSP opportunities in those states.

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1. Introduction

The 1000 MW CSP project was initiated in FY 2002 based on a Congressional request to DOE to investigate the "feasibility of 1000 MW of concentrating solar power in the Southwest by 2006." The original charge has grown and involved a number of activities including: outreach to the Southwestern states, support of state-level activities in New Mexico, California, and Colorado, and analysis in support of the Western Governors' Association (WGA) 30 GW Clean Energy Initiative.

The focus of the 1000 MW CSP Initiative is to accelerate the commercialization of concentrating solar power generation technologies. Analysis shows that cost reductions needed for the technologies to be competitive in central power generation markets will result from a combination of R&D advances, system scale-up, and learning/deployment. The 1000 MW CSP Initiative addresses cost reductions resulting from deployment.

This project links directly to the DOE Energy Efficiency and Renewable Energy (EERE) and Solar Program missions to “bring clean, reliable, and affordable energy technologies to the marketplace” and to “increase the viability and deployment of renewable energy technologies.” Cost reductions due to learning and deployment, the primary outcome of this project, directly support the Solar Program’s long-term goal of achieving wholesale, central power generation from solar energy at costs of $0.05–$0.08/kWhr.

2. Technical Approach

The report on the potential of 1000 MW of CSP power in the West was completed and submitted to Congress in August of 2002. During the preparation of this report, DOE formed the 1000 MW Team with the purpose of educating energy offices and professionals on the potential of CSP power in the Southwestern states. This “road show” sought to provide information on the characteristics of CSP technologies, the potential in each of the states, and the benefits that would accrue from its implementation. In April of 2004 at the North American Energy Summit in Albuquerque, New Mexico, the Western Governors’ Association resolved to evaluate diversification of Western energy resources. The mechanism for doing this is the 30 GW Clean Energy Initiative for the West, which includes a declaration to “establish a stakeholder working group to develop options for consideration by the governors in furtherance of the 1,000 MW Initiative.” The April 2004 resolution rolled up the 1000 MW Initiative under the umbrella of the 30 GW WGA Study. In FY 2005, we have continued to support the Southwestern states and the WGA analysis efforts, through a combination of in-house and subcontracted technical, policy, and market analyses.

Budget allocations by task are provided below.

Task Title	FY 2005 Budget ($K)
1000 MW Initiative Support - NREL	496
General Systems Analysis - NREL	50
1000 MW Initiative Support - SNL	255

3. Results and Accomplishments

The technical work plan for FY 2005 included tasks in the following three areas:

1) Support for WGA 30 GW Clean and Diversified Energy Initiative Solar Task Force
2) Support to the State of New Mexico’s Concentrating Solar Power Task Force
3) Development of a report defining the economic, energy, and environmental benefits of Concentrating Solar Power in California.

3.1 Support of the WGA 30 GW Clean Energy Initiative

- Performed analysis of the current and future performance/costs of CSP systems.
- Provided an assessment of the technical potential and economically feasible CSP capacity in the Western states. (Developed “supply curves” for further analysis by quantitative working groups.)
- Developed resource maps (NREL Resource Assessment Group) identifying the most suitable locations for CSP installations. The CSP plant map shown in Fig. 1 below was prepared to show some of the best locations for CSP in the Southwest.
- Evaluated market barriers and analyzed potential policies to overcome barriers. The primary market barrier is the gap between the cost of CSP power generation and that of fossil generation.
- Served as a technical resource for the solar task force, including participating in meetings of this task force. Staff from NREL (Mark Mehos) and SNL (Tom Mancini) participated as members of the WGA Solar Task Force.

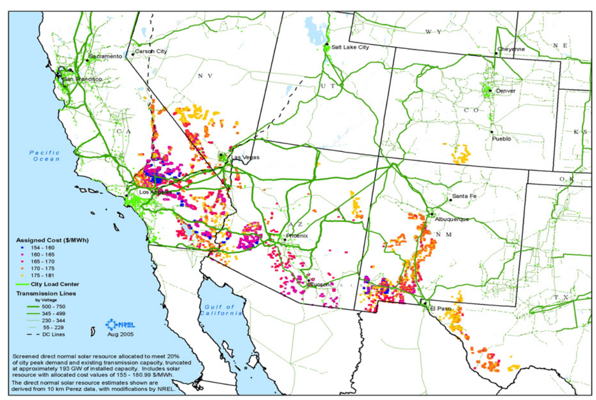

Fig. 1. Locations for CSP plants in the Southwest

3.2 Support of the NM CSP Task Force

In 2004, Governor Richardson formed a Concentrating Solar Power Task Force to identify a viable commercial CSP project of 50 MW (or larger) for the State of New Mexico. The CSP Task Force was chaired by the Cabinet Secretary of the New Mexico Energy, Minerals and Natural Resources Department and included members from state agencies, all of the state's investor-owned utilities, and representatives from industry groups and the national laboratories (Mark Mehos, NREL, and Tom Mancini, SNL). Black and Veatch was awarded a contract by the state to:

- Assess the commercial viability of the full range of CSP technologies.
- Identify favorable siting opportunities in New Mexico and analyze the impact of a range of incentives on the cost of electricity from a CSP plant.
- Review markets for CSP power in the state.
- Examine a range of plant ownership options.

At this time, the final report and recommendations of the Task Force have not been released.

3.3 Report on the Economic Impact of CSP in California

A subcontract was awarded to Black and Veatch for analysis of the economic, energy, and environmental impacts of concentrating solar power in California. As defined in the scope of work, Black and Veatch was required to:

- Assess the applicability of CSP technologies for California.
- Evaluate the direct normal incident in California.
- Estimate the potential economic impact in terms of direct and indirect employment created by the manufacturing, installation, and operation of representative CSP technologies located in California.
- Estimate the potential impact of tangible non-employment-related benefits to state and local decision makers (e.g., property, sales, and income tax revenues; procurement of local goods and services during construction and ongoing operation; air quality improvement).
- Estimate the potential impact of non-tangible benefits that may be of interest to state and local decision makers (e.g., local air quality improvements, community distinction).

This report has been completed and will be published soon.

4. Planned FY 2006 Activities

The activities of the 1000 MW CSP Initiative have resulted in an increased awareness of the technologies by energy decision makers in the Southwestern United States. In consideration of the upcoming WGA report, we anticipate opportunities to deploy these technologies in some states. And, although they cannot be directly attributed to the efforts of this project, one CSP company recently announced two projects totaling 850 MW in California.

Our planned activities for FY 2006 are to:

- Provide support to WGA with coordination of Task Force and stakeholder meetings and complete the Solar Task Force Report.
- Provide support to California Solar Task Force and explore ways to implement CSP.
- Continue our support of the New Mexico CSP Task Force to develop recommendations for 2006 legislature.
- Continue interactions in the West with Nevada, Arizona, Texas, and Colorado in support of developing further CSP opportunities in these states.

5. Major FY 2005 Publications

Draft Report of the Western Governors' Solar Task Force, September, 2005 (www.westgov.org/wga/initiatives/cdeac/solar.htm).

M. Mehos and R. Perez, "Mining for Solar Resource, U.S. Southwest Provides Vast Potential," Imaging Notes, Vol. 20, No. 3. Summer, 2005.

Black and Veatch, "New Mexico Concentrating Solar Plant Feasibility Study," Draft Final Report to the New Mexico Department of Energy, Minerals, and Natural Resources, February, 2005 (www.emnrd.state.nm.us/emnrd/ecmd/ConcentratingSolarPower/documents/NMCSPFeasibilityStudy.pdf).

Black and Veatch, "Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California," Draft Final Report, September, 2005

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
Morse Associates, Inc. Fred Morse	Washington, D.C. fredmorse@morseassociatesinc.com	Consulting for government and utilities on CSP applications and marketing policy	132
Black and Veatch Larry Stoddard	Overland Park, KS stoddardle@bv.com	Analysis of economic, energy, and environmental benefits of CSP in California	40

Solar Heating and Lighting

The Solar Heating and Lighting (SH&L) effort consists of research and technology development programs for solar water heaters and hybrid solar lighting systems. The program works with industry, the national laboratories, and others to develop and demonstrate systems and components that will improve the reliability and reduce the cost of these solar systems. The Technical Assistance Program aids builders, manufacturers, and others in designing and installing solar water heating systems. To ensure that safe and reliable systems are installed, the program supports the testing and certification activities of the Solar Rating and Certification Corporation.

Although solar water heaters have been manufactured and used for some time, there are still barriers to their widespread use, which the DOE Solar Program is working to overcome. The primary issues are the cost, reliability of systems, and the unfamiliarity of related but very necessary trades such as builders, architects, plumbers, roofers and other mechanical contractors.

SH&L research emphasizes the development of low-cost, polymer-based solar water heaters, which have the potential to cut the cost of today's solar water heating (8¢/kWh) to 4.5¢/kWh. The DOE program works with two industrial teams to develop a new generation of low-cost polymer water heaters that could reduce the cost of solar water heaters because of less expensive materials and simplified manufacturing, assembling, and installation.

The Hybrid Solar Lighting Project is developing an entirely new application of solar power in buildings through the use of fiber optic systems that bring sunlight into interior rooms of commercial buildings. This technology can improve the quality of indoor lighting with its associated benefits in worker productivity, student performance, and shoppers' buying behavior.

Following are some highlights from among the SH&L achievements in FY 2005.

Low-Cost Polymers

- Confirmed performance predictions through field monitoring for the Davis Energy Group/SunEarth solar water heating (SWH) system.
- With FAFCO, Inc., produced and tested full-scale prototypes of new thermosiphon SWH system designs.

Materials Durability

- Prepared and began testing candidate glazing samples for SWH systems, which have UV screening layers with increased photo-permanence.
- Quantified UV resistance of candidate absorber materials for SWH systems in terms of loss in percent strain at break as a function of UV weathering.

Industry Manufacturing Assistance

- Developed a project that will deploy and test a "freeze-protected" roof-integrated SWH collector in a Building America home in FY 2006.
- Developed and tested a thermochromatic film to prevent overheat failure of the polymer SWH collector.

Hybrid Solar Lighting

- Completed installation of a hybrid solar lighting unit at the American Museum of Science and Energy in Oak Ridge, Tennessee.
- Worked with Sunlight, LLC, to arrange for 16 additional beta tests to be installed in 2006.

Low-Cost Polymers

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

Key Technical Contacts: Jay Burch (NREL), 303-384-7508, jay_burch@nrel.gov
Glenn Doyle (DOE/GO), 303-275-4706, glenn.doyle@go.doe.gov

DOE HQ Technology Manager: Glenn Strahs, 202-586-2305, glenn.strahs@ee.doe.gov

FY 2005 Budget: $860K (NREL)

Objectives

- Collaborate with industry teams to reduce the levelized cost of saved energy for solar domestic water heaters suitable for mild climates by at least 50%, from ~10¢/kWht to less than ~5¢/kWht.
- Provide contract management and technical support for industry teams developing low-cost solar domestic water heater products.

Accomplishments

- Confirmed performance predictions through field monitoring for the Davis Energy Group/SunEarth solar water heater (SWH).
- With FAFCO, Inc., produced and tested full-scale prototypes of new SWH thermosiphon system designs.
- Developed new models and test methods for integral-collector-storage systems, including models with immersed heat exchangers.
- Measured degradation and scale rates for polymer heat exchanger materials.

Future Directions

- Conduct larger-scale field tests for prototype systems, substantially finishing mild-climate low-cost systems efforts.
- Begin efforts for cost reduction of cold-climate systems.

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1. Introduction

Domestic hot water is a major residential end use in the United States, totaling about 2.7 quads/yr and averaging about 13% of total residential usage nationwide. The cost of saved energy (C_{save}) for solar water heaters (SWHs) is currently ~10¢–25¢/kWht, varying because of varying solar resource and system cost. (C_{save} is defined as $C_{save} = C_{total}/Q_{saved}$, where C_{total} is the *total* cost including O&M and Q_{saved} is the discounted auxiliary energy savings over the analysis period.) C_{save} is to be compared with effective gas heating cost at ~3¢–4¢/kWht and electricity cost at ~6¢–20¢/kWhe. *Significant* reduction in C_{save} is needed for SWH to be an attractive investment and help realize the overall *DOE Solar Program Multi-Year Technical Plan* (MYTP) goal of significantly reducing conventional energy usage through solar technology. As detailed further in the MYTP and other studies, high cost is the key barrier to SWH markets. The Solar Heating and Lighting (SH&L) Subprogram set a major goal in 1998 of *reducing the cost of saved energy (C_{save}) for SWH by at least 50%.* This work started in 1999 and was focused on passive systems for mild climates to limit work scope commensurate with low funding levels. In response to Requests for Proposal (RFPs), five teams were initially funded for concept development. After down-selection in 2001, two teams were "stage-gated" through engineering development to field trials and manufacturing development in FYs 2005–2006: Davis Energy Group/SunEarth (DEG/SE) and FAFCO, Inc. The mild-climate SWH phase is to be substantially completed in FY 2005. The systems are shown in Figs. 1–4; each team has several variations of its system.

Support for the industry teams involved public domain work common to the teams, including: materials durability testing, modeling and testing methods, pipe freeze protection, overheat protection, immersed heat exchanger modeling and testing methods, and polymer heat exchanger materials life and testing.

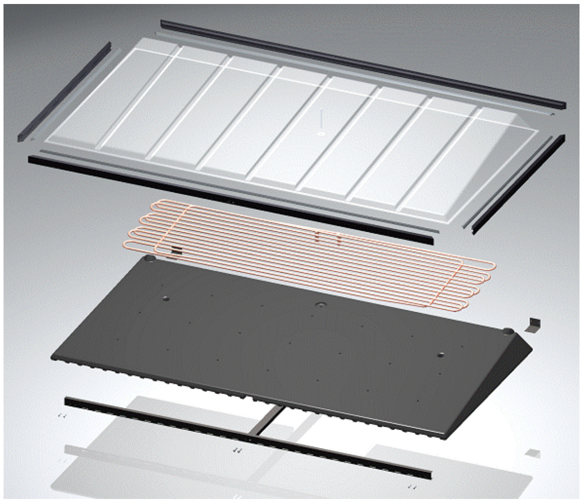

Fig. 1. Schematic of DEG/SE glazed ICS

Fig. 2. DEG/SE glazed ICS on field test

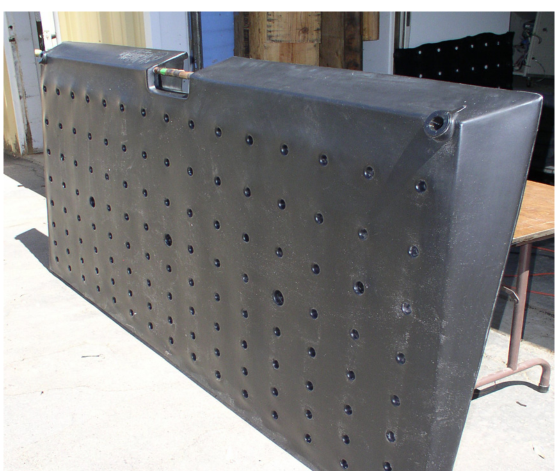

Fig. 3. DEG/SE unglazed ICS prototype

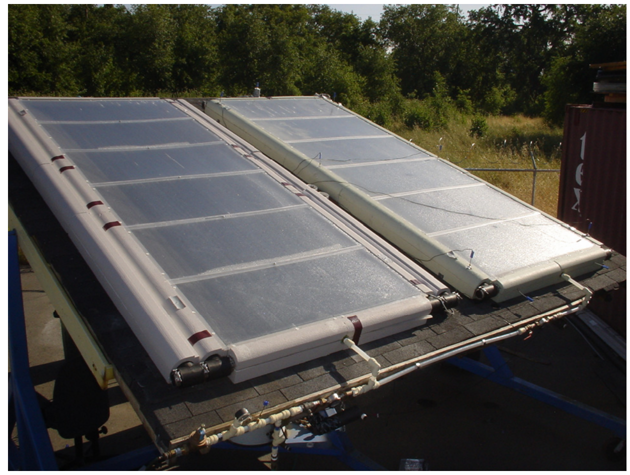

Fig. 4. Two thermosiphon prototypes on test at FAFCO

2. Technical Approach

With the cost-reduction objective, the technical strategy is to: (1) use low-cost polymer materials and manufacturing technology; (2) simplify system designs and installation, exploiting the formability of polymers to reduce part count and to provide molded-in joining features. The two teams, DEG/SE and FAFCO, are subcontracted to develop these systems. The DEG/SE team has been installing prototypes, seeking certification from the Solar Rating and Certification Corporation (SRCC) and addressing tank leakage issues seen in production and in field testing (as described in *SunCache Residential Solar Water Heating System – Phase VI).* They also developed a less-expensive, lower-performing unglazed version of the unit, as in Fig. 3. The FAFCO team changed system type in FY 2004 from integral collector storage (ICS) to flat plate, based on the company's polymer swimming pool collector. They developed full-scale prototypes, addressing issues with overheating and freezing. FAFCO plans both a thermosiphon system and a direct active system (as described in the 2005 Solar Program Review Meeting paper *Innovative Low-cost Polymer Solar Domestic Water Heater).*

With the polymer strategy comes new opportunities and new problems. The key problem to be addressed is materials durability under harsh environmental stresses and high temperatures. A minimum lifetime for polymer solar systems was set at 10 years; the desired lifetime, however, is at least 20 years. These criteria lead to the need for sophisticated and capital-equipment-intensive accelerated testing to identify appropriate materials. Polymer materials testing expertise at NREL and the University of Minnesota has fulfilled that need. NREL concentrated on identifying and testing good candidates for glazings and absorbers; this work is described in the SH&L project description *Materials Durability*. The University of Minnesota concentrated on heat exchanger design and testing and materials durability for polymer heat exchangers; this work is described in the SH&L project description *Next Generation Low-Cost Polymer Solar Heating Systems*.

Another common problem with use of polymers is the loss of material strength at higher temperatures. Low-cost commodity plastics have an upper use temperature around 80°C, depending on imposed stress. The stagnation temperature of flat-plate collectors, however, is in the range 130°–180°C. Thus, over-temperature protection is a key approach for use of low-cost polymers with glazed collectors. Approaches studied include venting, a thermochromic glazing film (at SNL: see the SH&L project description *Industry Manufacturing Assistance*), and a high-temperature dribble valve.

Passive systems have been very limited in geographical deployment, as shown in Fig. 6a. The limitation is due to the danger of metallic pipe freeze/burst. In mild climates, traditional metallic pipes are protected with insulation. Means for extending the market northward should be considered, because passive systems without pumps and controllers tend to be less expensive and more reliable. Freeze-protection valves were studied and water consumption was quantified.

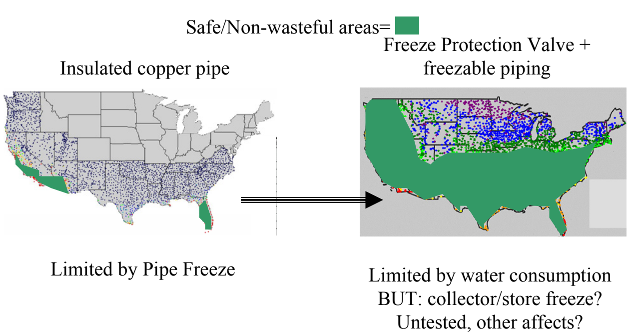

Fig. 5. a) Left, areas considered safe for passive SWH with insulated copper piping; b) Right, areas below 1000 gal/year water consumption (an arbitrarily chosen limit) with a freeze-protection valve configured as in Fig. 6.

Both industry teams developed systems that presented modeling challenges. The DEG/SE ICS collector has an immersed heat exchanger in the shallow ICS tank. In addition, collector temperature under stagnation was incorrectly predicted with the constant top loss approach. (The top loss coefficient varies nearly a factor of 2 between 0° and 100°C.) The FAFCO thermosiphon collector is subject to reverse thermosiphoning at night. Because this is so unusual, this feature was not adequately modeled in existing models. Related to the modeling issues are testing issues. New test procedures are needed for ICS with immersed heat exchangers and for thermosiphon systems subject to reverse thermosiphoning.

Task Title	FY 2005 Budget ($K)
Polymer ICS Field Test	210
ICS Development and Testing	160
Technical Support	490
SRCC	207*
Low-Cost Cold Climate Systems*	60**

* Funding for this task came through the Golden Field Office, and is not part of the project's $860K.

** Funding for this task came from SH&L Systems Analysis; a separate project description ("Cold Climate Solar Domestic Hot Water Systems Analysis") is in the *Solar Program Review Proceedings CD*.

Compared to copper heat exchangers, polymer heat exchangers have the potential to lower costs and weight. However, a number of design and materials issues arise, especially when considering use of lower-strength commodity plastics (which dictates small diameters). Oxidation and polymer degradation must be prevented, and antioxidant life must be at least 10 years. Scaling in the small-diameter heat exchanger tubing can be a problem in scale-prone waters, if scale rates are as high in polymers used as in copper piping.

3. Results and Accomplishments

3.1 Davis Energy Group/SunEarth

- Produced 40 prototypes of its ICS SWH for testing and for certification.
- Submitted both glazed and unglazed systems, with manuals, for SRCC certification.
- Field test results corroborated initial performance projection at 29% efficiency.

3.2 FAFCO

- Produced and tested full-scale prototypes of new thermosiphon system designs.
- Tested new designs incorporating overheat protection and freeze protection.

3.3 NREL

- Managed industry and university contracts.
- Produced new ICS models and a new thermosiphon model to accommodate new features.
- Produced new test protocols for ICS systems, for SRCC use.
- Characterized venting overheat protection.
- Characterized pipe-freeze protection with freeze-protection valves and freezable polymer piping.
- Tested and determined lifetime of polymeric materials for glazings and absorbers (see companion project description, *Materials Durability*).

Pipe-freeze protection is crucial to extending the geographical domain of these low-cost systems. As in Fig. 5a above, passive system deployment is currently limited to Florida, California, and Arizona, due to the practice of using insulated copper piping. With a freeze-protection valve installed as in Fig. 6, the market can be extended to more than half the country, as shown in Fig. 5b. It is essential in this approach that the supply/return pipe be freezable, as the freeze-protection valve may fail. NREL is testing three brands of PEX piping approved for potable water use, which is currently at about 400 freeze-thaw cycles without breaking.

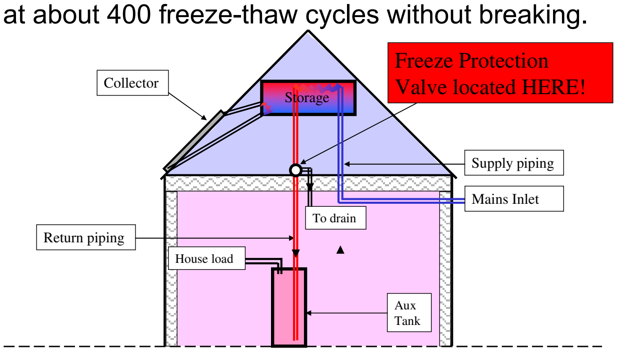

Fig. 6. An indirect thermosiphon system is shown, with a freeze-protection valve mounted at the roofline just before the return pipe enters conditioned space.

3.4 University of Minnesota

- Demonstrated a means to promote stratification in shallow ICS tanks.
- Measured creep properties of candidate polymer heat exchanger materials.
- Characterized $CaCO_3$ scale rate at high supersaturation for candidate polymer heat exchanger materials.

3.5 Thermal Energy System Specialists, Inc.

- Implemented a series of ICS models with capability of variable top loss coefficients and immersed heat exchangers of several types.

3.6 Solar Rating and Certification Corporation

- Maintained certification documents and directories, with more than 400 certified systems and 110 certified collectors.
- Adopted new testing procedures for ICS systems.

4. Planned FY 2006 Activities

4.1 DEG/SE

- Revise mold to eliminate remaining leaks.
- Produce 80 prototypes and install in large pilot program.

Details are available in "SunCache Residential Solar Water Heating System – Phase VI" in the *Solar Program Review Proceedings CD.*

4.2 FAFCO

- Refine and test thermosiphon and active system designs.
- Produce 100 prototypes in a small-scale production run (mid-2006).
- Install 60 systems through existing dealer network.
- Refine manufacturing plans.

Details are available in "Innovative Low-cost Polymer Solar Domestic Water Heater" in the *Solar Program Review Proceedings CD.*

4.3 NREL

- Manage industry and university contracts.
- Test pipe-freeze protection approach.
- Test glazed and unglazed thermosiphon systems.
- Develop new model calibration procedures for three types of thermosiphon.
- Continue durability testing of industry-proposed and candidate materials (more details in *Materials Durability*).
- Prepare to issue RFPs for low-cost cold-climate SWH, focused on balance of systems and contingent on sufficient FY 2006 funding.

4.4 University of Minnesota

- Develop means to promote stratification in vertical tanks with immersed heat exchangers.
- Develop model for diffusion and consumption of antioxidants to protect heat exchanger tubing materials.
- Determine scale rates in candidate polymeric heat exchanger tubing materials (particularly at low supersaturation).

4.5 Thermal Energy System Specialists

- Continue to support industry teams modeling needs.

4.6 Solar Rating and Certification Corporation

- Maintain certification documents and directories.
- Establish certification for commercial systems.

5. Major FY 2005 Publications

Burch, J., Salasovich, J., "Water Consumption from Freeze Protection Valves for Solar Water Heating Systems," *Proceedings of ISES/ASES 2005 Conference*, Orlando, FL.

Roberts, J., Brandemuehl, M., Krarti, M., and Burch, J., "Venting Overheat Protection in Solar Water Heaters," *Proceedings of ISES/ASES 2005 Conference,* Orlando, FL.

Burch, J., Hillman, T., and Salasovich, J., "An Assessment of Unglazed Solar Domestic Water Heaters," *Proceedings of ISES/ASES 2005 Conference,* Orlando, FL.

Burch, J., Hillman, T., and Salasovich, J., "Cold-Climate Solar Domestic Water Heating Systems: Life-cycle Analyses and Opportunities for Cost Reduction," *Proceedings of ISES/ASES 2005 Conference,* Orlando, FL.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
Davis Energy Group/SunEarth Dick Bourne	Davis, CA dbourne@davisenergy.com	Field monitoring of 10 systems, codes, leak elimination	213	53
FAFCO, Inc Mike Rubio	Chico, CA mrubio@fafco.com	Refine new designs, test prototypes	305*	100
University of Minnesota Jane Davidson	Minneapolis, MN jhd@me.umn.edu	Stratification, pipe materials testing, and scaling rates	200	85
Thermal Energy System Specialists, Inc. Jeff Thornton	Madison, WI thornton@tess-inc.com	Develop TRNSYS and TRNSED models in support of industry teams	50**	0
SRCC Jim Huggins	Cocoa, FL huggins@fsec.ucf.edu	Rating and Certification of Solar Thermal Collectors and Systems	207***	0

* Funded with prior year (FY 2004) funds.
** Open contract through FY2007, funds allocated in 2005.
*** Funded through the Golden Field Office from SH&L funds.

Materials Durability

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contact: Gary Jorgensen, 303-384-6113, gary_jorgensen@nrel.gov

DOE HQ Program Manager: Glenn Strahs, 202-586-2305, glenn.strahs@ee.doe.gov

FY 2005 Budget: $225K

Objectives

- Identify alternative polymeric glazing and absorber materials/constructions that will allow design trade-offs and can help reduce the costs associated with solar domestic hot water systems.
- Perform materials testing to demonstrate whether such candidate polymers will meet the durability requirements for real systems.

Accomplishments

- Investigated the reasons why thermally bonded ultraviolet (UV) screens provide less protection for polycarbonate glazings than adhesively bonded constructions; proposed solutions to overcome this problem.
- Prepared and began testing candidate glazing samples, which have UV screening layers with increased photo-permanence.
- Quantified UV resistance of candidate absorber materials in terms of loss in percent strain at break as a function of UV weathering.

Future Directions

- Test UV stability of new candidate polymeric glazing constructions.
- Measure impact strength of candidate glazings and compare with dynamic mechanical analysis results as a function of photothermal exposure.
- Continue long-term testing and evaluation of candidate polymeric absorber materials.

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1. Introduction

Improved polymeric glazing and absorber materials are required to increase the reliability of cost-effective solar collectors. As discussed in the *DOE Solar Program Multi-Year Technical Plan*, a major impediment to development of low-cost solar water heating systems is the uncertainty in durability of polymeric components.

Both passive solar water heating and active cold-climate solar water heating technologies require polymeric glazings and absorbers to survive in harsh operating environments. The objectives of this research are to: (1) identify alternative polymeric materials/constructions that will allow design trade-offs that can help reduce the costs associated with solar water heating (SWH) systems, and (2) perform materials testing to demonstrate whether such candidate polymers will meet the durability requirements for real systems. This task complements and supports the Low-Cost Systems Development/Low-Cost Polymers activities. Materials are evaluated and recommended to private sector partners for use with their prototype systems. We also test materials that are of interest to the project's subcontractors.

2. Technical Approach

The primary property of interest for candidate polymeric materials is the ability to avoid optical and mechanical degradation (yellowing and embrittlement) during exposure to temperature and UV light. A number of candidate glazing constructions have been subjected to photothermal weathering using three complementary forms of exposure. These include outdoors, in an Atlas Ci5000 accelerated weathering chamber, and at NREL's unique UV-concentrator facility.

To assess the photothermal stability of candidate polymeric absorber materials, mechanical properties (tensile modulus and strength, and percent strain at break) were measured as a function of time of Ci5000 exposure to UV light at 60°C.

3. Results and Accomplishments

The major results and accomplishments of the project during FY 2005 include the following:

- New glazing samples were provided by major polymer manufacturers and are under test. (09/05)
- UV resistance of candidate absorber materials was quantified in terms of loss in percent strain at break as a function of UV weathering. (09/05)

3.1 Glazing Materials

Based on accelerated screening tests, we have found that fluoropolymers and acrylic are UV weatherable, and all other polymeric glazing materials tested lose transmittance and yellow. However, fluoropolymers are relatively expensive and realistically would be limited to use as thin-film glazings. Acrylic tends to be too brittle and exhibits thermal sag, which is a concern for a glazing candidate for solar collector applications. We have also found that polycarbonate (PC) laminated to an acrylic UV-screening film (Korad®, a product of Polymer Extruded Products) can also be UV weatherable. The most promising construction uses a UV-screening film that is adhesively laminated to a PC sheet. Without the additional UV-screening layer, PC products exhibit 3%–5% loss in solar-weighted hemispherical transmittance after about 2–3 years' equivalent exposure. In addition, severe visual yellowing (an aesthetic concern) occurs in the same timeframe. With the addition of a UV-screening film, significant loss in hemispherical transmittance does not begin until between 10–15 years' equivalent outdoor exposure at elevated operating temperatures.

Based on these results, we interacted with industrial vendors to obtain samples in which the UV screening film was thermally bonded to a PC sheet in a manner more representative of commercial manufacturing processes. These sheets were subsequently thermoformed into collector glazings, and samples of the final construction were subjected to accelerated testing. Glazing constructions in which the UV-screen is thermally bonded to the PC substrate exhibit yellowing much earlier than when adhesives are used. The high temperature of the extruded PC sheet during thermal bonding thins and severely degrades the UV screening layer, resulting in loss of transmittance.

Another concern has been whether mechanical degradation accompanies optical yellowing. During UV exposure, greater crosslinking can occur, which can result in increased stiffness, embrittlement, and consequent lower impact strength. We have used an ARES rheometer to perform dynamic mechanical analysis (DMA) of PC glazing samples. The effect of UV exposure is clearly evident (Fig. 1); 7502 h exposure in an Atlas XR-260 WeatherOmeter (providing 1.9 years equivalent outdoor exposure) results in an increased modulus, implying increased stiffness and consequent loss in impact strength. Measurements were made at a tortional frequency of 10 rad/s over a wide temperature range (–25° to 75°C).

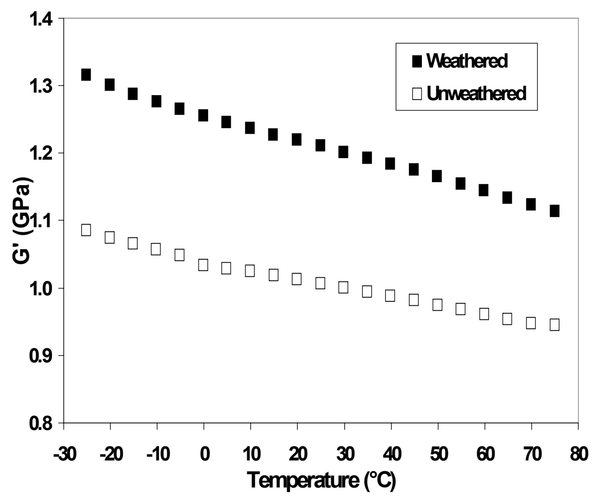

Fig. 1. Shear modulus as a function of temperature for accelerated weathered (1.9 years equivalent outdoor exposure) versus unweathered thermal-bonded Korad®/PC.

Further interactions have been held with material suppliers to identify several new types of samples that have the potential to preclude the thermal bonding problem. GE Plastics, a major supplier of PC sheet, is interacting with Polymer Extruded Products to provide thermally bonded Korad®/PC samples. The UV screening layer is thicker than previously used (0.08–0.15 mm versus 0.05 mm thick), and enhanced screening films (which provide twice as much UV absorption as previously tested) are incorporated into their laminate samples. PPG and Bayer have supplied samples in which UV-absorbing organic clear coats are applied to PC sheet. Such constructions are used in automotive headlamp applications. If a UV-screening film cannot be thermally bonded to PC sheet as it is extruded, and/or cannot avoid severe adverse thinning during thermoforming, then clear coats could be applied to thermoformed PC to avoid such damaging effects to the screening agent. Long-term testing and evaluation of these new material samples is under way.

3.2 Absorber Materials

Solar manufacturers have recently considered unglazed constructions in which the polymeric absorber is exposed to UV sunlight. Consequently, we have emphasized the effect of UV exposure on mechanical properties of polymer absorbers. One candidate material is metallocene-based multi-density polyethylene (MBMDPE). We have measured mechanical properties of this material as a function of exposure to UV light in our Ci5000 WeatherOmeter. The most sensitive parameter is percent strain at break. A threefold loss in percent strain at break is evident after exposure to a cumulative dose of UV irradiance equivalent to 4 years exposure in Miami, Florida (Fig. 2). As long as a reasonable residual strain at break is retained (i.e., does not drop to near zero), the absorber material is useable. For the length of time tested, MBMDPE seems suitable as an absorber material. Longer term testing and evaluation of MBMDPE is being continued.

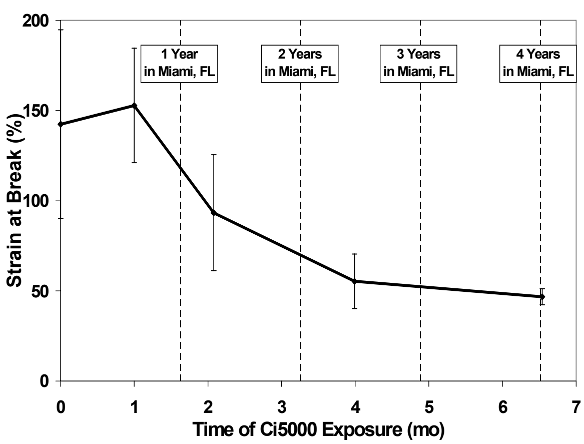

Fig. 2. Strain at break of MBMDPE as a function of Ci5000 exposure.

4. Planned FY 2006 Activities

The most significant activities planned for FY 2006 include:

- Testing UV stability of new candidate polymeric glazing constructions. (09/06)
- Measuring impact strength of candidate glazings and comparing with dynamic mechanical analysis results as a function of photothermal exposure. (09/06)
- Continuing long-term testing and evaluation of candidate polymeric absorber materials. (09/06)

5. Major FY 2005 Publications

B. Carlsson, K. Möller, S. Brunold, M. Heck, M. Köhl, M. Hall, A. Roos, M. Ghaleb, G. Jorgensen, B. Karlsson, M. Lopes Prates, M. Zinzi, "Assessment of Service Life of Some Passive Solar Thermal Materials," *CEEES 2nd European Weathering Symposium EWS, 24th Colloquium of Danubian Countries on Natural and Artificial Ageing of Polymers, Gothenburg, Sweden, June 15-17, 2005*.

B. Carlsson, S. Brunold, A. Gombert, M. Heck, M. Köhl, V. Kübler, O. Holk, G. Jorgensen, B. Karlsson, M. L. Prate, K.Möller, M. Brogren, A. Roos, A. Werner, M. Zinzi, and M. Ghaleb, "Study on Durability and Service Lifetime Prediction of some Static Solar Energy Materials," *10th International Conference on Durability of Building Materials and Components, Lyon, France, 17-20 April 2005.*

M. Köhl, G. Jorgensen, S. Brunold, B. Carlsson, M. Heck, and K. Möller, "Lifetime Estimation of Polymeric Glazing Materials for Solar Applications," *10th International Conference on Durability of Building Materials and Components, Lyon, France, 17-20 April 2005.*

A. Gombert, M. Heck, V. Kübler, M. Köhl, B. Carlsson, K. Möller, S. Brunold , B. Chevalier, M. Zinzi, G. Jorgensen, "Results of Durability Testing of Antireflective Glazing," *10th International Conference on Durability of Building Materials and Components, Lyon, France, 17-20 April 2005.*

Industry Manufacturing Assistance

Performing Organization: Sandia National Laboratories (SNL)

Key Technical Contact: Greg Kolb, 505-844-1887, gjkolb@sandia.gov

DOE HQ Technology Manager: Glen Strahs, 202-586-2305, glenn.strahs@ee.doe.gov

FY 2005 Budget: $200K (FY 2005) + 138K (FY 2004 Carryover) = $338K

Objectives

- Help solar thermal manufacturers improve their products.
- Help solar technology users design their systems to achieve maximum cost effectiveness.

Accomplishments

- Developed a project that will deploy and test a "freeze-protected" roof-integrated collector in a Building America home in FY 2006.
- Developed and tested a thermochromatic film to prevent overheat failure of the polymer collector.
- Salt River Project and SNL completed a techno-economic analysis of solar-powered heating, ventilating, and air-conditioning systems.
- SNL helped the City of Tucson develop a third-party-financed project that will heat five large municipal pools.
- Developed a Web site that will help other municipalities develop third-party-financed solar pool projects.
- Provided technical assistance to the Solar Rating and Certification Corporation (SRCC) and several other solar users and manufacturers.

Future Directions

- Continue to work with Building America and Artistic Homes to deploy and test a "freeze-protected" roof-integrated system.
- Help the manufacturer of a "non-freeze protected" roof-integrated thermosiphon solve technical problems that have precluded SRCC certification.
- Provide technical assistance to SRCC.
- Help solar industry and city officials integrate solar heating into new projects (TBD).
- Help solar industry resolve manufacturing issues (TBD).

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1. Introduction

Sandia National Laboratories (SNL) provides technical assistance to the solar thermal industry. Through its Industry Assistance Program, SNL follows a Systems-Driven Approach to help manufacturers improve their products. In addition, the program helps potential technology users design their systems to achieve maximum cost effectiveness. This assistance is often highly leveraged with funding from the U.S. Department of Defense (DoD) and the utility industry.

2. Technical Approach

Solar thermal technology users and manufacturers make a formal request to SNL for technical assistance. Guidelines for making this request are described on the program Web site (www.sandia.gov/Renewable_Energy/solarthermal/Center/index2.htm). Assistance is given on a "first come, first served basis" to government agencies and to the private sector. Proposed project activities must not compete with those offered in private industry.

3. Results and Accomplishments

During FY 2005, more than ten technical assistance projects were performed. The top four are discussed in sections 3.1 to 3.4. The remaining activities are summarized in section 3.5.

3.1 Developing a freeze-protected roof-integrated collector project

Roof integration is popular with both builders and architects, as shown in various studies and focus groups. Roof integration solves many objections for adopting solar hot water systems that have been raised in the past by builders. The advantages of roof integration include much improved aesthetics, a reduction in the number of roof penetrations, and the ability to replace/repair a roof without removing the solar collectors. In FY 2005, SNL worked with the Building Science Corporation to develop a project to demonstrate a roof-integrated design that is capable of operating in a freezing climate.

A test will be conducted in FY 2006 on a Building-America high-efficiency home (by Artistic Homes) in Albuquerque, New Mexico. This system will be flashed into the roof instead of on top of the roof, which has been the tradition for the past 30 years. SNL engineers will monitor the total energy from the system and record the reactions from the builder, homeowner, and potential buyers. A system price goal of $2,000 has been set, given a production scenario of several hundred per year. If this price can be achieved, the system will be cost effective for sunny locations in which natural gas is >$1/therm; the system can be included in the home mortgage and be paid off by the resultant energy savings.

Achieving the $2,000 cost goal for a freeze-protected system is challenging. Non-freeze protected systems have recently been installed in Florida for less than this cost, but additional equipment needs to be added to freeze-protect a system. SNL initially proposed a passive method to Building America using a passive thermosiphon technique. The design was almost as simple as a non-freeze system. To make it work, the system needed to be installed in an unvented attic with insulation on the roof plane; this is a high-efficiency construction technique promoted by Building America. However, after much discussion and analysis, it was determined that roof-plane insulation is too expensive when applied in freezing climates. Thus, a more conventional drainback method is now being used for freeze protection.

If the demo is successful and predicted costs are reasonable, Artistic Homes could offer solar hot water as an appliance option to homebuyers. Because there is no intellectual property involved, the project with Artistic will be documented and other U.S. homebuilders will be given this information. S.N.L. and Building America will help additional builders integrate solar into their production homes. Current drainback systems cost about $3,000. However, analysis by NREL indicates that several cost-reduction opportunities exist that can drop the cost to less than $2,000. One opportunity is to replace the separate drainback tank, heat exchanger, and pressurized solar storage tank with a single unpressurized combination drainback/storage tank. Our demo will incorporate this feature. NREL estimates that a 25% cost reduction is possible with no change in performance.

3.2 Helping City Officials and DoD Integrate Solar into New Projects

Commercial-scale solar heating projects can cost from $100,000 to $1 million or more, depending on the amount of heat required. Large-scale solar projects that look economically attractive on a life-cycle basis remain difficult to sell to commercial and government entities because of the perceived financial and maintenance risk; if the system does not perform or rapidly degrades over time, the buyer may need to pay for unexpected maintenance or may decide to abandon the system. Large purchases can also be difficult because of lack of capital funds. For example, DoD wants solar on more than 500 military bases, but they only have a very small amount of capital that can be used to purchase solar energy equipment. These problems can be eliminated if solar energy users purchase solar energy rather than solar systems. In this arrangement, an Independent Energy Producer (IEP) owns, operates, and maintains the system and sells the energy to the user via long-term contract. The IEP takes all financial/maintenance risk and is also responsible for securing capital.

Only a handful of U.S. solar projects have been developed and financed in this way. SNL hopes to greatly expand the number of these types of projects by helping city governments and DoD develop demonstration projects that can be replicated elsewhere. For example, in FY 2005 SNL assisted the City of Tucson in developing and releasing a solicitation for a private company to build, own, and operate solar pool-heating systems for all five city pools in Tucson, plus one new pool to be built next year.

Large pool projects are a good first application of the IEP business model because economics are generally favorable and because pools consume a large amount of energy (e.g., a typical indoor Olympic-size pool consumes as much natural gas as is used for water heating within ~600 homes annually). To help other municipalities replicate the Tucson model, SNL developed a Web site devoted to the IEP solar pool project.

SNL also investigated how U.S. military bases might best implement solar IEP projects. They found one called Enhanced Use Leasing (EUL). EUL allows the government to lease its land to a private party that in turn builds a project or system that provides benefits to on-base personnel. EUL has been in existence for many years and is used extensively in the military. However, it has not been applied to energy projects, even though such leasing is specially noted as being allowable. Personnel from the Marine Corps (MC) Base in Barstow have indicated their willingness to move forward with the idea, and it appears that megawatt-scale solar projects are possible. Discussions with the Marine Corps/Yuma and Kirtland Air Force Base/Albuquerque were begun at the end of FY 2005.

3.3 Preventing Overheat Failure of Polymer Collectors

Polymer solar water heating (SWH) collectors are currently being developed by an industry group led by NREL. The advantage of polymers is their very low cost. However, the cost advantage can only be fully realized if the lifetime approaches that of competing metal collectors. Excessive operating temperatures can rapidly degrade the polymers. Of primary concern is overheating of the absorber during dry stagnation conditions. Dry stagnation is unlikely, but could occur following a collector leak or if the collector was not refilled in the morning after being drained the previous night. SNL has developed a protective gel that should protect the collector from overheat failure. Applied to the underside of the collector glazing or on the absorber, the thermochromatic gel (a mix of polystyrene and polyvinylmethyl ether) “shuts off the sun” by changing from clear to opaque at a glazing temperature of 80^{o}C. (This temperature was selected because heat transfer calculations indicate the absorber will be ~125^{o}C when the glazing is 80^{o}C; if the absorber exceeds 125^{o}C, rapid degradation will occur.)

In FY 2005 laboratory testing indicates that the thermochromatic gel is stable within a UV environment and is capable of protecting a polymer collector from overheat failure. However, the cost of gel is currently too expensive (~\$100/m^2). The reason is because a specialty polymer (polyvinylmethylether or PVME) is needed and there is currently only a small market for it. In order for the thermochromatic gel to be economically viable method of protecting the polymer collector, the cost of the PVME must be similar to a commodity polymer.

3.4 Analysis of Commercial-Scale Solar HVAC Systems

Combined solar cooling and heating technology (solar HVAC) is immature; only a few commercial applications exist in the world. The systems are more complex and costly than conventional hot water systems, which makes the economics even more difficult. Nevertheless, manufacturers of solar HVAC are attempting to enter the marketplace in Arizona, and the utility commission has tentatively approved the installation of four demonstration projects. In particular, 60-to-100-ton projects have been proposed for a public school and senior center to be located in the Salt River Project (SRP) service territory. SRP asked SNL to help them perform a study to evaluate the performance and economics of hypothetical solar HVAC systems that could be installed at the school and senior center. The study was performed to help SRP understand the market potential for solar HVAC within its service territory.

The study compared the energy and economic performance of HVAC systems powered by commercial-scale flat plate, evacuated tube, and parabolic trough systems. SNL modeled the performance of the solar systems and SRP modeled the absorption-chiller subsystems, as well as the building loads. Significant improvements in collector and absorption chiller technologies have occurred in recent years, so it is appropriate to evaluate the current state of the art.

The historical technical barriers for solar HVAC have been low efficiency (i.e., coefficient of performance or COP ~0.7), high maintenance, and poor reliability. Using today’s technology, it appears that maintenance and reliability problems have been generally solved. However, solar COPs (0.7 to 1.25) are significantly below state-of-the-art conventional HVACs (COP >4). Thus, to be economically competitive using today’s solar HVAC technology, the price of conventional electricity and/or natural gas that is offset by solar HVAC must be relatively high.

Based on the results of the SRP study, commercial-scale solar HVAC has a long payback time (~19 years) in markets with relatively cheap electricity and gas (8¢/kWh and $1/therm in SRP territory). Additional analysis of the SRP results suggests that electricity cost must be ~20¢/kWh and gas $1.5/therm to obtain a payback of less than 10 years, relative to a state-of-the-art conventional chiller. Because Hawaii has very high energy costs, good sun, and a 12-month cooling load, commercialization of today's technology may be possible there. The results of the SRP study will be released to solar HVAC suppliers.

3.5 Other Industry Assistance Activities

- Measured optical properties of Heliodyne solar collectors.
- Analyzed valve failures in SWH systems of interest to Maui Electric Company.
- Provided assistance to SRCC. Served on standards committee, advised on SWH system reliability, and developed an SWH inspector training video.
- Consulted on solar heating projects with Quest E Group, Santa Fe Indian Hospital, University of New Mexico, Sandia Labs, Drum Hadley, and Arizona Public Service.

4. Planned FY 2006 Activities

- Deploy and begin testing a freeze-protected roof-integrated solar hot water collector on a Building America high-efficiency home. (3/06)
- Solve the technical problems that have precluded SRCC certification for the "non-freeze-protected" roof-integrated thermosiphon solar hot water system and resubmit the RITH to SRCC for certification. (12/05)
- Help users of solar thermal implement large solar thermal projects. TBD. (9/06)
- Help manufacturers improve the quality of their products. TBD. (9/06)

5. Major FY 2005 Publications

SRP Solar Thermal HVAC Feasibility Study, prepared for Salt River Project by DMJM Technology, draft report, April 2005.

Sandia National Laboratories letter report from Benjamin Ash to Greg Kolb, subject: Summary of Work on Thermochromatic Polymer Gel for Solar Collector Overheat Protection, August 1, 2005.

6. University and Industry Partners

The following organizations received subcontracts during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share
Building Science Corporation Mark Sevier	Westford, MA mark@buildingscience.com	"Freeze-protected" roof-integrated solar hot water project for Building America	11	11
Greater Tucson Coalition Valerie Rauluk	Tucson, AZ vajra@vecat-inc.com	Develop solar pools Web site	18	5
Venture Catalyst, Inc. Donald Speer	San Diego, CA info@vcat.com	Web site support	5	0
Florida Solar Energy Center Jim Huggins	Cocoa, FL huggins@fsec.ucf.edu	Develop solar hot water system inspector training video	18	10

Hybrid Solar Lighting

Performing Organization: Oak Ridge National Laboratory (ORNL)

Key Technical Contact: Melissa Lapsa, 865-576-8620, lapsamv@ornl.gov

DOE HQ Technology Manager: Glenn Strahs, 202-586-2305, glenn.strahs@ee.doe.gov

FY 2005 Budget: $500K

Objectives

- Design, fabricate, and test a low-cost solar collector incorporating an acrylic primary mirror and a centralized optical fiber bundle.
- Communicate about hybrid solar lighting (HSL) technology and installation/monitoring of HSL systems at beta sites.

Accomplishments

- Completed enhancement of the system's tracker controller.
- Designed and fabricated casting pattern for the system's solar tracker central mounting hub.
- Measured optical performance of alternative PMMA (acrylic) optical fiber for use with HSL.
- Designed and fabricated 48-inch-diameter aluminum mold for use in thermoforming the system's acrylic primary mirror.
- Evaluated early models of a new segmented, plastic primary mirror design.
- Completed installation of HSL unit at the American Museum of Science and Energy.
- Installed HSL unit at the Sacramento Utility District's (SMUD's) headquarters in Sacramento, California (50% complete).
- Worked with Sunlight, LLC, to arrange for 16 additional beta tests to be installed in 2006.

Future Directions

- Third-party market assessment of HSL.
- Deploying two best-test systems at ORNL and one each in Texas and California.
- Development of real-time monitoring hardware.
- R&D on enlarged, segmented mirror and self-calibrating tracker
- Reporting on benefits associated with "Sunlight Inside Initiative" beta sites.
- Improving the total system performance and reducing system cost from $24K to less than $12K.

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1. Introduction

In the United States, artificial lighting represents the single largest component of electricity use in commercial buildings, costing building owners nearly $17 billion a year. Despite the high energy consumption and the continued demand by occupants for more natural lighting, natural lighting from conventional options, such as skylights and windows, illuminates only a tiny fraction of the available commercial space. This limited use of natural lighting is a result of the architectural limitations of skylights and windows and the uncontrollable nature of the sunlight itself (e.g., it fluctuates in intensity and can be highly directional, producing glare and unwanted heating). A significant market exists for a natural lighting product that can offer the benefits of natural lighting with all of the conveniences and control of an artificial lighting system.

Hybrid solar lighting (HSL) technology meets this previously unmet need and has the potential to provide a product with an economic payback of three to four years for commercial buildings in the Sunbelt regions of the world. In the U.S. Sunbelt alone, there exists 20 billion square feet of commercial space that meets the requirements for implementation of an HSL system. Each year, this amount of applicable space grows by 600 million square feet of new construction.

Commercialization of HSL technology will initially focus on a small subset of retailers representing jewelry, furniture, and apparel markets. This niche market of early adopters is expected to increase sales volumes of HSL technology, permitting cost reductions through economies of scale. With system price reductions, greater market penetration into this niche market and the larger commercial building market (including office buildings) is anticipated. Full-spectrum solar energy systems, such as HSL, provide a new and realistic opportunity for wide-ranging energy, environmental, and economic benefits. Their development is directly inline with the mission of the DOE Solar Program 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.

Advantages of HSL include:

- Small and minimal roof penetrations, reducing the potential for leaks.
- Infrared and ultraviolet energy in sunlight is separated from the visible light, rather than being transmitted into buildings. Heating, ventilation, and air-conditioning (HVAC) loads are thus reduced by 5% to 10% compared to electric lighting systems.
- Ready adaptability to commercial buildings with multiple floors, relatively low ceiling heights, and interior walls. A single system can distribute enough sunlight to co-illuminate several rooms in a typical office building.
- No need for large portions of precious plenum space—the area between the roof and drop ceiling—so there is little competition with other building services, such as HVAC ducts, sprinkler systems, and electrical conduits.
- Versatility of use for both direct, ambient lighting (as in skylights) and for indirect, task, and accent lighting applications.
- Easily incorporated into existing building designs (for retrofit markets), and the optical fibers can be rerouted to different locations as lighting needs change. By intentionally misaligning the solar collector from the sun, occupants can even dim or curtail distributed sunlight.

2. Technical Approach

Research in HSL technology for FY 2005 was aimed at significant cost reduction and manufacturability potential while maintaining the high performance level of the systems. This was achieved through the successful fabrication of an acrylic primary mirror and through the testing of redesigned and simplified controller and tracking mechanisms. A third-party market potential analysis was planned to gauge the commercial market size and characteristics. The benefits of the HSL activity are prioritized as (1) light quality, (2) reduction of waste heat compared to other lighting systems, and (3) fossil energy conserved by using solar energy for lighting applications. The first HSL market will likely be on the uppermost two floors of commercial buildings having the following characteristics: (1) located in the Sun Belt and in areas where daytime electricity prices are highest, (2) occupied every day, including weekends, and (3) in lighting applications where lighting quality (or color rendering) is important and less-efficient electric lamps are currently used.

Task Title	FY 2005 Budget ($K)
Conduct R&D for tracker controller enhancements	250
Advance R&D on low-cost fiber bundles	50
Finalize fabrication of new hybrid solar acrylic mirrors	100
Develop and deploy two cost-shared new pre-commercial hybrid solar lighting systems for 1-year field trial program across the United States	100

3. Results and Accomplishments

To date, a fabrication technique has been identified for manufacturing an acrylic mirror that meets the tolerances and requirements of an HSL solar collector. A 48-inch-diameter parabolic acrylic mirror is being fabricated by Bennett Mirrors of New Zealand. Early efforts appear promising, with the surface quality of the mirror rivaling that of its glass counterpart. The estimated cost of the new mirror is less than $300 (compared to $3,500 for the glass mirror) and weighs only 9 pounds (compared to 50 pounds for the glass mirror). Completion of a prototype mirror is expected in early FY 2006.

The development of a reduced-cost tracker mechanism for the HSL solar collector was begun in FY 2004. An initial "manufacturability" analysis was completed by Protomet Corp. and design modifications were suggested. The use of a high-precision linear actuator in combination with a gear-train drive unit was recommended for reducing cost while still providing high tracking accuracy. From this analysis, the tracker cost has been reduced from $25,000 to less than $8,000. Detailed modeling and final drawings have been completed and fabrication and testing of the new solar tracking unit is expected in early FY 2006.

On August 30, 2005, a dedication of the first system demonstration installation, co-sponsored by the Tennessee Valley Authority (TVA), was held at the American Museum of Science and Energy in Oak Ridge, Tennessee (Fig. 1). Glenn Strahs of the DOE Solar Program and Bill Baxter, Chairman of TVA, were among the invited speakers. There has also been a lot of press on the hybrid solar lighting system this year (see list at end of report).

Fig. 1. Dedicating the installation of the HSL unit at the American Museum of Science and Energy in Oak Ridge, Tennessee

Accomplishments:

- Completed enhancement of the system's tracker controller to utilize Global Positioning System (GPS) and time stamp information. Modified controller circuit board to accept sensor inputs for future implementation of a self-calibration technique. (09/05)
- Designed and fabricated casting pattern for the system's solar tracker central mounting hub. Casting reduced tracker weight by 20 pounds and reduced overall system fabrication costs. (07/05)
- Measured optical performance of alternative PMMA (acrylic) optical fiber for use with HSL. Early tests demonstrated equivalent optical performance to previous PMMA fibers, but at half the cost. (09/05)
- Designed and fabricated 48-inch-diameter aluminum mold for use in thermoforming the system's acrylic primary mirror. Resulting mirrors to be tested in the first quarter of FY 2006. (09/05)
- Evaluated early models of a new segmented, plastic primary mirror design. Modeled effects of wind loading and thermal expansion on mirror performance. (09/05)
- Completed installation of HSL unit at the American Museum of Science and Energy (Fig. 2). (08/05).
- Installed HSL unit at SMUD headquarters in Sacramento, California (50% complete). (09/05)
- Worked with Sunlight, LLC, to arrange for 16 additional best tests to be installed in 2006. (09/05)

Fig. 2. Newly installed HSL unit at the American Museum of Science and Energy in Oak Ridge, Tennessee

4. Planned FY 2006 Activities

The greatest technical challenges/barriers remaining for the HSL project are: (1) the reliability and installed cost of the 2-axis tracking mechanism and control electronics, (2) the high optical absorption and costs associate with the system's plastic fiber optic bundles, and (3) demonstration and quantification of waste heat avoidance from HSL vis-à-vis fluorescent or incandescent illumination. Great progress has been made in improving the reliability and cost of the HSL tracking mechanism and control electronics in recent years. However, smarter controls (that utilize feedback sensors and self-learning algorithms) and improved mechanical designs combined with extensive field testing of the HSL tracker are needed to continually improve the system's reliability and lifetime.

The goal is to achieve an HSL system with a lifetime of 20 years with reliable performance and self-correcting alignment capabilities under harsh environmental conditions. Tracking system costs will be reduced from $8,000 to $3,000, and installation costs will be reduced from $12,000 to $3,000. In addition, a less expensive plastic optical fiber bundle with improved optical performance is critical to the success of the HSL project. Currently, the HSL technology distributes sunlight via a 30-foot plastic optical fiber bundle. Significantly increasing the length of the bundle results in undesirable reductions in delivered light and can result in noticeable changes to the lighting color. In addition, the cost of this 30-foot bundle is currently $3,500.

To reduce the overall cost of the HSL system, a bundle target cost of $1,000 should be achievable through improvements to the bundle fabrication process and use of an improved PMMA purification technique. The improved bundle fabrication process and PMMA purification techniques result in lower optical absorption by the optical fibers, allowing for greater bundle lengths that better maintain the intensity and color of the delivered sunlight. To address the above technical issues and to conduct our market assessment, a budget of $750 K is requested for FY 2006.

FY 2006 Milestones:

- Third-party market assessment of hybrid solar lighting.
- Deploy two beta-test units in Texas and California.
- Deploy two beta-test units at ORNL for R&D and continued test and evaluation.
- Develop real-time monitoring hardware for Sunlight Inside Initiative beta sites.
- Report on benefits associated with 2005 Sunlight Inside Initiative describing energy savings and user feedback.
- Conduct R&D on enlarged, segmented, plastic mirror design with study of mirror wind loading and evaluation of low-cost aluminum-on-acrylic mirror coating technique.
- Conduct R&D to develop, test, and implement self-calibrating tracker controller algorithm.

5. Major FY 2005 Publications

Technical Seminars on HSL given at:

- LightFair 2005, New York, April 2005
- 2005 Solar World Congress, Florida, August 2005.

Press Coverage:

- Solar Reception, *Satellite Technology*, September 2005.
- BioReactor applications featured in *Scientific American*, September 2005.
- HSL featured in the *Popular Science* What's New Section, June 2005.
- Discovery Channel Canada story, April 2005.
- MSNBC article on Hybrid Solar Lighting: “Bringing a Little Sunshine into Our Lives,” March 2005.

Report:

C. Maxey (ORNL), T. Fisher, (Agri-Grow Technologies, Inc.), and R. Anderson (University of Kentucky), “Final report for lighting design support of novel Agri-Grow fruit production facilities.” February 2005.

6. University and Industry Partners

The following organizations partnered in the project’s research activities during FY 2005 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
University of Tennessee Rao V. Arimilli	Knoxville, TN arimilli@utk.edu	Research was conducted by a graduate student and professor on a segmented acrylic mirror design.	50
Protomet Corp. Jeff Bohanon	Oak Ridge, TN jb@protomet.com	Redesigned and produced solar collectors.	114
Milan Machining Mark Pecharich	Cicero, IL rfqmilans@milansmaching.com	Produced mold for parabolic acrylic mirror.	15
Bennett Mirrors Alastair Bennett	Tauranga, New Zealand alastair@bennettmirror.com	Produced acrylic mirrors.	15

Systems Integration and Coordination

The National Center for Photovoltaics (NCPV), headquartered at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, provides overall coordination of the PV Subprogram at the request of DOE. NREL and Sandia National Laboratories (SNL) in Albuquerque, New Mexico, are partners in the NCPV, and provide the management oversight for the respective projects in their laboratories, as well as management support for the NCPV. The Concentrating Solar Power (CSP) Subprogram is managed collaboratively between SNL and NREL in the virtual entity referred to as Sun♦Lab. NREL, SNL, and Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, jointly participate in managing the Solar Heating and Lighting Subprogram.

Management activities include analysis, administration, budget control, reporting, and integration of programs, including oversight of staff, equipment, and facilities at NREL, SNL, and ORNL. The management team develops inputs for new program initiatives, conducts review meetings at the request of DOE, and provides oversight for communications, outreach, and cross-cutting analysis activities. The team also provides leadership and support for various Solar Program activities, such as development of the *DOE Solar Program Multi-Year Program Plan* (MYPP) and the Systems-Driven Approach to program management.

Some significant accomplishments in FY 2005 are listed below.

Systems-Driven Approach

- Provided analytical support to the Government Performance and Results Act process for the Solar Program.
- Continued extensive collection and detailed evaluation of performance and life-cycle cost data at the system and component level for residential, commercial, and utility-scale PV systems.

Communications and Outreach

- Developed and distributed critical program documents (e.g., *Solar Program Review Meeting Proceedings, PV Industry Roadmap*, MYPP draft plan) to key stakeholders.
- Represented the interests of the Solar Program at strategic events (technical conferences, meetings, workshops, community events).

International Activities

- Developed the *Solar International Activities: Strategic Plan* to identify new directions and develop a strategic framework to be evaluated against Solar Program metrics, thus bringing the greatest value and benefits to the overall program.

Capital Equipment and Facilities

- Developed the integrated hardware standards for future tools used in the new Science and Technology Facility. This includes maximum substrate size, substrate platen dimensions, a docking interface for equipment, and inter-tool transport mechanisms.
- Designed and awarded contracts for a cluster tool to support crystalline silicon research and a stand-alone tool for transparent conducting oxide development.

Program Management

- Met two EERE Joule milestones in FY 2005: 13.7%-efficient crystalline silicon and 11%-efficient thin-film module, made by U.S. manufacturers in commercial production.
- Organized the FY 2005 Solar Program Review Meeting and helped organize and develop a DOE Peer Review of the Solar Program (both held November 2005).

Systems-Driven Approach

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL)
Key Technical Contacts:	Joe Tillerson (SNL on detail to DOE, Primary Contact), 202-586-1495, Joe.Tillerson@ee.doe.gov Chris Cameron (SNL), Paul Gilman (NREL), Charles Hanley (SNL), Robert Margolis (NREL), Mark Mehos (NREL), David Mooney (NREL)
DOE HQ Technology Manager:	Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov
FY 2005 Budgets:	$990K (NREL), $410K (SNL)

Objectives

- To develop and apply a market-driven, validated, user-friendly, analytical framework for determining research priorities within the DOE Solar Program, including the following:
    - **Analysis** – To improve the analytical basis for understanding the system and policy drivers of solar technologies in various markets.
    - **Benchmarking** – To benchmark current system, component, and subcomponent performance and the cost to provide validated input to the Systems-Driven Approach (SDA) model and to validate SDA model output.
    - **Modeling** – To develop a user-friendly solar energy systems model that will allow program managers and others users to investigate the impact of variations in physical, cost, and financial parameters to inform R&D and design decisions.

Accomplishments

- **Analysis**
    - Provided analytical support to the Government Performance and Results Act (GPRA) process for the DOE Solar Program.
    - Completed detailed analyses of the levelized cost of energy (LCOE) of PV reference systems using Solar Advisor Model (SAM).
    - Established potential impact of Technology Improvement Opportunities (TIO) on reducing LCOE for PV reference systems.
    - Assessed sensitivity of LCOE to variability of selected parameters.
- **Benchmarking**
    - Continued extensive collection and detailed evaluation of performance and life-cycle cost data at the system and component level for residential, commercial, and utility-scale PV systems.
    - Benchmarked residential, commercial/utility, and an off-grid island system with extensive partnering with industry participants
    - Defined reference systems and their parameters as input to SDA models and the *DOE Solar Program Multi-Year Program Plan.*
- **Modeling**
    - Added single-point efficiency model with temperature correction (previously King performance model only).
    - Enabled linkage of advisor model inputs to detailed user-defined cost and performance spreadsheet models.
    - Extended finance model to include commercial and utility-scale financing (previously cash or residential home mortgage).
    - Developed concentrating solar power (CSP) and solar domestic hot water (SDHW) models and integrated them into SAM interface (needs validation).

- Currently updating parametric capability to allow additional parameterization of non-numerical values (e.g., single case comparison of multiple modules types operating under multiple climate conditions using tracking or no-tracking configurations).

Future Directions

- **Analysis**
  - Continue work on analysis of long-term benefits of solar.
  - Complete review of out-year cost and performance targets.
- **Benchmarking**
  - Continue to benchmark all solar technologies, with this year's emphasis on broadening the technology base to include thin-film technologies on a statistically significant basis.
  - Quantify non-hardware costs of PV installations and establish related cost-reduction targets.
- **Modeling**
  - Continue detailed evaluations of TIO and technology impacts on reducing system costs as direct input to PV portfolio balancing and stage-gate criteria definition.
  - Evaluate beta version of multi-technology model (CSP and SDHW models).
  - Begin external review and validation of model.
  - Add risk and uncertainty analysis capabilities.

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1. Introduction

The DOE Solar Program began the formulation of a Systems-Driven Approach (SDA) to R&D portfolio management and prioritization with a workshop held in December 2002. The *DOE Solar Program Multi-Year Program Plan* (MYPP) states that "we have implemented the use of our Systems-Driven Approach to guide us through difficult programmatic options and to make sound decisions considering limited resources." The SDA provides a framework for program planning that supports this objective. Under the tasks described below, data and tools are being developed and applied to support the use of SDA in decision-making by program management. The SDA team works closely with other projects, especially the PV Systems Analysis project.

2. Technical Approach

The SDA is the basis for the multi-step planning process used in the Solar Program for portfolio decision-making. The SDA allows us to assure that all technical targets for R&D on the components and systems funded through the Solar Program are derived from a common market perspective and national goals, and the resultant technologies are tested and validated in the context of established criteria for each market. The key steps in the decision-making process are:

- Identifying technology improvement opportunities and analyzing impact on LCOE
- Assessing research activity contributions to technology improvement
- Developing a multi-year research portfolio
- Assessing progress.

Analysis, Benchmarking, and Modeling activities are the three primary components of the SDA efforts. In FY 2005, activities focused primarily on new PV modeling capabilities and associated applications directly in support of the development of the MYPP.

Task Title	FY 2005 Budget ($K)
Analysis	430
Benchmarking	410
Modeling	560

2.1 Analysis

Analysis is used to establish a sound basis for understanding the system and policy drivers of solar technologies in various markets. Results from analysis activities are linked to the broader SDA process and provide a market context for the benchmarking and modeling efforts.

We are developing long-term market-penetration projections for solar technologies by examining both 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 program's economic and environmental benefits. Existing models, such as MARKAL and the Energy Information Administration (EIA) National Energy Modeling System (NEMS), are used to carry out analysis, and feedback is provided on how to improve the representation of solar technologies in these models. New models, such as the Solar Deployment Systems (SolarDS) model, are also being developed. This model analyzes the market penetration of PV on buildings in the United States under different policies and rate structures.

We are also reviewing the feasibility of achieving the program's technical and economic targets. This task examines proposed research goals given technical, funding, and other constraints. Here, our emphasis is on reviewing the existing literature on cost and performance projections, drawing on experts from both within and outside the solar community to review detailed technology cost models, and grounding the program's targets in real-world experience. In addition, value analyses are completed in which we evaluate policies, as well as other factors, that impact the value of solar energy technologies in various markets.

In carrying out these tasks, we utilize resources at NREL and SNL, as well as subcontracts (as described below in section 6)

2.2 Benchmarking

Benchmark data provide validated input to the SDA models and are used to validate model output. Data collection spans all elements of life-cycle cost, including component and system performance, as well as cost of components, system design, installation, permitting, operation and maintenance, financing, and so forth. Analysis of the data provides the basis for cost and performance models.

This has been a team effort, involving the incorporation of data that have been collected by program personnel and partners over the last two years. The approach to gathering and assessing the needed benchmarking data for PV systems is deeply founded on the basis of strong partnerships with providers and users of the fielded systems, as shown in Table 1. This list is growing as additional parties join the effort. Currently, this work is done cooperatively, without significant subcontract funds. However, the Southeast and Southwest Regional Experiment Stations are supported, as documented as a separate project. Over the course of the last year, the focus has been to develop parameters as input to SDA-modeling efforts, and more recently has morphed into input to the latest *Multi-Year Program Plan*. This work has focused on U.S. markets, but will expand to include international markets in the future.

National Center for Photovoltaics (NCPV) program personnel made the decision to focus on specific PV market sectors where technical improvements are likely to have the greatest impact. These are residential retrofit, commercial rooftop, utility-scale ground-mounted (both flat-plate and concentrating), and off-grid island systems. For each of these sectors, a "typical" PV system has been defined, and benchmarking data have been normalized to determine "typical" parameters for such a system. This means that, from the potentially wide range of values for several parameters, a midrange value was selected to represent this typical system.

Table 1. Partners and Other Sources of PV Benchmarking Data

Residential
Florida (FSEC database)
Conservation Services Group
CA, NJ Web sites
Others
Commercial
CA, NJ Web sites
Conservation Services Group
CA Construction Authority
First Solar
Spire Chicago
Others
Utility
Tucson Electric Power
Arizona Public Service
Others
Off-Grid
Arizona Public Service
Navajo Tribal Utility Authority
Northwest, Verendrye Coops
Florida Solar Energy Center
Others

2.3 Modeling

The primary function of the 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. The model is intended for use by DOE and laboratory management and research staff in implementation of the SDA to program planning. The model may also be used by members of the solar industry to inform internal R&D direction and to estimate systems cost and performance.

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, which 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.

Subcontracted work, listed in Table 6, includes a graphical user interface expert, Software Design Works, which was retained to aid in the development of the interface. Steven Janzou and the University of Wisconsin were retained to assist in model code development.

3. Results and Accomplishments

3.1 Analysis

Improving our understanding of the long-term market potential for solar technologies is an important part of our analysis task. For example, SolarDS is being developed to examine sensitivity of PV market share to PV capital cost and performance, rate structures, competition with other DG technologies, tax and environmental policies, storage and load controls, and financing options and consumer choice

Reviewing the program's technical and economic targets and carrying out detailed value analysis of solar technologies are other impactive analysis activities. This year has seen quantification of how the value of solar energy to the end-user is influenced by rate structures, demand charges, and demand profile. In addition, best practices are being identified and documented for estimating benefits and cost of distributed PV technology. Information sharing is being enhanced through implementation of a Web-based clearinghouse on the value of distributed grid-tied PV, through incorporating best practices into a Web-based benefit-cost calculator, and through informing state-level policymaking groups.

3.2 Benchmarking

Major results, as input to SDA models and the *Multi-Year Program Plan*, are shown in Table 2.

Table 2. Key PV Benchmarking Parameters for Systems-Driven Approach Analyses

System Element	Units	Res.	Com	Util.	Off Grid Island
Size	kW	4	150	10M	1.2
Module Price	$/Wdc	4.00	3.50	3.30	4.00
Module eff.	%	13.5	13.5	13.5	13.5
Inverter Price	$/Wac	0.90	0.60	0.46	0.90
Inverter Size	kW	4	150	150	2.4
DC-AC eff.	%	90	92	92	90
Inverter Life	Years	5	10	10	5
Other BOS	$/Wdc	0.61	0.54	0.97	2.10
Install	$/Wdc	1.66	0.55	0.27	1.00
Other	$/Wdc	1.30	1.10	0.55	4.71
Installed Sys. Price	$/Wdc	8.47	6.29	5.55	12.71
Lifetime	Years	30	30	30	30
Degradation	%/Yr	1	1	1	1
O&M cost	% inst. price	0.5	0.45	0.15	3.6

3.3 Modeling

In the analyses specific to the MYPP, the model was populated with the 2005 benchmark parameters to calculate the 2005 reference LCOE. Sensitivity evaluations were made by changing one parameter at a time to the 2011 target, while leaving all others at the 2005 reference level. Overall impact was explored by changing all parameters to the 2011 targets.

Figure 1 shows an example of the results; this example is of the TIO systems analysis for residential PV systems. Similar analyses have been performed for systems in the other reference applications as well.

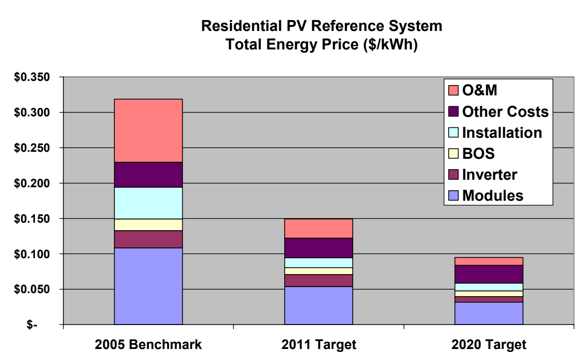

Fig. 1. Residential PV reference system total energy price ($/kWh) for current and future years.

“Other costs” include design and other engineering, site preparation, permitting and interconnection, inspection, and related costs. This part of the bar graph does not change much over time because this analysis assumes increased investment in systems engineering and integration, while the rest of the “other” category is reduced through resultant innovations. Thus, while “other” does not decrease much as a part of the cost, it leads to decreases across the rest of the system.

The main improvements that drive reductions in LCOE for these systems are: improvements in PV module cost and efficiency; reductions in installation costs through improved systems engineering; and improved inverter reliability and performance and associated reductions in operations and maintenance costs.

For utility-scale systems, LCOE can be reduced principally through improved modules and improved systems integration. For off-grid systems, the greatest potential for LCOE reduction exists with improved systems integration and inverter reliability, thereby decreasing O&M costs, and through the same module improvements as in the other systems.

Detailed evaluations of various module technologies have also been completed that show the relative costs of systems with the different types of modules (e.g., CIGS, CdTe, a-Si) and the principal opportunities for cost reductions.

4. Planned FY 2006 Activities

4.1 Analysis

During FY 2006, the analysis team will continue to work on improving our understanding of the long-term market potential for solar technologies and reviewing the program’s technical and economic targets, as follows:

- Better evaluation approaches of market penetration
- Assessments of impacts of CSP for electricity and hydrogen production
- Updates of analyses to assess progress toward program goals.

4.2 Benchmarking

Benchmarking in FY 2006 will continue, but its focus will shift to more specific gap evaluations and specific technology assessments, as follows:

- Update of baseline reference system data
- Improvement of installation cost, system-integration cost, and thin-film manufacturing cost data
- Benchmark data on CSP trough and dish deployments.

4.3 Modeling

The capability of the SDA model will be expanded and applied, as follows:

- Analytic approaches for troughs, dishes, and SDHW integrated within current models to assure consistency
- Addition of probability and risk considerations
- Application of SDA model supporting PV portfolio prioritization and stage-gate criteria definition
- Complete integration of parabolic trough and solar water heating.

5. Major FY 2005 Publications

U.S. Department of Energy, *Solar Energy Technologies Program: Multi-Year Program Plan 2007–2011*, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, DC, September, 2005 (Draft).

L. Moore et al., “Photovoltaic Power Plant Experience at Arizona Public Service; a 5-Year Assessment,” *Progress in Photovoltaics,* 2005.

R. Perez et al., “Solution to the Summer Blackouts? How Dispersed Solar Power-Generating Systems Can Help Prevent the Next Major Outage,” *Solar Today*, Vol. 19, No. 4, pp. 32-35, July/August 2005.

ASES/ISES 2005 Solar World Congress, Orlando, FL, Aug. 6–12, 2005:

N. Blair, M. Mehos, C. Christensen, S. Janzou, “Cost and Performance Solar Analysis Model for All Solar Technologies.”

K. Comer et al. “Characteristics and Feedback from Residential PV Early Adopters.”

T. Hoff, R. Perez, and R. Margolis. “Maximizing the Value of Customer-Sited PV Systems Using Storage and Controls.”

J. Levene et al. “Analysis of Hydrogen Production from Renewable Electricity Sources.”

L. Moore and H. Post, Sandia National Laboratories; R. Skinner, Northwest Rural Public Power District and R. Hauck,Verendrye Electric Cooperative, USA (ISEC/ASME), "Operation and Maintenance Field Experience with Photovoltaic Water Pumping Systems."

Wiese, Moore, Hanley, "Multi-Year Performance Assessment of Two PV Installation Clusters."

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
Conservation Services Group Steve Wiese	Austin, TX Steve.Wiese@csgrp.com	Collection and preliminary analysis of data related to over 80 PV installations, mostly in Massachusetts and Texas, using SNL's SolarDB as the basis.	20
Borrego Solar Ryan Burrowbridge	San Diego, CA ryan@borregosolar.com	Assist in the collection and analysis of benchmarking data from fielded PV systems.	5
Navigant Consulting, Inc. Lisa Frantzis	Burlington, MA Lfrantzis@navigantconuslting.com	A review of PV inverter technology cost and performance projections	55
SENTECH, Inc. Gerry Braun	Bethesda, MD gbraun12@comcast.net	Experience scaling up manufacturing of emerging photovoltaic technologies	30
Janzou Consulting Steve Janzou	Evergreen, CO steve@janzouconsulting.com	Provide coding support for advisor model development	125
University of Wisconsin Madison Sandy Klein	Madison, WI klein@engr.wisc.edu	Development of PV performance model, CSP power plant model, and support for TRNSYS/SAM integration.	47

Communications and Outreach

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL) DOE Golden Field Office (DOE/GO) National Energy Technology Laboratory (NETL)
Key Technical Contacts:	Don Gwinner (NREL), 303-384-6570, don_gwinner@nrel.gov Susannah Pedigo (NREL), 303-384-6624, susannah_pedigo@nrel.gov Connie Brooks (SNL), 505-844-4383, cjbrook@sandia.gov Glenn Doyle (DOE/GO), 303-275-4706, glenn.doyle@go.doe.gov
DOE HQ Technology Managers:	Robert Hassett, 202-586-8163, robert.hassett@ee.doe.gov Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov
FY 2005 Budgets:	$595K (NREL), $132K (SNL), $663K (DOE/GO and NETL)

Objectives

- Focus on innovative ways to reach critical audiences and improve business performance—get the right information to the right people at the right time in the right form.
- Unify the outreach efforts of the Solar Program so that communications and knowledge transfer emphasize all, rather than individual, solar technologies leading to understanding, collaboration, and partnership to advance solar energy technologies.
- Use communications products and activities to inform and persuade audiences, move them to action, and help overcome barriers for particular technologies and applications.

Accomplishments

- Developed and implemented public relations and communications strategies for the 2005 Solar Decathlon.
- Designed and developed the 50-Year Anniversary exhibit for the International Solar Energy Society (ISES), for debut at the Solar World Congress in Orlando, Florida.
- Assisted in completing the draft of the *2007–2011 DOE Solar Program Multi-Year Program Plan* (MYPP).
- Developed exhibits, determined key messaging, and staffed booths at various solar-related conferences: American Solar Energy Society Conference, International Builders' Show, Solar Power 2005, IEEE Photovoltaics Specialist Conference.
- Interacted with the buildings and consumer audiences (e.g., Solar Decathlon, International Builders' Show).
- Developed and distributed critical program documents (e.g., *Solar Program Review Meeting Proceedings, PV Industry Roadmap*, MYPP draft plan) to key stakeholders.
- Conducted a gap analysis of communications products and evaluated their effectiveness.
- Worked with our program management to streamline business processes.
- Developed and maintained content for all Solar Program Web sites that reflects research and program accomplishments. Activities included audience and statistics analysis to improve content on Solar Heating, with content and new navigation to "go live" in FY 2006.
- Published a new NREL Concentrating Solar Power (CSP) Web site, which describes the R&D work done by NREL as part of the CSP Subprogram.
- Represented the interests of the Solar Program at strategic events (technical conferences, meetings, workshops, community events).
- Worked with program management to streamline planning and budgeting processes to maximize our efforts in supporting solar energy research.
- Under a multi-year financial assistance award issued by the Golden Field Office in 2000, the North American Solar Challenge (solar car race) was successfully conducted. This event reached

a significant international media audience as the route took the racers from Austin, Texas, through six states and into Canada and through three provinces, ending in Calgary, Alberta.

- Under multi-year financial assistance awards issued by the Golden Field Office in FY 2004: (1) the 2005 National Solar Tour was successfully conducted, (2) the 2005 Solar Power Conference/Expo was successfully conducted concurrent with the 2005 Solar Decathlon, and (3) the National Solar Directory was developed and available at the 2005 Solar Decathlon.
- In August 2005, NETL issued a 5-year grant to the Interstate Renewable Energy Council (IREC) to facilitate outreach and education efforts to Million Solar Roof (MSR) stakeholders, including MSR partnerships, solar industry professionals, and consumers.

Future Directions

- Manage Solar Decathlon media relations and communications on the National Mall, October 2005.
- Refine the implementation section of the *Solar Program Communications Plan* to improve project tracking, cost monitoring, and usability.
- Redesign the National Center for Photovoltaics (NCPV) Web site.
- Support Solar Program activities through the development and distribution of key programmatic documents such as the Annual Report, Review Meeting Proceedings, Solar Program Overview, and MYPP to target audiences.
- Develop a metrics process to measure effectiveness of selected projects and the communications plan, prioritize projects and complete high-priority projects, and seek strategic connections with other activities and programs.
- Continue to work with program management to streamline planning and budgeting processes to maximize our efforts in support of solar energy research.
- Establish the new brand for Solar Powering America (which MSR is transitioning to), and continue outreach and education efforts started under the MSR program.
- “Go live” with improvements to Solar Heating content on Solar Program Web site.
- Analyze existing CSP Web content and presence (i.e., the outdated SunLab and TroughNet Web sites) and make recommendations regarding improvements, especially with regard to integrating the content into the Solar Program Web site.

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1. Introduction

Advances made through the DOE Solar Program must be communicated effectively to appropriate audiences if further technical and market growth will occur. Therefore, the solar communications team carefully tailors communications products and activities to targeted audiences. At the same time, Solar Program managers are refining the Systems-Driven Approach to assess the potential of various solar energy technologies. This approach considers target markets for these technologies, along with relevant technical and market barriers to their success. Understanding these factors helps in targeting research that more effectively achieves the promise the technologies have in the markets. As communicators, we key into this approach by focusing on these same markets and determining how communications can be used to overcome barriers and address key issues.

In FY 2005, the Solar Communications Team implemented complementary strategies and tactics on behalf of the Solar Program to generate awareness of solar energy technologies, the research activities, and the potential for solar energy technology advances.

These strategies and tactics were set forth in our strategic communications plan developed in FY 2004. At that time, our communications efforts were realigned to integrate communications across the various solar technologies and minimize redundancy; better target audiences and messages; respond better to changes in markets, technology perceptions, audiences, and funding; develop communication projects within the context of other relevant plans; leverage limited resources; and cultivate a multi-year mentality. The planning approach includes eight key audiences and their perceptions of solar technologies; audience-specific messages and communication objectives and strategies; and communications tactics (projects) to reinforce the objectives.

The Solar Communications Team's primary objective is to get the right information to the right people at the right time in the right form. The team develops, or assists in developing, a wide range of products, including technical reports, conference papers, journal articles, proceedings, brochures, fact sheets, presentations, posters, databases, exhibits, displays, Web sites, and CDs, as well as programmatic pieces such as the Solar Program Overview, Annual Report, and MYPP. The team is also planning to enhance distribution efforts of these products to key audiences of the Solar Program.

2. Technical Approach

Our planning efforts evolved from the following simple objectives:

- Represent the Solar Program appropriately.
- Save money by reducing duplication of effort among separate subprograms.
- Brand all communications and outreach products and activities in a consistent and appropriate manner.

Our team has come to view our core activities as covered by four primary areas:

1) Planning: Activities associated with strategic planning, budgeting, and aligning with the Solar Program System-Driven Approach.
2) Developing and producing: Activities associated with creating and producing a variety of communications products, including print, Web, and exhibits, to convey research results and the program's messages.
3) Transferring knowledge: Activities associated with transferring research and program information (both internally and externally) to critical audiences from the national laboratories and program management.
4) Measuring: Activities associated with measuring and assessing the relationships to critical audiences and the effectiveness of messages to them.

The Communications and Outreach Project consists of the following tasks.

Task Title	FY 2005 Budget ($K)
NREL NCPV/PV Communications	595
SNL NCPV/PV Communications	132
DOE/GO and NETL Subcontracted Outreach Communications	663

3. Results and Accomplishments

3.1 Planning

The team communicates on a regular basis through conference calls and an annual workshop to collaborate on projects, update the plan, and evaluate progress. In FY 2005, the team spent a majority of its time in the "implementation" and "assessment" phases of planning. Implementation is executing proposed communications projects in support of Solar Program messages to our key audiences. Assessment involves analyzing our performance and the effectiveness of our communications products. The team identified several lessons learned regarding the strategic planning process. Specifically, we need to:

- Evaluate our strengths and weaknesses annually in terms of the strategies we use and the impact we have on critical audiences.
- Improve the usability and integration of the implementation plan in our business processes for budgeting, costing, and accountability.
- Develop a metrics process as part of our strategic planning effort to assess business performance.

3.2 Developing and Producing

- Completed *Proceedings CD-ROM for the 2004 Solar Program Review Meeting*, which includes PDFs of 2-page papers for all subtask activities. (01/05)
- Completed *Solar Program Annual Report, FY 2004*, which includes extended papers for all subtask activities, plus summaries on major task areas. (10/05)
- Planned and facilitated communications strategies around the development of the "Home by Design" house for the 2005 International Builders' Show. (2005)
- Designed and produced an historical exhibit for the 2005 ISES Conference. (08/2005)
- Assisted in producing the *2007–2011 Solar Program Multi-Year Program Plan*. (09/2005)
- Assisted in the communications needs and logistical planning for the 2005 Solar Decathlon. (FY 2005)
- Assisted in developing and distributing the second *U.S. PV Industry Roadmap*. (10/2004)
- Prepared the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS): U.S. National Survey Report with W. Bower of SNL. (06/2005)

- Contributed to the IEA PVPS: Trends Report. (09/2005)

3.2. Transferring Knowledge

- We have interacted with the builders and consumer audiences at such events as the International Builders' Show and the Solar Decathlon. (FY 2005)
- We have focused our work on the Solar Program Web site on content for consumers. (FY 2005)
- We revamped the PV Manufacturing R&D Project Web site to include searchable summaries of all contracted research completed and in progress from all research partnerships. (04/05)
- We also reached others within the solar community at the 2005 ISES Solar World Congress and the Solar Power 2005 Conference. (08/05 and 09/05)

3.4 Measuring

A metrics framework for communications is needed. As we develop the process and collect data, this will allow us to:

- Make better business decisions.
- Measure the impact of messages.
- Show relevance, in the longer term, to research through indirect and direct correlations.
- Control costs.
- Demonstrate our value to our management.

4. Planned FY 2006 Activities

- Manage Solar Decathlon media relations and communications on the National Mall, October 2005.
- Complete *Proceedings CD-ROM for the 2005 Solar Program Review Meeting*, which will include PDFs of 2-page papers for all subtask activities. (02/06).
- Complete the *Solar Program Annual Report, FY 2005*, which will include extended papers for all subtask activities, plus summaries on major task areas. (02/06)
- Produce updated and redesigned displays and summary posters for the PV Manufacturing R&D display cases in the Solar Energy Research Facility at NREL. (02/06)
- Publish the *Solar Program Overview, FY 2005* (if the need is established); this publication will cover R&D highlights from the Photovoltaics and Solar Thermal Subprograms. (4/06)
- Publish a redesigned NREL PV Program Web site, which will update information currently on the NCPV Web site and provide a portal to other stand-alone NREL solar R&D-related sites. (09/06)
- Develop a process to measure selected communications projects in the *Solar Program Communications Plan* and capture audience data to measure changes in attitudes and behaviors with regard to solar energy technologies. (09/06)
- Identify and develop rapport with key members of each target audience (e.g., non-governmental organizations, utilities) to improve distribution channels and encourage collaboration. (FY 2006)
- Via IREC, promote better communications among MSR partnerships and facilitate flow of information among key stakeholders to address infrastructure barriers to solar energy and to coordinate with industry, federal, and regional DOE offices and national laboratories and the states. (FY 2006)

5. Major FY 2005 Publications

S. Moon et al., *Proceedings CD-ROM for the 2004 Solar Program Review Meeting.* DOE/GO-102005-2067 (January 2005).

S. Pedigo et al., *IEA Photovoltaic Power Systems Programme: U.S. National Survey Report*, 25 pp., (June 2005).

D. Gwinner et al., *2007–2011 Solar Program Multi-Year Program Plan (Draft).* NREL Report No. MP-520-37988 (September 2005).

S. Pedigo et al., *IEA Photovoltaic Power Systems Programme: Trends Report*, 31 pp.; Report IEA-PVPS T1-14:2005 (September 2005).

S. Moon et al., *Solar Program Annual Report, FY 2004,* 188 pp., DOE/GO-102005-2173 (October 2005).

R. Nahan et al., *2005 Solar Decathlon Rules and Regulations*, NREL Report No. MP-520-34627 (2005).

R. Nahan et al., *Solar Decathlon 2005*, 5 pp., NREL Report No. CP-520-37076. (2005).

Solar Program Review Meeting Web Site, www.eere.energy.gov/solar/review_meeting.

PV Manufacturing R&D Project Web Site, www.nrel.gov/ncpv/pv_manufacturing.

6. University and Industry Partners

The following organizations partnered in some of the project's activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
Interstate Renewable Energy Council (IREC) Jane Weissman	Latham, NY jane@irecusa.org	Million Solar Roofs Outreach	300	0
New Resources Group Dan Eberle	Freeman, MO daneberle@forumulasun.org	American Solar Challenge	305	0
Solar Electric Power Association Julia Judd	Washington, D.C. jjudd@solarelectricpower.org	2004 and 2005 Solar Power Conferences and Expos	24	0
American Solar Energy Society Brad Collins	Boulder, CO bcollins@ases.org	2005–2009 National Solar Energy Tour	125*	247**

*Funded with prior year (FY 2004) funds. **Spread over 5 years.

International Activities

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

Key Technical Contacts: John Thornton (NREL), 303-384-6469, john_thornton@nrel.gov
Vipin Gupta (SNL), 915-491-1158, vpgupta@sandia.gov

DOE HQ Technology Manager: Robert Hassett, 202-586-8163, robert.hassett@ee.doe.gov

FY 2005 Budgets: $275K (NREL), $192K (SNL)

Objectives
- Understand the drivers associated with international growth in PV sales.
- Determine the performance of PV products abroad.
- Help U.S. industry bring more affordable and reliable PV technology to the marketplace.
- Execute DOE commitments in international agreements and activities.

Accomplishments
- Developed the *Solar International Activities: Strategic Plan* to identify new directions and develop a strategic framework to be evaluated against Solar Program metrics, thus bringing the greatest value and benefits to the overall program.
- Supported participation in both International Energy Agency (IEA) Task 9, “Coordination of Renewable Energy Training and Certification Activities,” and IEA Task 10, “Urban Scale PV Applications,” which is the first IEA Photovoltaic Power Systems Programme (PVPS) Task for which the United States is an operating agent (NREL).
- Conducted field performance evaluations of U.S. thin-film products operating in year round hot and humid climates.

Future Directions
- Publish and execute *Solar International Activities: Strategic Plan*.
- Continue to support participation in IEA Task 10, “Urban Scale PV Applications,” for which the United States is the operating agent (NREL).

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1. Introduction

The primary mission of the Solar International Activities Task is to continually learn from the international adoption of solar technologies and improve U.S. solar technologies sold domestically and abroad. Because Germany, Japan, and Europe currently drive the growth of the solar market, our task includes: keeping current on why this is happening, understanding policy impacts, sharing this information with interested U.S. constituents, and determining how to improve U.S. PV product performance at a lower cost. We also try to provide timely data on emerging markets, nurture relationships with key manufacturers and integrators abroad, and distribute this information, where appropriate, to U.S. industry.

2. Technical Approach

The international groups at SNL, NREL, and the Southwest Regional Experiment Station (SWRES) consist of a diverse group of technical and policy experts with private sector experience, field expertise, and multiple language skills. Each institutional group uses their specialized talents, international partners, and collaborations with the U.S. Agency for International Development (USAID) and DOE Weatherization and Intergovernmental Program-International (WIP-I) to achieve the previously enumerated objectives. SNL focuses on the development and testing of new solar technologies and systems for international applications. NREL focuses on technical support for major rural electrification initiatives, hybrid testing, system modeling, and facilitation of business partnerships and projects.

SWRES field tests the latest U.S. solar technologies, develops new productive-use applications, and provides technology assistance for large-scale PV projects abroad. Together, all three institutions collaborate with partners abroad, providing U.S. companies with useful information on technology performance, customer needs, and market conditions.

Based on our newly developed strategic plan, we are pursuing four strategies designed to:

1) Contribute international market and system data to the Systems-Driven Approach (SDA) process for improved modeling and analysis
2) Provide market information to DOE to increase the competitive edge for the U.S. solar industry
3) Use international experience as a surrogate for U.S. market development
4) Contribute to improved performance and reliability for U.S. solar products using international systems application samples for testing and monitoring.

Task Title	FY 2005 Budget ($K)
Program Planning and IEA Support (NREL)	275
Field Performance, Analysis, and Planning (SNL)	192

3. Results and Accomplishments

3.1 National Renewable Energy Laboratory

NREL's International PV Project hosted planning meetings, wrote sections of text, coordinated planning activities, and assembled the *Solar International Activities: Strategic Plan* to identify new directions and develop a broad strategic framework to be evaluated against Solar Program metrics, thus bringing the greatest value and benefits to the overall program.

In response to a specific request from a U.S. solar start-up company that won a second round of venture capital funding, NREL International provided market information on China, as well as contacts for selling U.S. PV product in China.

Through two subcontractors, the Institute for Sustainable Power and Segue Energy Consulting LLC, NREL supported participation in IEA Task 9, "Coordination of Renewable Energy Training and Certification Activities," and IEA Task 10, "Urban Scale PV Applications." IEA Task 10 is the first IEA PVPS Task for which the United States is an operating agent.

NREL expanded the testing of PV/wind hybrids, PV applications, and thin-film PV. NREL completed installation of the wind/PV hybrid test facility, which powers village applications such as water purification, lighting, and refrigeration. Collaborations with the Solar Energy Center in India have yielded test results from 21 kW of U.S.-manufactured thin-film PV.

3.2 Sandia National Laboratories and New Mexico State University

SNL and the New Mexico State University (NMSU) international group participated in the planning meetings hosted by NREL, wrote sections of text, and conducted informal interviews of the U.S. solar industry for the *Solar International Activities: Strategic Plan.* SNL and NMSU then incorporated the content of this plan into the *DOE Solar Program Multi-Year Program Plan* (MYPP) formulation process.

In the technical arena, SNL, together with NMSU, conducted fact-finding visits to U.S.-based solar companies to identify cost and reliability issues that the national laboratories could tackle. A key outcome of this research was the need for independent field-performance evaluations of U.S. PV product (particularly thin film) in year round hot and humid climates. This field experience was needed to develop and enable the latest U.S. PV product to be more widely sold in climates that are hotter and more humid than northern Europe.

The SNL/NMSU team searched for relevant PV products in such demanding climates and located four CdTe PV systems in Morelos, Mexico. A full field performance evaluation was done, and the results were shared with the appropriate U.S. PV company for its use. The company checked and acknowledged the results, which were also presented at the DOE Annual Program Review in November 2005 (see publication citation below).

4. Planned FY 2006 Activities

- Publish and execute *Solar International Activities: Strategic Plan*.
- Continue to support participation in IEA Task 10, "Urban Scale PV Applications," for which the United States is the operating agent.
- Recommend technical and policy options for rapidly emerging PV markets abroad (e.g., China, India, Spain) that affect production of and investment in U.S. PV products.

- Identify and document commercialization pathways for promising future-generation technologies via partnerships between universities and industry.
- Introduce voluntary PV systems certification program, based on thorough benchmarking analysis of system performance, cost, and reliability, and supporting government-listed (and tribal) procurements of PV systems for remote, grid-connected, and micro-grid applications.

5. Major FY 2005 Publications

Solar International Activities: Strategic Plan (to be published in FY 2006).

Robert E. Foster, Vipin P. Gupta, Martín Gómez, Áaron Sánchez-Juárez, José Ortega Cruz, and J. Cesar Rosas, "Field Testing of CdTe PV Modules in Year Round Hot and Humid Climates," *DOE Solar Program Review Meeting,* Nov. 7–10, 2005.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
Segue Energy Consulting, LLC Christy Herig	Redington Shores, FL cherig@tampabay.rr.com	IEA PV Power Systems Task 10 (Urban PV) Support	109
Institute for Sustainable Power Roger Taylor	Evergreen, CO roger_taylor@nrel.gov	Coordination of Renewable Energy Training and Certification Activities and Support of IEA Task 9 Activities	38.8

Capital Equipment and Facilities

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL)
Key Technical Contacts:	Larry Kazmerski (NREL-NCPV, Primary Contact), 303-384-6600, larry_kazmerski@nrel.gov Tom Surek (NREL-PV), Brent Nelson (NREL-S&TF) Tom Mancini (SNL, Primary Contact), 505-844-8643, trmanci@sandia.gov
DOE HQ Team Leaders:	Thomas Rueckert, 202-586-0942, Thomas.Rueckert@ee.doe.gov Robert Hassett, 202-586-8163, Robert.Hassett@ee.doe.gov
FY 2005 Budgets:	$1,971.7K (NREL), $370K (SNL)

Objectives

- Maintain and enhance the capabilities of the laboratories at the National Center for Photovoltaics and leading universities participating in the PV Subprogram.
- Complete designs and initiate acquisition of capital equipment for the new Science and Technology Facility (S&TF) at NREL. This is the highest program priority in FY 2005.
- Operate and maintain the National Solar Thermal Test Facility (NSTTF) at SNL.

Accomplishments

- Developed the integrated hardware standards for future tools used in the new S&TF. This includes maximum substrate size, substrate platen dimensions, a docking interface for equipment, and inter-tool transport mechanisms.
- Designed and awarded contracts for a cluster tool to support crystalline silicon research and a stand-alone tool for transparent conducting oxide development.
- Designed an inter-tool transport pod to move samples between tools in a controlled ambient (high vacuum) and awarded a contract for the construction of that pod.
- Completed concept designs of a cluster tool for copper indium (gallium) diselenide device growth and for a chemical bath deposition system for cadmium sulfide growth.
- Project leader for the S&TF capital equipment completed Earned Value Management System (EVMS) training in order to manage this project under NREL's new EVMS, and created a control account and ten separate work packages with which to manage this project.
- Minimal level of maintenance and required environmental health and safety (EH&S) activities were performed at the NSTTF.
- President George Bush's visit to the NSTTF in August, coincident with the signing of the Energy Bill, initiated substantial clean up at the facility.

Future Directions

- Continue to seek funding support for the multi-year capital equipment plan submitted to DOE in FY 2004. The plan called for a total investment of $47.6 million in capital equipment at NREL, SNL, and universities from 2005 to 2010, including $36.5 million at NREL.
- Continue acquisition and begin installation of capital equipment in the S&TF. Specifically, this includes procurement of general use characterization equipment compatible with the new standard substrate form factor (ellipsometer, UV-visible spectrophotometer, thickness profiler, and current voltage/quantum efficiency system).
- Design and construction of other characterization equipment that is compatible with other tools or as mobile diagnostic tools (e.g., Auger electron spectrometer, X-ray photoelectron spectrometer, ultraviolet photoelectron spectrometer).
- NSTTF activities to support EH&S requirements and training. No new activities.

1. Introduction

The National Center for Photovoltaics (NCPV), headquartered at NREL, serves as the focal point for the PV Subprogram. The laboratories at NREL and SNL, partners in the NCPV, conduct leading-edge research in PV materials, devices, modules, and systems. The laboratory facilities are maintained as resources for the U.S. PV community. Conducting leading-edge research and providing state-of-the-art measurement capabilities requires the latest experimental and analytical equipment. The NCPV developed a *Multi-Year Capital Equipment Plan: 2005-2010* in FY 2004 and submitted the plan to DOE. Based on DOE's budget guidance for FY 2005, the majority of the new capital equipment funds at NREL (all but $100K of the funding listed above) was designated for the design and acquisition of capital equipment for the new Science and Technology Facility (S&TF), planned for occupancy in FY 2006. Activities at the National Solar Thermal Test Facility (NSTTF) at SNL focused on supporting the six-dish mini power plant of Stirling Energy Systems (SES) and the operation and maintenance (O&M) of the facility in the context of complying with all environmental health and safety (EH&S) requirements. No new facilities or equipment are being developed.

2. Technical Approach

During FY 2004, the NCPV prepared and submitted a multi-year capital equipment plan to the DOE Solar Energy Technologies Program with inputs from leading university research partners in the program. The multi-year strategy is to: (1) replace and upgrade seriously deficient and aging equipment that is several generations old and/or has become "cost ineffective" based on maintenance considerations; (2) acquire new equipment that provides capabilities introduced in the past 10 years and that are essential to the competitiveness of the U.S. PV Program; and (3) provide the capital equipment necessary to fully outfit the new S&TF so that we can meet our goal of reducing the time it takes to move a technology from the laboratory to the marketplace. The focus of the PV Subprogram funding in FY 2005 was on the S&TF capital equipment, as shown in the following table.

Task Title	FY 2005 Budget ($K)
PV capital equipment for Science and Technology Facility (NREL)	1,871.7
PV capital equipment for core program (NREL)	100
Operation and maintenance of the National Solar Thermal Test Facility (NREL)	370

The technical approach of the process integration project in the S&TF is to provide flexible and robust integration of deposition, processing (e.g., etching, annealing), and characterization tools via a standardized transfer interface such that samples move between tools in a controlled ambient. The benefits of having integrated tools include allowing researchers to:

- Answer previously inaccessible research questions.
- Control and characterize critical surfaces and assess the impact of these interfaces on subsequent layers.
- Assess process-related source chemistry, surface chemistry and kinetics, and bulk reconstruction.
- Grow layers and alter interfaces using controlled transfer ambients (without exposure to air).
- Develop new techniques, methodologies, device structures, materials, and tools.

Because of the need to handle a variety of substrate sizes, shapes, and materials in a sample platen, there are no "off the shelf" solutions to integrating the tools. Therefore, we had to develop our own set of design standards for future tool development, especially for the transfer interface (pod). The progress on each of the various tools in this project is discussed below. Each custom tool involves the following development steps:

- Conceptual design specifications
- Obtain budgetary quotes
- Budgetary re-scoping (change scope to fit budget)
- Final specifications
- Award contract and vendor fabrication
- Site preparation (for tool hookup at NREL)
- Acceptance and full operation at NREL.

The technical approach to operating and maintaining the NSTTF is to support the six-dish mini power plant and to assure that all EH&S requirements are met.

3. Results and Accomplishments

3.1 S&TF Capital Equipment

There is a three-year budget for essential capital equipment associated with the construction and operation of the S&TF. This essential capital equipment includes the following ten work packages, which are divided by status according to the development steps listed above.

Projects with contracts awarded and being fabricated:

1. Silicon Chemical Vapor Deposition Cluster Tool
2. Transparent Conducting Oxide (TCO) Sputtering Stand-Alone Tool

Projects undergoing budgetary re-scoping:

3. User Characterization Equipment
4. Optical Thickness Profiler

Projects developing conceptual specifications:

5. Auger Electron Spectrometer Mobile Tool
6. Chemical Bath Deposition CdS-Controlled Ambient Stand-Alone Tool
7. Polycrystalline Thin-Film Cluster Tool
8. X-ray and Ultraviolet Photoelectron Spectrometer Stand-Alone Tool
9. Optical/Processing Cluster Tool
10. Characterization Stand-Alone Tool.

Items 1 to 6 will be completed in FY 2006. Items 7 to 10 will be completed in FY 2007/2008. The silicon cluster tool will be completed in approximately March 2006 and operated at the vendor site until the construction of the S&TF is completed (around May 2006). The TCO sputtering tool will be completed at about the same time and shipped to NREL, where it will be operated in the existing facilities until it can be moved to the S&TF.

The silicon cluster tool will not only perform thin-film silicon deposition and processing (supporting the technology plan goals), but will also serve as the project's first test for intra-tool transport having an internal transfer zone containing a vacuum robot. The TCO sputtering tool will not only perform thin-film TCO depositions, but will also serve as the project's first test for inter-tool transport via the accompanying pod.

We are also developing the use of recipe/run control, as well as data logging, using XML-based data transfer. Software is critical to having fully integrated tools, not only for automation, but also for easy access to the data—out of which information can be gleaned and knowledge built. The approach we are pursuing is illustrated in Fig. 1. Currently, the Georgia Institute of Technology is assisting us in the development of the integrated software architecture.

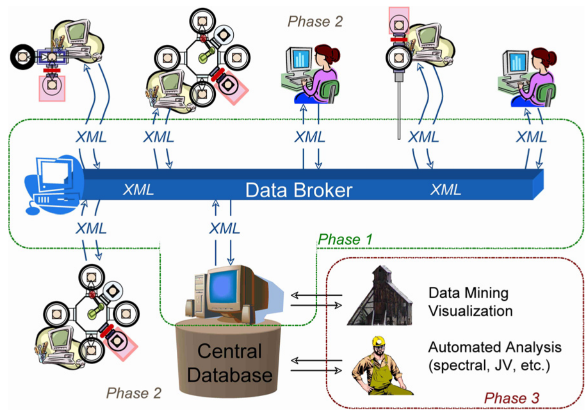

Fig.1. Schema for software integration

3.2 Operation and Maintenance of the NSTTF

We continued operating the SES six-dish mini power plant and complied with all EH&S requirements. We also hosted a visit from President George Bush (see Fig. 2).

Fig. 2. President George Bush visited the NSTTF on August 8, 2005, as part of his signing of the Energy Bill at Sandia National Laboratories.

4. Planned FY 2006 Activities

Activities in FY 2006 will be determined by the funding available for capital equipment. The major focus, as in FY 2005, will be on developing the equipment for the S&TF, as outlined above. The key milestone will be installation and operation of capital equipment in the S&TF, starting around June 2006. At SNL, O&M of the NSTTF will continue in an EH&S-compliant manner.

5. Major FY 2005 Publications

B. Nelson, S. Robbins, P. Sheldon, "NCPV Process Integration Project: Purpose, Status, and Direction," *Proc. 31st IEEE Photovoltaic Specialists Conference, January 3–7, 2005, Lake Buena Vista, Florida.* Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc. (IEEE); pp. 243–246; NREL Report No. CP-520-38864.

6. Capital Equipment List for FY 2005

The following capital equipment items were purchased for installation at the NCPV laboratories or the S&TF during FY 2005. The new equipment provides new and improved capabilities to support our industry and university partners in the PV program.

Vendor Address (City, State)	Equipment Item	Description of New/Improved Capability	FY 2005 ($K) [NREL/SNL]
MV Systems, Inc. Golden, CO	Combinatorial Silicon Deposition	First semiconductor deposition tool conforming to the new process-integration design standards. Combinatorial deposition of silicon-based materials and contact materials.	1,250
Transfer Engineering, Fremont, CA	Mobile Pod and Docks	First mobile pod to perform inter-tool transport. This is an entirely new transport mechanism to NREL.	120*
AJA International North Scituate, MA	TCO Sputtering Tool	First TCO deposition tool conforming to the new process-integration design standards.	336
Optical Reference Systems St. Asaph, UK	Optical Reflectance Monitor	Real-time optical monitor for growth systems.	60
TBD	Optical Thickness Profiler	Thickness-measurement tool capable of measuring the full new standard substrate area (with stress and surface roughness capabilities).	184
Instrument Systems Ottawa, Ontario, Canada	UV/Visible Scanning Spectral Radiometer	This spectral radiometer replaces an existing, obsolete radiometer and is used for our primary reference cell calibrations that critically affect PV cell and module performance measurement at NREL and throughout the PV community.	70.5
Kruss USA Matthews, NC	Dynamic Mapping	New capabilities: computer-controlled drop volumes, real time camera imaging, software for calculating surface energy. Improved capability: ability to reproducibly calculate surface energy from contact angles and liquid surface tension from drop size.	27.5

* FY 2004 funds

Program Management

Performing Organizations:	National Renewable Energy Laboratory (NREL) Sandia National Laboratories (SNL) DOE HQ Solar Energy Technologies Program
Key Technical Contacts:	Roland Hulstrom (NREL, Primary Contact), 303-384-6420, roland_hulstrom@nrel.gov, Tom Surek (NREL-PV), Mark Mehos (NREL-CSP), Tim Merrigan (NREL-SH&L) Joe Tillerson (SNL, Primary Contact), 505-844-1806, jrtille@sandia.gov, Tom Mancini (SNL-CSP)
DOE HQ Program Manager:	Raymond A. Sutula, 202-586-8064, raymond.sutula@ee.doe.gov
FY 2005 Budgets:	$2,088K (NREL), $1,090K (SNL), $536K (DOE)

Objectives

- Provide overall program management, planning, coordination, and integration of research activities at NREL and SNL to conduct an efficient and effective program leading to the achievement of the goals of the DOE Solar Energy Technologies Program.
- Provide budget analyses, planning, control, corrective actions, and reporting for the in-house research tasks, equipment, and facilities at NREL and SNL.
- Provide leadership and support for various Solar Program activities, such as EERE Strategic Reviews, revisions of the *2007–2011 DOE Solar Program Multi-Year Program Plan* (MYPP), and employing the Systems-Driven Approach (SDA) and stage-gate process to guide program management.

Accomplishments

- Met two EERE Joule milestones in FY 2005: 13.7%-efficient crystalline silicon and 11%-efficient thin-film module, made by U.S. manufacturers in commercial production.
- Completed major contributions to the final draft of the 2007–2011 MYPP for the Solar Energy Technologies Program.
- Conducted the FY 2004 Solar Program Annual Review Meeting (held Oct. 2004).
- Led the publishing process and published the *FY 2004 Solar Program Annual Report* document.
- Developed and organized the FY 2005 Solar Program Review Meeting (held Nov. 2005).
- Helped organize and develop a DOE Peer Review of the Solar Program (held Nov. 2005).
- Facilitated and contributed to a 21-page white paper addressing the cost targets for PV technology.
- Produced a three-page white paper entitled "Accelerating the Commercialization of U.S. PV Technologies." A key feature of this document was the new approach consisting of the use of focused industrial/national laboratory/university manufacturing technology partnerships to significantly accelerate U.S.-based PV manufacturing capacity building.
- Provided detailed technical assistance and analyses to the Western Governors' Association (WGA) Solar Task Force.
- Initiated construction and reached 51% completion status for the NREL Science and Technology Facility (S&TF), with completion scheduled for June of 2006.
- Created and formalized a dedicated project for the development and advancement of crystalline silicon technologies.
- Completed construction of the SNL PV System Performance Optimization Laboratory.
- Implemented the SDA as a basis for the 2007–2011 MYPP and the stage-gate process.

Future Directions

- Organize the FY 2006 Solar Program Review Meeting.
- Publish the *FY 2005 Solar Program Annual Report.*

- Support DOE HQ in the completion and publishing of the 2007–2011 MYPP.
- Continue to use and refine the SDA and stage-gate process to help guide Solar Program management. Guide the development and use of the Solar Advisor Model.
- Reflect SDA results in R&D portfolio balancing and activity prioritization.
- Complete the FY 2006 Annual Operating Plan using the DOE Corporate Planning System (CPS) tool and database. Complete first draft of the FY 2007 Annual Operating Plan, using the CPS.
- Complete (May 2006) the construction of the NREL S&TF and initiate occupancy (June 2006) of labs and offices.
- Continue support of and involvement in the WGA Solar Task Force.
- Hold industry/laboratory/university meeting on accelerated testing techniques to assess value to industry decision-making and need for advancement of methods to accelerate aging of PV components and systems.
- Hold a Mid-Year Review that includes a portfolio review and evaluation, technical progress review, and program status review.

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1. Introduction

The DOE Solar Energy Technologies Program maintains a goal-oriented R&D portfolio that incorporates a balance of short-, mid-, and long-term research. In support of the DOE Solar Program, this project coordinates and integrates the research activities at the national laboratories in accordance with the *DOE Solar Program Multi-Year Program Plan* (MYPP). The objectives of this project are to provide the overall leadership, management, planning, coordination, and integration of the R&D projects assigned to NREL and SNL. The NREL and SNL activities are managed as an integral part of the management activities and functions of the DOE Solar Program Office.

2. Technical Approach

The management of the research activities at NREL and SNL is coordinated under the various subprograms and is integrated within the laboratories by Solar Program Technology Managers. Activities in the Photovoltaics Subprogram are coordinated by the National Center for Photovoltaics (NCPV), headquartered at NREL. NREL and SNL are partners in the NCPV and provide management oversight for the respective projects in their laboratories. The Concentrating Solar Power (CSP) Subprogram's research activities are managed in collaboration between SNL and NREL in a virtual entity referred to as SunLab. NREL, SNL, and Oak Ridge National Laboratory (ORNL) jointly participate in the Solar Heating and Lighting (SH&L) Subprogram.

The table below shows the budgets for program management in the subprograms. In the PV Subprogram, communications and outreach activities are funded separately and are described elsewhere in this Annual Report. Some program-management activities (e.g., SDA and MYPP) are supported by subcontractors, as detailed in Section 6 of this report. In CSP, operations and maintenance efforts related to the National Solar Thermal Test Facility are included here.

Task Title	FY 2005 Budget ($K)
PV Program Management (NREL)	1,464
CSP Program Management and Communications (NREL)	430
SH&L Program Management (NREL)	194
PV Program Management (SNL)	447
CSP Program Management, Facilities O&M, and Communications (SNL)	643
Support Services (DOE HQ)	536

3. Results and Accomplishments

The overall effectiveness of the Solar Program's management activities at the laboratories is measured by the many technical accomplishments of the in-house researchers and subcontractors, as detailed in other projects of this Annual Report. The research activities supported by the Solar Program also garnered a number of major international and national awards and recognitions, both for individuals and for organizations involved in the program. The most significant awards are listed below; some of the technical details are described in other sections of the Annual Report.

- NREL and Sinton Consulting (CO) received a 2005 R&D 100 Award, the 20th such award for the NREL PV program since 1982.

- Dr. L.L. Kazmerski (Director of the NCPV) was elected a member of the National Academy of Engineering.
- Dr. Timothy J. Coutts, Research Fellow in the NCPV, received the prestigious IEEE William Cherry Award.
- Cecile Warner (NREL) received the 2004 American Solar Energy Society (ASES) Women in Solar Energy Award at the Annual ASES Meeting.
- NREL received the American Association for Laboratory Accreditation (ISO 17025) for secondary PV module, secondary solar cell, and primary reference cell calibration/ certification (in addition to the ISO 17025 Accreditation for primary reference cell calibration), making the NCPV the only laboratory in the world that holds both accreditations.

The Solar Program's management team supported a number of key planning and review activities in FY 2005. The team supported the Strategic Review of the Solar Program, conducted by the Deputy Assistant Secretary of EERE, and updating the 2007–2011 *DOE Solar Program Multi-Year Program Plan* (MYPP) (see Fig. 1). In addition, the team supported development of the EERE Corporate Planning System (CPS) database and approaches to the Annual Operating Plan (AOP) process for FYs 2005 and 2006. Finally, the management team provided leadership for the FY 2004 Solar Program Review Meeting, held in October 2004. This was the largest-ever review meeting for the program, with some 335 participants from industry, academia, and the laboratories. The proceedings of the meeting were published as a CD and included as an appendix to the *FY 2004 Solar Program Annual Report*.

Another significant undertaking involved the organization of the FY 2005 Solar Program Review Meeting and supporting DOE in the development and organization of the FY 2005 Peer Review. The two were scheduled concurrently to facilitate the efficient use of staff time and travel dollars.

3.1 Photovoltaics Subprogram
The PV Subprogram achieved two EERE Joule milestones for the Solar Energy Technologies Program in FY 2005: a 13.7%-efficient crystalline silicon module and a 11%-efficient thin-film module made by U.S. manufacturers in commercial production.

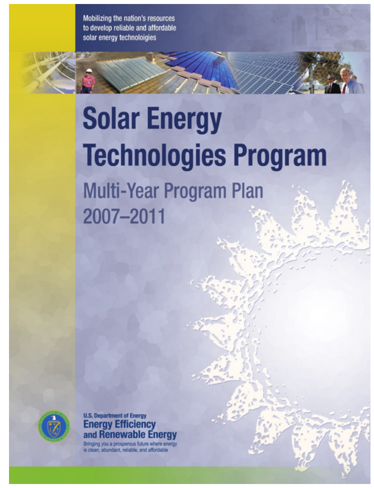

Fig. 1. The final draft of the *2007–2011 Solar Program Multi-Year Program Plan* was completed August 31, 2005.

The NCPV Advisory Board continued to provide guidance and recommendations to the Solar Program for research priorities. As a result, plans for FY 2005 involved the formation of a crystalline silicon project to strengthen the research program in this market-leading technology.

Finally, there was significant progress on the Science and Technology Facility (S&TF) at NREL, the laboratory's first major capital improvement project in the last 10 years (see Fig. 2). The facility will house state-of-the-art research capabilities that include a process-integration concept designed to accelerate the time it takes to move a technology from the laboratory to the marketplace. At the close of FY 2005, the S&TF was 51% complete and was on schedule and budget. The initial research efforts in FY 2006 will focus on crystalline silicon technology.

Fig. 2. The Science and Technology Facility at NREL is on track for completion in FY 2006.

3.2 Concentrating Solar Power Subprogram

The CSP Subprogram has developed a strategy that balances applied research, focused on reducing the cost and increasing performance and reliability of CSP systems, with deployment facilitation, which supports stakeholder awareness of near-and long-term opportunities. To that end, several significant developments occurred in FY 2005.

- Arizona Public Service and Solargenix, working with NREL and SNL, completed construction of a 1-MW Organic Rankine Cycle (ORC) parabolic trough plant.
- Solargenix announced financial closure and began construction of a 64-MW solar-only parabolic trough plant near Las Vegas, Nevada.
- Stirling Energy Systems (SES) announced power purchase agreements with Southern California Edison and San Diego Gas and Electric, which could result in over a gigawatt of installed systems over the next decade.

The CSP Subprogram provided significant analytical support to the Western Governors' Clean and Diversified Energy Initiative. The effort was highly leveraged by analysis previously undertaken for the states of California, Arizona, New Mexico, and Nevada. An initial draft of the central station solar task force was completed in September of 2005.

Facilities at SNL and NREL were used to support near- and long-term R&D. Six SES dishes have been deployed at the SNL National Solar Thermal Test Facility and will continue operation in FY 2006 in support of SES's commercialization goals. NREL completed fabrication of a large-payload 2-axis tracker as a supplement to SNL's rotating platform. NREL initiated work on a receiver test laboratory to support near- and long-term receiver development activities.

3.3 Solar Heating and Lighting Subprogram

SH&L Subprogram management participated in the development of the 2007–2011 MYPP. Through analysis of specific SH&L Technology Improvement Opportunities, it was shown that much more research needs to be performed to lower the cost of cold-climate solar water heating systems and combined space heating and cooling systems. These solar thermal systems are necessary in order for the Building Technologies Program to reach its goal of marketable net zero energy homes by 2020.

The SH&L Subprogram completely revamped the SH&L Web site in FY 2005. Also, the PV and SH&L Subprograms jointly sponsored an exhibit, "Your Home in the Sun," for the DOE Solar Program at the 2005 International Builders Show in Orlando, Florida, January 13–16, 2005. With more than 100,000 industry professionals in attendance, this National Association of Home Builders show is the largest home-building show in the world

4. Planned FY 2006 Activities

Significant plans for FY 2006 include:

- Hold the FY 2005 Solar Program Annual Review Meeting and publish the *FY 2005 Solar Program Annual Report*.
- Organize the FY 2006 Solar Program Annual Review Meeting.
- Support the independent Peer Review of the Solar Program.
- Support DOE headquarters in the completion and publishing of the 2007–2011 MYPP.
- Continue to use and refine the SDA and stage-gate process to help guide Solar Program management. Guide the development and use of the Solar Advisor Model.
- Complete the FY 2006 AOP using the DOE CPS tool and database. Complete first draft of the FY 2007 AOP, using the CPS.
- Complete (May 2006) the construction of the NREL S&TF and initiate occupancy (June 2006) of laboratories and offices.
- Continue support of, and involvement in, the WGA Solar Task Force.
- Hold industry/laboratory/university technical meeting to assess status of accelerated testing as a decision-making tool in the PV industry, and determine if substantial progress is needed (and achievable) to better support the industry. Test techniques and systems will be evaluated and improvement opportunities identified in each area.
- Hold a Mid-Year Review that includes a portfolio review and evaluation, technical progress review, and program status review.
- Incorporate recommendations of FY 2005 Peer Review Panel in program planning and execution.

5. Major FY 2005 Publications

Solar Energy Technologies Program, U.S. Department of Energy, *FY 2004 Solar Program Annual Report,* 188 pp., DOE/GO-102005-2173 (2005).

Solar Energy Technologies Program, U.S. Department of Energy, *Proceedings of the DOE Solar Energy Technologies Program Review Meeting, October 25–28, Denver, CO,* DOE/GO-102005-2067 (2005).

Solar Energy Technologies Program, U.S. Department of Energy, "Accelerating the Commercialization of U.S. PV Technologies," draft white paper, 3 pp. (2005).

Solar Energy Technologies Program, U.S. Department of Energy, "Cost Targets for PV Technology," draft white paper, 21 pp. (May 6, 2005).

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005 (no cost share).

Organization/ Principal Investigator	Location, e-mail	Description/Title of Research Activity	FY 2005 ($K)
McNeil Technologies Kevin DeGroat	Springfield, VA kdegroat@Mcneiltech.com	Support for the Solar Decathlon, Million Solar Roofs Initiative, and the Solar Program Peer Review, roadmapping activities, and expansion of the Systems-Driven Approach	606.7
SENTECH, Inc. Jonathan Hurwitch	Bethesda, MD jwitch@sentech.org	Multi-Year Program Plan support	131
Science Communications, Inc. Mark Fitzgerald	Highlands Ranch, CO markfitz@ispq.org	Evaluation and assistance support for NREL's PV-related certification and validation activities	40
Shirley Neff, Consultant	Washington, DC shirleyneff@earthlink.net	Inputs and policy evaluation for the *U.S. PV Industry Roadmap*	58.5
Renewable Energy Leadership Group	Scottsdale, AZ. keytaic@aol.com	Portfolio standard analysis and support of solar and renewable energy infrastructure development	50
Western Renewables Group Les Nelson	Rancho Santa Margarita, CA. lnelson@westernrenewables.com	Support for program reviews and Systems-Driven-Approach activities	90

EERE Crosscutting Activities

Energy efficiency and renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for the United States. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) invests in a diverse portfolio of energy technologies. These include solar-related research, development, and deployment projects that crosscut with, and complement, the objectives of the DOE Solar Program.

EERE's corporate planning, analysis, and evaluation (PAE) functions are the responsibility of the Office of Planning, Budget, and Analysis. The PAE team is responsible for providing relevant, accurate, consistent, and timely information for decision-making at the EERE corporate level. PAE plays a leading role in strategic and policy planning, assessment of target markets, and evaluation of retrospective and prospective benefits and a supporting role in the areas of program planning and evaluation.

Small Business Innovation Research (SBIR) is a highly competitive program that encourages small business to explore their technological potential and provides the incentive to profit from its commercialization. By including qualified small businesses in the nation's R&D arena, high-tech innovation is stimulated and the United States gains entrepreneurial spirit as it meets its specific research and development needs. Each year, ten federal departments and agencies (including DOE) are required by the SBIR Program to reserve a portion of their R&D funds for award to small, U.S.-owned businesses.

The six solar-related Congressionally directed projects (described later) are earmarks under the Energy and Water Development Act. Of the six, Nevada has three projects and California, Kentucky, and Massachusetts have one each. These projects involve researching solar-hydrogen generation, investigating a new type of light-emitting diode, and educating the public and community groups about the benefits of solar energy.

Some activities and accomplishments in this arena for FY 2005 are listed below.

Planning, Analysis, and Evaluation

- Analyze the installed cost of grid-connected PV systems (nearly 19,000) in California, using data provided by the state's two largest rebate programs.
- Analyze the feasibility of operating small, solar-powered desalination units for brackish water.

Small Business Innovation Research

- Produced thin (less than 30 micron) Silicon Film solar cells on glass-ceramic substrates.
- Automated assembly-line production of materials for high-performance CdTe PV modules.

Congressionally Directed Projects

- Install solar technologies and demonstrate to public officials, developers, commercial establishments, industries, and citizens the economic, social, and environmental benefits of using them.
- Conduct research to prove that transparent conductive coatings based on carbon nanotubes can perform at an electrical resistivity and optical transparency in the range required for use in solar cells.

Feasibility of Solar-Powered Desalination and Pumping Unit for Brackish Water

Performing Organizations: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Ken J. Touryan (NREL, Overall Project Manager), 303-275-3009, ken_touryan@nrel.gov

DOE HQ Technology Manager: Allan Hoffman (PAE), 202-586-8302, allan.hoffman@ee.doe.gov

FY 2005 Budget: $15K (DOE/EERE/PAE)

NOTES: (1) PAE provided $15K in 2005 for a report on the ***feasibility*** *of solar PV powered reverse osmosis desalination systems for brackish water in remote villages. (2) The technology demonstration, which began in 2003, was funded in previous years by the USAID ($550K) and DOE/EERE ($350K). In addition, Jordan provided substantial in-kind resources through the Ministry of Water and Irrigation and the National Energy Research Council. (3) This brief describes the technology demonstration that the PAE-funded report covers.*

Objectives

- Analyze the feasibility of operating small, solar-powered desalination units for brackish water (**PAE emphasis**).
- *NOTE: The objectives of the full technical demonstration were:*
  - *Foster cooperation and confidence building among regional partners.*
  - *Increase local institutional and individual technical capacity.*
  - *Stimulate a joint design effort by the regional partners of the desalination units suitable for use in remote villages.*
  - *Stimulate regional manufacturing of the jointly designed desalination units.*

Accomplishments

- The analysis is currently in process.

Future Directions

- Complete and deliver final report.
- *NOTE: According to the contract NREL has with the U.S. Agency for International Development, the final report for the whole project is due by February 28, 2006.*

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1. Introduction

The purpose of this project is to analyze the viability of small-scale, solar-powered desalination units for brackish water. The context of the project is a regional cooperation among the United States, Israel, Jordan, and the Palestinian Authority that was initiated several years ago. In the project, Jordan received two desalination units. The first unit is a surplus U.S.-military reverse osmosis (RO) water purification unit (ROWPU), installed and operated in the remote village of Qatar in the southern part of Jordan. The second RO unit, model Delta-15, is a commercial unit manufactured by Crane Environmental, a division of Crane Co. (U.S.). It is now installed at the Aqaba Industrial Estates, which is part of a U.S. Agency for International Development (USAID) program for the Aqaba region. (In a similar fashion, the Palestinian Authority has received a smaller Crane Environmental unit, which is being installed outside Jericho and connected to the power grid.)

Solar insolation is relatively high in both Jordan and the West Bank. The yearly average horizontal radiation is approximately 5.6 kWh/m^2/day. On a tilted surface, the mean values vary from 5.9–6.8 kWh/m^2/day. For the proposed sites of the desalination systems, the Aqaba area and Jericho, the annual average solar radiation is 6.2 kWh/m^2/day.

2. Technical Approach

Technically, the project studied the technical characteristics of the reverse osmosis systems so as to utilize the output results in designing a new system that will be powered solely by a photovoltaic power system (PVPS).

The challenge in implementation of the PVPS-powered desalination unit was the optimum matching of the intermittent PVPS power output with the steady energy demand for the desalination process. Power management and demand side management are the two options available to solve this problem. In the first case, an appropriately controlled hybrid power supply system that is able to provide a steady energy output is used, and it is sized at the nominal power demand of the desalination process. In the second case, the desalination process operates only when the energy output of the PVPS is able to cover the energy demand. Given these options, the PVPS was designed as a hybrid system with three power sources: PVPS, storage battery bank, and utility grid.

To determine the feasibility of the hybrid system, the PVPS was operated normally as a stand-alone power system, independent of the utility grid. It charged the storage battery bank and provided power for the AC-load of the desalination unit for 6 hours during a sunny day. When the system was no longer able to keep up with the AC power requirement of the desalination unit, but before the storage battery bank became deeply discharged, the system changed over directly to the utility grid to operate the desalination unit and recharge the battery bank. When the batteries became well charged, the system disconnected from the utility grid and once again operated the desalination unit from the batteries.

The Jordanian National Energy Research Center carried out detailed tests and analysis to study the performance characteristics of RO technology. Field tests were carried out at different operational settings. Data were collected, evaluated, and analyzed. Interesting results show that power consumption, permeate flow rate, and recovery ratio increase with pressure increase.

3. Results and Accomplishments

The results of evaluation measurement data for the first RO-unit (ROWPU) in Qatar show that the hybrid system is feasible. It is now under the guidance of the Ministry of Water and Irrigation of Jordan.

4. Planned FY 2006 Activities

- Evaluate the economic and technical viability of these units for other locations in Jordan and the West Bank.
- Prepare and deliver a final report to the USAID by February 28, 2006.

5. Major FY 2005 Publications

There are no major publications for 2005. The final report for the whole project (by NREL to USAID) is due by February 28, 2006.

Long-Term Climate Modeling of EERE Technologies

Performing Organization: Pacific Northwest National Laboratory (PNNL)

Key Technical Contact: James A. (Jae) Edmonds (Primary Contact), 301-314-6749, jae@pnl.gov

DOE HQ Technology Manager: Linda A. Silverman, 202-586-3896, linda.silverman@ee.doe.gov

FY 2005 Budget: $100K (DOE/EERE/PAE)

Objectives

- PNNL/JGCRI is working to improve the state of art in long-term (100-year) analysis of the potential of solar energy supply in the United States. *NOTE: The JGCRI is the Joint Global Change Research Institute—a partnership between PNNL and the University of Maryland.*

Accomplishments

- As the first step toward this goal, JGCRI is currently implementing an improved representation of solar energy in the ObjECTS MiniCAM model for use in scenarios that will be an integral part of the technology analysis process for the U.S. Climate Change Technology Program. Solar electricity supply will be constrained by resource base and cost, but without an arbitrary capacity limit.

Future Directions

- Future JGCRI work on solar energy will implement for the United States an explicit set of solar technology options, including central station solar, large-scale PV, distributed rooftop PV, and solar thermal technologies.

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1. Introduction

This multi-year project will develop descriptions of DOE Office of Energy Efficiency and Renewable Energy (EERE) technologies that are currently not well represented in the PNNL long-term integrated climate change assessment model. These descriptions will complement the more technologically detailed descriptions that are presently available for other energy supply and transformation options.

The first phase (FY 2004 funding) of this project developed and implemented an improved representation of wind energy and building energy efficiency. The second year of this project (FY 2005 funding) is building on this work and focuses on the improvement of representations of solar energy supply and energy efficiency technology in the industrial sector in PNNL's new integrated assessment modeling framework.

The goal of the integrated assessment models used at PNNL is to incorporate realistic dynamics of each portion of the climate-energy-economic-agricultural system, but at a level of detail that is transparent and manageable in a 100-year modeling context. The first stage of this work is, therefore, to develop a representation of these two sectors—solar energy and energy use in industry—that is both realistic and compatible (in terms of units, scale, and parameters) with more detailed ongoing work in these areas. To develop these representations, PNNL staff are working with DOE and technical experts in the specific areas of interest to insure accuracy, compatibility and relevance.

2. Technical Approach

Solar Energy Supply Module(s) Development. The goal of this portion of the project is to develop a solar energy module for the PNNL modeling system that is consistent with the best present understanding of solar resources, conversion technologies, and integration of solar energy supplies into the power generation system. Two different tasks are involved: (1) development of the conceptual representation of the solar energy supply, and (2) implementation of the solar energy supply module with data for the United States.

This work builds on our current EERE-funded work on wind energy. Solar energy is more complex than wind, although there are similarities. Like wind, solar energy is an intermittent and geographically heterogeneous resource. The techniques used for estimating wind energy resources will be adapted to apply to solar. PNNL/JGCRI will consult with NREL experts in this effort, noting that NREL's renewable modeling efforts are currently focused on wind (through the WinDS model). As part of our current work to represent wind energy, a methodology for representing the incorporation of an intermittent electricity supply into the grid is being implemented. This methodology can also be used to model the addition of PV/solar into the electric grid.

The provision of solar energy can take many forms: solar energy supply will likely be integrated into our modeling system in a number of places. PV electric generation can be distributed or centralized. Electricity can also be generated through central solar-thermal plants. Distributed solar water heating can be used on buildings. Our conceptual plan will consider all of these modes. Residential hot water heating, for example, can be implemented building on the first year's work on building energy services (where residential building hot water heating is a specific energy service). The detailed buildings sector will also supply an estimate of building roof space that can be used to estimate the potential for rooftop solar electric generation. The solar resource calculation will need to take into account the difference between total solar irradiance (at ground level) and direct solar irradiance: the later is necessary for central solar thermal power stations.

3. Results and Accomplishments

At the beginning of the FY 2005 work, we will have implemented a detailed representation of wind and building energy in our long-term modeling framework. Using this representation, we will conduct an analysis of the potential for these sectors to contribute to climate stabilization. This analysis is intended to demonstrate how this modeling capability can be applied to address how specific renewable and energy efficiency technologies compare to other potential mitigation technologies. We would anticipate that the initial communication of this analysis will be through a seminar presented to EERE staff, through which we can obtain feedback on the methodologies used.

FY 2005 tasks and timeline:

3 Months:
- Memo outlining technical plan for creation of solar energy supply module(s), version 1.0.
- Develop solar supply module(s).
- Meet with NREL researchers and others to collect necessary solar technology data.

6 Months:
- Memo outlining progress
- Implement solar supply module(s), and demonstrate with dummy data.
- Continue data development.

9 Months:
- Version 1.0 model description
- Complete phase 1 of solar supply model development(s).
- Demonstrate with U.S. data.

12 Months:
- Updated model description. Sample results with U.S. data.

Solar Deployment Systems Model

Performing Organization: National Renewable Energy Laboratory (NREL)

Key Technical Contacts: Robert Margolis (NREL, Primary Contact), 202-646-5053, Robert_margolis@nrel.gov
Paul Denholm (NREL), 303-384-9051, paul_denholm@nrel.gov

DOE HQ Technology Manager: Scott Hassell, 202-586-4434, scott.hassell@ee.doe.gov

FY 2005 Budget: $50K (DOE/EERE/PAE)

Objectives

- Develop a flexible model to evaluate the potential market penetration of solar PV technology.

Accomplishments

- Completed an “alpha” version of the Solar Deployment Systems (SolarDS) model.
- Presented an overview of model methods and results to the Office of Planning, Budget, and Analysis for feedback.

Future Directions

- Complete a more fully featured version of the SolarDS model.
- Solicit feedback from NREL solar program and incorporate changes as needed.
- Prepare documentation of the basic model structure for client and anticipated model users.
- Develop a basic set of “scenarios” (including fuel prices, capital costs, etc.) and perform model runs to develop PV penetration analysis under these basic scenarios.

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1. Introduction

The Energy Analysis Office (EAO) at NREL is developing the Solar Deployment Systems (SolarDS) model to evaluate the potential market penetration of solar PV technology. SolarDS examines the market competitiveness of solar PV technologies from the building user’s perspective, considering capital costs, electricity prices and utility rate structures, incentives, and net metering policies. SolarDS is being developed with the flexibility to consider market penetration of a range of DOE Office of Energy Efficiency and Renewable Energy (EERE) technologies, including distributed generation and other end-use energy technologies.

SolarDS is designed to provide a quick-turnaround, internal-analysis alternative to more complicated (and often less flexible) models such as NEMS. It provides flexible analysis of potential PV market penetration in buildings, explicitly considering coincidence of PV output and building loads and enabling multiple sensitivities (e.g., technology improvements, changes in electricity prices and rate structures, tax policies, financing) The model also provides the potential for analysis of multiple EERE technologies including PV and other distributed-generation technologies from the end user’s perspective in a competitive marketplace, tracking building stock on a regional basis.

2. Technical Approach

The project is a modeling effort using these tools:

- Solar PV analysis engine (TRNSYS, Excel spreadsheets, FORTRAN)
- Financial performance calculator (Excel)
- Market penetration simulator (Excel and VBA).

3. Results and Accomplishments

This project was funded late in FY 2005. In FY 2005 an “alpha” version of the SolarDS model was completed, which incorporates the basic financial calculators, PV supply and building load simulation tools, customer choice simulation, and market penetration estimator. Initial findings were presented at the Office of Planning, Budget, and Analysis weekly review meeting in April 2005.

Additional input data requirements and potential enhancements were also identified.

4. Planned FY 2006 Activities

The primary FY 2006 activity is to complete a “beta” version of the model by adding additional functionality, which includes: improved treatment of building load profiles, improved electricity rate structures, a more diverse customer choice simulation reflecting different customer classes, and improved treatment of PV installation on new versus retrofit buildings. Other planned activities include:

- Solicit feedback from NREL Solar Program and incorporate changes as needed.
- Prepare documentation of the basic model structure for client and anticipated model users.
- Develop a basic set of scenarios (including fuel prices, capital costs, etc.) and perform model runs to develop PV penetration analysis under these basic scenarios.

The planned completion data for the SolarDS model “beta” version with documentation is May 15. The planed completion data for the preliminary scenario analysis and report is June 15.

Statistical Analysis of PV System Installed Cost Trends in California

Performing Organization: Lawrence Berkeley National Laboratory (LBNL)

Key Technical Contacts: Ryan Wiser (LBNL, Primary Contact), 510-486-5474, RHWiser@lbl.gov
Mark Bolinger (LBNL)

DOE HQ Technology Manager: Scott Hassell, 202-586-4434, scott.hassell@ee.doe.gov

FY 2005 Budget: $50K (DOE/EERE/PAE)

Objectives

- Analyze the installed cost of grid-connected PV systems in California, using data provided by the state's two largest rebate programs (overseen by the California Energy Commission [CEC] and the California Public Utilities Commission [CPUC]).
- Using multivariate regression techniques, tease out interesting cost trends and identify potential drivers of those trends.
- Based on regression results, identify important policy or program design issues that can be implemented to more effectively support the development of a market for PV and drive PV installed system costs lower.

Accomplishments

- Cleaned the data (consisting of information on nearly 19,000 PV systems) during summer 2005.
- Completed the statistical analysis in October 2005.
- Drafting of LBNL report in progress, with external peer review expected in December 2005.

Future Directions

- Publish final LBNL report, as well as peer-reviewed journal article, in early 2006.
- May expand analysis to other state PV programs and/or conduct a cross-state cost comparison.

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1. Introduction

Markets for photovoltaics (PV) are expanding rapidly, albeit from a small base. In 2004, more than 955 MW_{AC} of PV capacity was installed worldwide, up from 658 MW_{AC} in 2003. The growth in worldwide annual capacity additions has averaged about 35% since 1996, dominated by grid-connected applications. Despite this vigorous growth, the share of worldwide electricity demand met with PV power remains miniscule, well below 0.1%, and the aggregate PV capacity added in 2004 equates to just one mid-sized natural gas-fired generating plant.

The primary constraint to future expansion is economics. Simply put, solar PV is not yet cost-competitive in most grid-connected applications, and substantial cost reductions will be required for PV to meaningfully contribute to worldwide electricity supply. As a result, local, state, and federal government incentives have been (and will continue to be) the principal drivers of growth in grid-connected PV capacity. A key goal of these policy efforts is that of market transformation: to drive down the cost of PV over time to a level that does not require substantial government stimulation. The cost of PV installations is not uniform, however, and can vary based on time, system size, type of installation (e.g., retrofit versus new construction), installer experience, and other factors. Solar costs might also be affected by the level and design of policy incentives provided to those installations.

This project presents the results of a statistical evaluation of cost trends in California's market for residential and commercial grid-connected PV. It is based on an analysis of 18,942 PV systems totaling 254 MW, which have either been completed, approved, or wait-listed under California's two largest solar rebate programs. (NOTE: The data represent both CEC and CPUC programs. The CPUC program only funds systems larger than 30 kW, and many of the systems are in the several 100-kW range.)

This analysis provides insights on California's PV market by exploring cost trends over time, and by helping to untangle the various factors that affect the installed cost of PV systems. Results may also have important policy ramifications, because they address the interaction between incentive levels and installed costs and the relative cost of different solar applications. Finally, this analysis provides a critical update to DOE's benchmarking, validation, and analysis efforts, as part of its Systems-Driven Approach.

2. Technical Approach

The type of data provided by each of the two rebate programs is suitable for multivariate regression techniques, with pre-rebate installed costs as the dependent variable, and numerous potential drivers of pre-rebate installed costs as independent variables. LBNL engaged Neenan Associates, a well-respected applied-economics consulting firm with statistical expertise, to execute the multivariate regression analysis. To evaluate different hypotheses and policy design issues, we constructed four separate regression models, applied to each of the two datasets. Results are presented both in terms of regression coefficients and their statistical significance (with textual explanation in laymen's terms of important implications), as well as graphical representation of interesting bivariate relationships. Robert Margolis of NREL provided input to the analysis.

3. Results and Accomplishments

Work on the project began during summer 2005, with the statistical analysis complete in October 2005. Drafting of a formal LBNL report is currently under way, with external peer review expected to take place in December 2005. Results will be of interest to policymakers at both the state and federal levels, as well as to DOE's Solar Program.

4. Planned FY 2006 Activities

We plan to complete this project in early FY 2006 (using FY 2005 funding). Pending interest and additional funding, we will potentially expand the analysis to other state PV programs (e.g., New Jersey, New York), and ideally conduct a cross-state cost comparison to try to explain, for example, why installed system costs in New Jersey appear to be significantly lower than installed system costs in California.

5. Major FY 2005 Publications

We began drafting a major LBNL report on this project in FY 2005, and will complete this report in early FY 2006. We also intend to publish our results in an appropriate peer-reviewed journal.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)	Cost Share ($K)
Neenan Associates Peter Cappers	Syracuse, NY pcappers@bneenan.com	Conducted multivariate regression analysis of California PV cost data.	$15	Entirely cost-shared*

*Funds were provided under a different DOE, non-PAE, account.

Small Business Innovation Research

Performing Organization: DOE HQ Solar Energy Technologies Program

Administrative: DOE HQ Germantown

Support (Proposal Evaluation): National Renewable Energy Laboratory
Sandia National Laboratories

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

FY 2005 Budget: $1,593K

Objectives

- Support small business energy R&D.
- Implement Executive Order 13329, which involves assisting the private sector in manufacturing innovation.
- Continue to pursue wise cost/benefit investments
- Augment the core research of the DOE Solar Program.

Accomplishments

Awards that matured in FY 2004:

- Advanced high-packing density of concentrating solar cells with high reliability.
- Produced thin (less than 30 micron) Silicon Film solar cells on glass-ceramic substrates.
- Automated assembly-line production of materials for high-performance CdTe PV modules.
- Developed advanced machinery for slicing crystalline silicon ingots.

Future Directions

- Focus on material and process cost-saving techniques for manufacturing solar/PV (silicon and other thin films).
- Seek new solar concentrator designs for ease of manufacturing and cost reduction.
- Incorporate innovative ways to use thermal energy in PV concentrators' electric output.
- Intensify the pursuit of the newest breakthrough in inexpensive organic PV solar cells (nanotechnology applied to PV).
- Achieve significant cost reduction in production of crystalline silicon PV products.
- Seek cost-effective PV-powered hydrogen production via electrolysis of water.

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1. Introduction

Each year, ten federal departments and agencies (including DOE) are required by the Small Business Innovation Research (SBIR) Program to reserve a portion of their R&D funds for award to small, U.S.-owned businesses. Over the life of the SBIR Program, the Solar Program has contributed $14 million and received $30 million in research funding. The very high popularity of the SBIR program at DOE has necessitated crosscutting topics, eliminating the once-separate PV/Solar topic. This step was taken to remove lengthy hiatus periods (for solar it has been some 3 years between solicitations) and provide all programs with the opportunity to participate on an annual basis. The Solar Program is nested mainly in the Renewable Energy Sources SBIR category (Topic 31). The SBIR Solar Program fits very nicely into the *DOE Solar Program Multi-Year Technical Plan* because it augments and supports the core program, in all aspects, with integrated solutions from the vast U.S. small business community.

2. Technical Approach

Renewable energy technologies have achieved significant advances in recent years, but further improvements are needed if they are to reach their full potential. The solar technologies included in the scope of this SBIR work address both solar electric (photovoltaic or PV) and concentrating solar power (CSP) systems. Grant applications for FYs 2005 and 2006 are required to clearly demonstrate the applicants' ability to proceed to hardware development, fabrication, testing, and manufacture of technologies.

2.1 FY 2005 Phase 2 Awards (June FY 2005)
GT Equipment: An Innovative Technique of Preparing Solar-Grade Silicon Wafers from Metallurgical-Grade Silicon by In-Situ Purification.
Crystal Systems: Development of Solar-Grade Silicon.
UQM Technologies: Power Converters for Diverse Applications.
Amonix, Inc.: A High Efficiency PV-to-Hydrogen Energy System.

2.2 Phase 1 Awards (September FY 2005)
GT Equipment: Novel Low Cost Process for Production of Crystalline Wafers for the Photovoltaic Industry.
MetroLaser, Inc.: Thermal (Solar) Photovoltaics Using Luminescence of Upconverters (efficient conversion of heat into electricity to increase electrical output of PV cells).
Distributed Power, Inc.: Improved Performance, System-Integrated Power Converter with Advanced Circuit Topology for Renewable Energy Applications.

See the SBIR Web site (http://sbir.er.doe.gov/sbir) for details on FY 1998–2005 awards.

3. Results and Accomplishments

Several SBIR awards matured in FY 2004. Amonix completed its improved volume production on advanced high-packing density of solar cells with high reliability. There were very successful field demonstrations over several years. AstroPower produced thin (less than 30 micron) Silicon Film solar cells on glass-ceramic substrates. First Solar completed its automated assembly-line production of materials for high-performance CdTe PV modules. GTi Technologies and Crystal Systems each developed advanced machinery for slicing crystalline silicon ingots.

4. Planned FY 2006 Activities

Further development of PV and CSP systems will be addressed through creative and innovative approaches in engineering and design, and new materials and processes.

4.1 PV Module Packaging, Interconnects, and Reliability Verification
This work seeks to develop cost-effective module packaging (encapsulation) to protect PV devices from water. Heavy and costly encapsulation schemes are currently used, which require replacement or modification to reduce cost. One are of interest is to use directly deposited barrier coatings to protect the PV devices.

4.2 Improved Thin-Film Materials, Modules, and Material Recovery
Two leading thin-film technologies used in PV systems, $CuInse_2$ and CdTe, use relatively rare elements—indium and tellurium, respectively—that could constrain very large-scale production (terawatt range). Other components, particularly cadmium, raise concerns about toxicity and require cradle-to-grave tracking and management to ensure public health and to reassure the public (despite the fact that detailed technical analyses have demonstrated no significant risk compared to other sources of cadmium in the environment). This work seeks to develop: (1) effective designs, systems, and hardware to enable the cost-effective recovery of valuable materials for reuse by the PV industry and to simultaneously clean the waste stream and end-of-life wastes of those materials that may be toxic; (2) new thin-film materials for use in high-efficiency, low-cost PV systems; and (3) new materials, such as innovative p-type transparent conducting oxides, to carry electricity over the front surface of the module to the top junction of the thin-film cell.

4.3 Innovative Reflector Materials and Designs for CSP Systems
Mirror systems—troughs, dishes, and heliostats—typically account for half or more of the total cost of CSP systems. This work seeks to develop technology leading to significant reductions in cost, and improvements in the performance, of these mirror systems. Areas of interest include: (1) innovative reflector materials and systems that can reduce capital and O&M costs while maintaining or increasing performance; and (2) innovative designs, using either current or innovative materials, that can significantly reduce costs compared to current systems and designs.

5. Major FY 2004 Publications

The SBIR Program holds the awardee responsible for a final report at the end of both Phase 1 and Phase 2. The SBIR Office in Germantown, MD, has on file the final reports of all the projects awarded in the past.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2005 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2005 ($K)
GT Equipment Kedar Gupta	Merrimack, NH gupta@gtequipment.com	An Innovative Technique of Preparing Solar-Grade Silicon Wafers from Metallurgical-Grade Silicon by In-Situ Purification	600
Crystal Systems Fred Schmid	Salem, MA fschmid@crystalsystems.com	Development of Solar-Grade Silicon	600
UQM Technologies Jon Lutz	Frederick, CO jlutz@uqm.com	Power Converters for Diverse Applications	600
Amonix, Inc. Vahan Gharboushian	Torrance, CA drvahan@earthlink.net	A High Efficiency PV-to-Hydrogen Energy System	600
GT Equipment Kedar Gupta	Merrimack, NH gupta@gtequipment.com	Novel Low Cost Process for Production of Crystalline Wafers for the Photovoltaic Industry	100
MetroLaser, Inc. Bauke Heeg	Irvine, CA bheeg@metrolaserinc.com	Thermal (Solar) Photovoltaics Using Luminescence of Upconverters	100
Distributed Power, Inc. Richard West	San Luis Obispo, CA Rick.west@distributedpower.us	Improved Performance, System-Integrated Power Converter with Advanced Circuit Topology for Renewable Energy Applications	100

Conductive Coatings for Solar Cells Using Carbon Nanotubes

Performing Organization: Eikos, Inc., Franklin, Massachusetts

Key Technical Contact: Paul J. Glatkowski, Vice President, 508-528-0300
pglatkowski@eikos.com

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

FY 2005 Budget: $1,500K (DOE), $372K (Eikos cost share)

Objectives

- Conduct research to prove that transparent conductive coatings (TCCs) based on carbon nanotubes (CNTs) can perform at an electrical resistivity and optical transparency in the range required for use in solar cells.
- Explore several potential experimental pathways expected to advance this TCC material system to the next generation of performance.

Accomplishments

- Award was issued in September 2005.

Future Directions

- Work with commercial producers of PV cells to develop an implementation plan for inserting CNT TCCs into solar cell types that are at or near commercial production.

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1. Introduction

The project consists of conducting research to prove that transparent conductive coatings (TCCs) based on carbon nanotubes (CNTs) can perform at an electrical resistivity and optical transparency in the range required for use in solar cells. Today's solar cells are fabricated using metal- oxide-based TCCs with optoelectronic performance significantly exceeding that currently possible with CNT-based TCCs. The motivation for replacing metal-oxide-based TCCs is their inherent brittleness, expensive deposition cost, and relatively high deposition temperatures, which leads to reduced optoelectronic performance on plastic. Alternatively, CNT-based TCCs overcome all these shortcomings while offering the ability to be applied in existing, very low cost, plastic film processing equipment, such as continuous roll-to-roll coating.

At today's level of development, CNT-based TCCs are nearing commercial use in touch screens, some types of information displays (e.g., computer LCD monitors), and some military applications. However, the requirements for use in solar is nearly ten times higher than for those applications. Significant exploratory research is required on the fundamental CNT composition, dispersion, and deposition (film forming). Theoretical calculations indicate that the current CNT TCC is capable of meeting the optoelectronic performance needed for solar cells. However, the path to reaching optoelectronic performance near theoretical limits will require successful application of carbon nanotechnology, which uses highly specialized tools and processes discovered in the past 2 years.

Specifically, Eikos will explore several potential experimental pathways expected to advance this TCC material system to the next generation of performance. Eikos will use specialized analytical services and proprietary nanotube purification processes to isolate and characterize specific types of nanotubes. Eikos will further purify, disperse, formulate, coat on films, and test the resulting TCC. Eikos will build working solar devices using the coatings, measure performance, and most importantly provide consultation on the direction, specification, and utility of the resulting TCC materials. Eikos has set a goal of 3x improvement in optoelectronic performance and to develop an understanding of the remaining potential for further improvement. Sample films will be fabricated and used in laboratory-scale solar devices to serve as the proof of concept.

2. Technical Approach and Planned FY 2006 Activities

1) Develop requirements list for each solar cell type, wherein the transparent conductive (TC) specifications are listed and the advantages and disadvantages of applying the technology are assessed and compared to existing TCCs.
2) Improve optoelectronic performance to achieve greater than 90% transmission at 100 ohms/square through improved purification, dispersion, and morphology and helicity control.
3) Determine the best application method(s) in terms of compatibility with the solar industry.
4) Define photovoltaic design and determine commercial obstacles for implementation in commercial markets.

2.1 Task 1: Determine Requirements

Collaborate with team members to create requirements list for each solar cell type, wherein the TC specification are listed and an assessment of technology insertion advantages and disadvantages compared to existing TCCs are summarized. Also an evaluation of the potential uses of Invisicon™ coatings in organic PV fabrication in both the TC layer and other potentially beneficial layers will be conducted.

One goal is to have a comprehensive market assessment of where the Invisicon™ coating can be most useful across all PV technologies. Both technical and financial performance metrics will be defined based on this study and incorporated into the implementation plan for Eikos' transparent conductive coating material in photovoltaic cells.

In this task, Eikos will be mining known information and applying the team's expertise in developing a map where we should focus our efforts in developing the CNT coatings to meet PV cell requirements. Some of the best candidates will be fabricated and tested in the following tasks.

<u>Expected Outcome of Task 1:</u> Report detailing applicability for CNT TCC in all known types of PV cells and suggestions for future development and technology insertion.

2.2 Task 2: Optoelectronic Performance Improvements

Eikos will research four approaches to enhance optoelectronic performance in the TCC. Each of these is interdependent, yet distinct enough to be described in separate tasks. As the mechanisms are better understood, they will be immediately applied and exploited to increase optoelectronic performance. This will be demonstrated through the fabrication of TCC for testing and possible insertion into PV cells. A brief description of each factor is provided below.

Purification and Yield Improvements. It is desirable to remove all impurities from the CNT layer to allow for the network of ropes to form without hindrance. In this task, Eikos will further increase the purity of the coatings by modifying its purification procedure. This will be done while attempting to increase yield from the process, thereby using as much of the source/raw CNT material in the final coating as possible. This will also act to reduce cost of the coating. Eikos has shown significant improvement in both of these areas over the past year and will continue this effort under this task.

Morphology Evaluation and Control. A detailed evaluation of the relationship between the morphology of the CNT in the coatings and their performance will be undertaken. This will involve use of new imaging techniques and those more commonly applied for determining structure property relationships. It is known that the structure of ropes of CNT and how the ropes form greatly influence the optoelectronic performance of TCC. By understanding and exploiting that understanding, we hope to modify the formulation and deposition technology to enhance optoelectronic performance.

Study Dispersion Effectiveness. Eikos will develop a family of formulations with tailored solids content and rheology to yield the desired sheet resistance range and optical transmittance. In many cases, the solids content needs to be 10 to 100x higher than our current formulations for use in traditional coating processes. To avoid particle agglomeration in this higher solids formulation, enhancements to CNT dispersion stability is required. This will be accomplished by modifying surface chemistry and dispersion energy. Additional dispersing additives may also be used. It is important to note that if dispersion stability is inadequate, then the consequence to optoelectronic performance is very significant (i.e., for a given sheet resistance value, the visible light transmittance will be lower than expected). In reformulating the coating, various dispersion techniques will be investigated and new analytical techniques for evaluating the dispersion quality will be evaluated and used.

Metallic-Type CNT Enhancement. Another approach to reducing coating surface resistivity (and improving optoelectronic performance) is to increase the proportion of nanotubes that are metallic in the coating. Today, all nanotubes produced commercially are a mixture of different chiralities or twists in the graphite structure forming the tube. Small-diameter nanotubes (<3 nm) typically have a distribution of one part metallic to two parts semiconductive nanotubes. The resulting bulk mixture exhibits volume conductivity lower than that measured for purely metallic nanotubes. Recently, methods have been discovered to separate different types of tubes in a given raw feedstock. Most academic and commercial researchers are interested in separating the semiconductive nanotubes for use in solar and discrete electronic devices and discarding the metallic nanotubes as waste. By using only metallic-type CNTs, it is estimated that the electrical resistivity the coating will be lower by at least a factor of 3. Eikos will use special separation processes to enhance the content of metallic CNT in ink formulations, create TCCs from the formulations, and evaluate optoelectronic performance. If possible, PV cells will be fabricated from the enhanced CNT material.

<u>Expected Outcome of Task 2:</u> Demonstrate CNT TCC with champion optoelectronic performance.

2.3 Task 3: Characterize CNT Transparent Conductive Coatings

During this task, transparent conductive coatings developed under this program will be evaluated. Eikos will fabricate and test a variety of organic and inorganic PV cells, incorporating the CNT in the transparent conductive layer and the electrostatic layer. The inorganic cells of most interest are the thin-film CIGS type, however other thin-film types will also be considered as an outcome from Task 1.

Invisicon will be incorporated into organic photovoltaic cells based on bulk heterojunction technology. The initial goals will be to compare a number of Invisicon materials with conventional ITO/PEDOT:PSS as a transparent bottom contact. We will make a comparison of a variety of Invisicon coatings that differ in resistivity and transparency resulting from different nanotube loadings. In addition, we will test various Invisicon coatings that differ in the type of polymer binder that is used and test those that contain no additional binding polymer. Finally, we will insert a number of semiconducting and conducting conjugated polymers to examine the effect that this has on coupling to the active device material.

In general, the performance will be evaluated according to suitability for present PV designs and additional types of PV. Comparisons will be made through device performance under AM 1.5 illumination. Finally, samples of CNT coatings will be provided to, and evaluated by, a few of the leading organic PV cell producers to begin understanding their unique materials and processing requirements.

<u>Expected Outcome of Task 3:</u> Demonstrate PV cells made using CNT layers; test results indicating current performance, future requirements, and capabilities based on these results.

2.4 Task 4: Investigate Application Methods

Various methods for applying Invisicon during PV cell fabrication will be evaluated primarily for their performance, but also for utility as a method of inserting the coating into the PV cell fabrication procedure. The Invisicon coating technology is a versatile system that can be applied by various conventional application methods, such as spray coating, coating, transfer coating, and direct application. However, each application method influences the optoelectronic performance of the coating, and the performance is related to the dispersion quality, stability of the CNT in solution, and drying conditions.

<u>Expected Outcome of Task 4:</u> Tabulated assessment of applications methods and their suitability to each application.

2.5 Task 5: Program Management and Implemention

This task encompasses pre-award administration and project planning, project management, and development of a plan for commercial implementation. Work involves the time and expenses associated with starting and running the project during the first year; protection of intellectual property developed during the project and necessary to support the technology; and project planning and administration. Finally, in this task Eikos will develop an implementation plan for inserting CNT TCCs into solar cell types that are at or near commercial production. This will involve working with commercial producers of PV cells.

<u>Expected Outcome of Task 5:</u> An implementation plan for future development and documentation for project initiation and reporting results.

Photonics Research and Development

Performing Organization: University of Nevada Las Vegas (UNLV)

Key Technical Contact: Tom Williams, UNLV Research Foundation, 702-895-2833, thomas.williams@unlv.edu

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

FY 2005 Budget: $1,500K (DOE), $372K (UNLV cost share)

Objectives

- Further develop advanced lighting technologies that will improve national energy conversion efficiencies, reduce heat load, increase brightness, and significantly lower the cost of conventional lighting technologies.
- Establish a comprehensive infrastructure within UNLV focused on photonics research and development, thus bringing improved lighting technologies to Las Vegas, Nevada, the world's largest entertainment venue.
- Develop and implement an academic program within the UNLV College of Engineering that concentrates on photonics research, development, testing and evaluation, thus providing credentialed lighting professionals for the entertainment industry and for the nation.

Accomplishments

- Award was issued in September 2005.

Future Directions

- Advance these lighting technologies toward a demonstration phase, which would provide DOE with solid data on performance and costs.

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1. Introduction

Annual energy consumption for lighting in the United States is estimated to be eight quadrillion British thermal units, which is 20% of all electricity consumed and 8% of total energy consumption in the nation. Replacement of current lighting with solid-state lighting could result in a 20% reduction in energy consumption, which would translate to a cumulative savings on electric bills of more than $125 billion from 2005 to 2025 for the consumer. In addition, hybrid solar lighting holds promise to provide the benefits of natural lighting, thus enhancing national energy savings and increasing worker productivity, without the disadvantages of conventional daylighting techniques.

The UNLV Research Foundation, a nonprofit affiliate of UNLV, has teamed with UNLV, Boston University (BU), and Oak Ridge National Laboratory (ORNL) to conduct a multi-faceted, multi-year photonics R&D program. The goal is to further develop advanced lighting technologies that significantly lower the cost of conventional lighting.

2. Technical Approach and Planned FY 2006 Activities

2.1 Task 1: Light Emitting Diode Research

UNLV and BU will team to develop quantum dot light-emitting diodes (QDLEDs) that will have improved energy conversion efficiency. Unlike traditional light-emitting diodes (LEDs), in which the color of the emitted light is determined by the LED material, the color of QDLED emission is determined by the size of the quantum dots (QDs). Thus, multiple-color light output can be realized from a single LED by incorporating QDs of the same material with different dimensions.

Displays based on QDLEDs will have significantly improved characteristics, including longer lifetimes, increased brightness, reduced heat load, and lower cost. In addition, display lighting will have the ability for dual use as PV panels with the potential for being self-powered.

The team will also conduct research, led by BU, focused on the indium gallium nitrogen (InGaN) part of the electromagnetic spectrum to understand why the efficiency of green LEDs is significantly lower than the LEDs in the violet-blue part of the spectrum, and to use this knowledge to fabricate green LEDs with significantly higher efficiency (by at least a factor of 2). InGaN-based LEDs and laser diodes (LDs) have great commercial potential because they work in the short-wavelength region, which has, up to now, been inaccessible for LED and LD technologies. By improving our understanding of these mechanisms, it should be possible to significantly improve the structural design, and with it, the performance of the devices.

Subtask 1: QDLED Development. The QDLED development project, planned for three 1-year phases, will focus on design and demonstration of QDLEDs fabricated by the all-solid-state approach during Phase I.

Project tasks will include: (1) complete design data for the QDLEDs; (2) detailed description of the technology developed for the fabrication of QDLED using the all-solid-state approach; (3) characterization results for the QDLEDs implemented using inorganic semiconductors; (4) design, fabrication, and characterization details for organic semiconductor QDLEDs; and (5) evaluation of the two technologies.

Subtask 2: Green LED Research. BU will fabricate the active region of the green LEDs using self-assembled InGaN QDs. It is well known that QDs are generally free of strain, and thus, one would not expect either phase separation or long-range atomic order to occur, because both of these phenomena are strain driven.

An additional problem with LEDs based on InGaN alloys grown on foreign substrates (such as sapphire) is the high concentration of dislocations, which act as non-radiative recombination centers. BU proposes to investigate the incorporation of GaN or InN QDs in the nucleation layer of the device structure to deflect the dislocations and facilitate their annihilation as the film grows thicker.

The current method of making InGaN LEDs is metal-organic chemical vapor deposition. In this method, the formation of the active region of the LED structure, which consists of InGaN/GaN multiple quantum wells, is done at a single temperature (~700°–800°C). This temperature range is appropriate for the growth of the InGaN wells, but it is low for the growth of the GaN barriers. Thus, the quantum well structures are grown under less than optimum conditions. In BU's approach, the active region of the device would be fabricated by molecular beam epitaxy (MBE), under which the optimum temperature for growth is ~700°–800°C.

The LED structures will be fabricated and packaged in the well-equipped facilities at the BU Photonics Center, using optical lithography and flip-chip bonding processes. Materials will be characterized using various structural and optoelectronic probes, and devices will be evaluated for spectral purity and optical power.

The proposed 1-year program should result in higher (by factor of 2) external quantum efficiency than the current green LEDs. BU proposes to deliver two prototype green LED structures at month 6 and month 12 of the program. The first deliverable will be an unprocessed LED structure, which can be probed at the wafer level. The second deliverable will be a flip-chip bonded and packaged green LED device. In addition, BU proposes to deliver a semiannual and an annual report describing the program's progress.

UNLV-BU Collaboration on Inorganic QDLED. The collaborative effort between UNLV and BU will include the investigation of (1) QDLEDs on GaN/AlGaN heterostructures and (2) capping layers to improve extraction efficiencies of LEDs, including surface plasmon effects in metallic nanoparticles. Toward these goals, BU will provide MBE-grown GaN/AlGaN heterostructure LED structures to UNLV, which will carry out the deposition of QDs and nanoparticles. The principal investigators from UNLV and BU will closely interact in the design of the heterostructures, deposition of the nanomaterials, and fabrication and characterization of LEDs. For this collaborative component, BU will provide about four GaN/AlGaN heterostructures to UNLV during the project year.

2.2 Task 2: LED Display Engineering

UNLV's College of Engineering will identify, develop, and implement engineering solutions for display-related problems, such as quality of display, durability, energy efficiency, and economics. A primary objective is to develop a nascent entertainment-engineering program to provide a future workforce of skilled and trained engineers for the development and deployment of energy-efficient lighting technology.

Variability of quality and performance of LEDs (which can result from the manufacturing process and component aging) make LED displays expensive and relatively inefficient. Engineering solutions can cost-effectively rebalance an installed LED display. Also, current displays are not designed for optimized power efficiency, resulting in loss of energy efficiency and increased heat load. Automatic adjustment of the picture characteristics due to ambient parameters, use of more efficient power converters such as the electronic ballast, or other specific designed power supply will make the displays more energy efficient, thus reducing the heat generated.

The primary objective will be achieved by first developing a team of experts from industry and academia to discuss problems and develop intelligent and inexpensive engineering solutions. The problems will be identified based on the needs of the industry, keeping in mind cost and durability. Collaborations will be developed between UNLV and the display and entertainment industry. The active industrial collaborators currently identified are Macon Gaming, Inc., Las Vegas; Video Walls USA, Inc., Las Vegas; and Tecnovision, Milan, Italy. Additional partners will be identified and included into the consortium as the project progresses. All industrial partners will provide in-kind cost-sharing through materials, components, testing facilities, and testing.

Subtask 1: Organization. A technical workshop, consisting of faculty members and industrial partners, will be organized to develop engineering design solutions to identified problems and to plan for implementation of solutions. The subtask will be accomplished by (1) organizing a consortium of display industries and academic institutions; (2) conducting a series of workshops to identify problems; (3) identifying components and systems that will be given to the project by industrial partners; and (4) identifying testing facilities available to the project from industrial partners.

Subtask 2: System Development. A photometer system, based on video camera and solid-state sensors, will be developed to study and measure the emission of either the single LED or clusters. This is an important first step for the successful completion of future technical work. This will be used as part of the final automatic testing robotic system to test the whole display. As part of this engineering work, various displays with different pixel spacing and indoor/outdoor use will be identified and cataloged for emission studies. The subtask will be accomplished by (1) designing and building the photometer system to reliably study the emission and emission patterns of various LEDs and (2) using the system to study the emission/emission patterns from LEDs of various colors and manufacturers.

Subtask 3. New algorithms and electronic circuitry will be developed to achieve better color balance, with the final goal of developing a self-diagnostic and reconfigurable system. Specifically, they will allow the (1) study of the responses of various LEDs with respect to intensity and linearity; (2) development of different algorithms to achieve the necessary color balance dictated by the application; and (3) development, design, and build-out of electronic circuitry to achieve optimal performance with a view toward energy conservation.

Subtask 4. New methods of remotely controlled current adjustment to achieve the desired overall brightness of the display will be investigated. This will by (1) studying the performance and energy efficiency of the displays under various ambient conditions and (2) developing an automatic feedback control system to respond to the ambient conditions to save energy.

Subtask 5. Other possible LED configurations besides the classic red green blue (RGB), such as the use of a fourth white LED to increase the overall brightness and gray-scale linearity, will be studied.

Subtask 6. New modifications in the photonics section with the use of virtual pixels to improve resolution, and in the processing section for faster refresh rate, signal processing, and distribution, will be developed. Variability of response of the human eye to the various visible wavelengths has allowed for deviating from the normal RGD LED containing pixels without sacrificing the perception by the human eye. This is done using the virtual pixel concept, wherein RG and BG are used instead of RBG and RGB. This will not only reduce the number of LEDs, but also save energy and cost. The objective is to study the quality of such displays, identify potential improvements, and then design and build better systems.

Expected outcomes of the project are:

- A consortium of industrial and academic partners to collaborate in identifying and solving engineering problems with displays.
- A prioritized list of display-related problems of great interest to the industry, with a view to achieving cost and energy efficiency.

- A well-equipped laboratory at UNLV for prototype testing, along with an identified list of industrial laboratory facilities for extensive large-scale testing.
- A photometer system for all LED emission and brightness studies.
- A new algorithm and electronic circuitry to achieve better color balance with the final goal of developing a self-diagnostic and reconfigurable system.
- A new method for remotely and/or automatically controlled current adjustment to achieve the desired overall brightness of the display.
- Other possible LED configurations besides the classic RGB.
- The ability to design and build better LEDs with virtual pixels.

This task will develop practical light-engineering solutions for entertainment displays for increased energy efficiency and reduced costs. In addition, UNLV will build a lighting engineering infrastructure and educational program to provide credentialed lighting engineers, a stated goal of the DOE "Vision 2020" Lighting Roadmap.

2.3 Task 3: Hybrid Solar Lighting with Improved Optical Efficiencies

ORNL and UNLV will team to conduct research, development, and demonstration related to improving fiber optic systems used in conjunction with hybrid solar lighting (HSL). For the past 5 years, DOE has funded the development of HSL, a technology with the potential to collect sunlight and distribute it, via optical fibers, into the interior of a building. This technology has the potential to provide the benefits of natural lighting without many of the disadvantages of conventional daylighting techniques.

Currently, the application of HSL is limited to only the first or second floor beneath the rooftop light-gathering system, which is due to the high optical loss inherent in the system's plastic optical fibers. Materials with improved solar light distribution are presently not economically feasible. This limitation, coupled with the high cost of the installed system, has hindered efforts to conduct a large-scale demonstration of the technology and its associated benefits.

This project proposes to extend the system's maximum fiber length from 30 to 50 feet, while maintaining the current delivered optical flux of 50,000 lumens. This increase in length will be achieved by optimizing the design of the system's solar collector components and optical fiber bundle configuration to improve the system's overall collection/coupling efficiency.

Subtask 1: Investigation and Quantification of Heating Mechanisms in Optical Fiber Bundle. Thermographic images and measurements of photo-induced heating in optical fiber bundles will be studied to isolate mechanisms responsible for bundle overheating. Lab-based constructions of various bundle configurations will be prepared and measured, and results will be documented.

Subtask 2: Design/Specification of Optical Fiber Requirements for High-Flux Capacity Bundle. Based on findings in Subtask 1, a recommended bundle design/configuration will be recommended and the expected performance of the specified bundle will be modeled. The improved bundle design will be optimized to mitigate the heating mechanisms previously identified. A 15%–20% increase in the flux carrying capacity of the optical fiber bundle will be targeted.

Subtask 3: Fabrication of Optical Fiber Bundle and Redesign of Solar Collector for Integration. The optical fiber bundle designed in Subtask 2 will be fabricated to specification. An investigation of alternate fabrication techniques that minimize the degradation to the fiber's PMMA core will be sought. Fabrication techniques will be explored, and a final best-performance bundle sample will be produced. The integration of this optical fiber design into the existing solar collector will be conducted, emphasizing collector modifications that will result in fewer parts or reduced manufacturing and material costs.

Subtask 4: Solar Collector Fabrication and Installation at UNLV Solar Site. The solar collector designed in Subtask 3 will be fabricated and installed at UNLV's Solar Site.

Subtask 5: System Testing, Monitoring, and Reporting. UNLV, ONRL, and Sunlight Direct will coordinate to assist in testing and monitoring of the installed solar collector. Data from the tests will be reported and conclusions drawn.

With improved HSL distribution, the technology will be ready for the demonstration phase to provide DOE with solid data on performance and costs. A demonstration project in Southern Nevada will benefit the program because of the existing solar capabilities in the UNLV College of Engineering and the Southern Nevada climate.

Solar Energy Project in Yucca Valley, California

Performing Organization: Town of Yucca Valley, California

Key Technical Contact: David Munro, Senior Management Analyst, 760-369-7207, dmunro@yucca-valley.org

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

FY 2005 Budget: $245K (DOE), $248K (Yucca Valley cost share)

Objectives

- Demonstrate the feasibility of local government using PV systems to provide clean electricity and cut electric utility bills.
- Install 55-kW PV system on the town hall/library roof and a 20-kW PV system in the parking lot of the community development/public works compound.

Accomplishments

- Award was issued in September 2005.

Future Directions

- Design the PV systems, apply for grid connection, select a contractor, and install the systems.

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1. Introduction

Located in the Southwestern corner of the Mojave Desert and shielded by windward mountain ranges, the Yucca Valley area receives over 320 days of sunshine per year, making it a prime location for use of solar energy. Installation of a PV system on the civic center will reduce energy consumption and provide significant benefits to the environment. The center uses 140,000 kWh per year, costing $52,000 in electricity consumption.

2. Technical Approach and Planned FY 2006 Activities

Yucca Valley will install two PV systems totaling 75 kW at its town civic center and community development/public works compound. The tasks for each project are identical; both projects will follow the same process for completion.

Task 1: Prepare Bid Documents. Prepare a set of design/build specifications and bid documents with some assistance from a consulting engineer and advertise for bids. The town will obtain bids from PV system retailers and installation contractors for the purchase and installation of the PV system. At the conclusion of this task, design/build specifications will be completed and project will be advertised for bids.

Task 2: Award of Bid. A review and ranking by town staff of bid proposals will be submitted and a recommendation of award will be forwarded to the town council, which awards the bid.

Task 3: Application for Interconnection. Town staff will fill out an application for interconnection to the grid and submit it to Southern California Edison for approval. Interconnection agreement is approved.

Task 4: Preliminary and Final Design. The selected contractor will perform preliminary analysis of the proposed PV system and provide a preliminary design report. After review and approval by town staff, a final design report will be prepared. This will be the basis for development of design drawings and final specifications. This task will determine the required components for the PV system, the roof array layout, electrical details, and interconnection details. Bid-ready plans and specifications will be complete at the conclusion of this task and will be utilized for procurement and installation.

Task 5: System Installation. Contractor will begin installation of the PV system as shown on the completed plans and specifications. A functioning PV system, complete and in place, should be accomplished at the end of this task.

Task 6: Testing and Interconnection. A series of field operational tests, performance tests, and acceptance tests will be conducted and interconnection of the PV system to the grid will take place. The PV system should be fully functional at the conclusion of this task.

Task 7: Project Close Out. A notice of completion will be filed with the county recorder, and the project will be accepted as complete and as an addition to the town's assets by the town council. Project is complete.

Solar Hydrogen Generation Research

Performing Organization: University of Nevada Las Vegas (UNLV) Research Foundation

Key Technical Contact: Tom Williams, 702-895-2833, thomas.williams@unlv.edu

DOE HQ Technology Manager: Thomas Rueckert, 202-586-0942, thomas.rueckert@ee.doe.gov

FY 2005 Budget: $4,214K (DOE), $841K (UNLV cost share)

Objectives

- Research economically feasible concepts for solar-powered production of hydrogen from water.

Accomplishments

- Award was issued in September 2005.

Future Directions

- Identify thermochemical cycles that are attractive for hydrogen production.
- Accelerate development and characterization of state-of-the-art photovoltaic components, coupled to durable photoactive oxide films immersed in electrolytes that would be suitable for generating hydrogen.

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1. Introduction

The Solar Hydrogen Generation Research (SHGR) Project, led by the University of Nevada Las Vegas Research Foundation, will define economically feasible concepts for solar-powered production of hydrogen from water, consistent with the cost and schedule goals outlined by DOE. The SHGR Project integrates efforts that cross the program boundaries of two DOE activities: the Hydrogen Fuel Cells and Infrastructure Technology Program, which is responsible for R&D of hydrogen-production technologies, and the Solar Energy Technologies Program, which is responsible for collection and use of solar thermal and photolytic energy.

Solar energy can be collected and used in at least two approaches to hydrogen production: thermal energy applied to thermochemical water splitting and photoelectrolysis of water in a photoelectrochemical (PEC) process. These two processes are completely different in their approach to hydrogen generation, but they are similar in that they both split water into oxygen and hydrogen with no other products, and they both use only solar energy and water as feedstocks. The programmatic deliverable product is a pilot plant design and implementation plan for a solar-powered hydrogen production system that meets or beats the metrics articulated in the DOE multi-year program plan for “Hydrogen Production and Delivery” and contributes to reducing dependence on foreign oil supplies.

The project consists of three related research and development tasks: (1) solar thermochemical hydrogen generation processes, (2) metal oxide laboratory studies, and (3) photoelectrochemical hydrogen generation. Tasks 1 and 2 focus on identifying attractive thermochemical cycles for hydrogen production. Task 3 accelerates development and characterization of state-of-the-art photovoltaic components, coupled to durable photoactive oxide films immersed in electrolytes that would be suitable for generating hydrogen.

2. Technical Approach and Planned FY 2006 Activities

The proposed project has two tasks, which are to be accomplished over a 12-month period. On completion of these tasks, information will be available with which to evaluate the economic potential of hydrogen derived from solar thermal energy. The first task, the primary effort of the proposed work, is the identification and selection of thermochemical cycles for water splitting. The second task is the continuation of current work on aerosol flow reactor technology and extension to high-temperature water splitting cycles. These tasks involve collaboration with Sandia National Laboratories (SNL), the National Renewable Energy Laboratory (NREL), the Georgia Institute of Technology, and the University of Colorado (CU). Most of the tasks are collaborative endeavors between all of the organizations represented on the team, but one organization will be responsible for leading each task.

Work under Tasks 1 and 2 identifies attractive thermochemical cycles for hydrogen production. For selected competitive cycles, the project establishes chemical feasibility and detailed kinetics data through laboratory investigations, develops process flow charts and establishes cycle thermal efficiency, develops and analyzes solar thermal energy collection and utilization systems, and develops capital and operating costs for production plant concept designs.

Task 3 will accelerate the development and characterization of state-of-the-art photovoltaic components coupled to durable photoactive oxide films immersed in suitable electrolytes. The scope of this research includes performance-enhancing doping of sputtered bulk metal oxide films; development of integrated hybrid photoelectrode prototype designs using amorphous silicon tandem substrates with the best-available metal oxide coatings; atomic and molecular scale characterization of PEC materials and material interfaces using surface-sensitive X-ray and UV photoelectron spectroscopy and inverse photoemission to study the occupied and unoccupied electronic states, respectively.

The goal of this project is to define economically feasible concepts for solar-powered production of hydrogen from water. Key activities are identified below by task.

Task 1: Solar Thermochemical Hydrogen Generation

- Comprehensive assessment of all known thermochemical cycles and documentation in a publicly accessible database.
- Laboratory validation of chemical steps of potentially competitive cycles.
- Integrated bench-scale evaluation of feasible cycles.
- Detailed process flow charts of the best several thermochemical cycles.
- Design, testing, and evaluation of effective solar thermal energy collection and utilization concepts for driving thermochemical cycles.
- Simulation and testing of the solid particle receiver concept.
- Development of low-cost, high-performance heliostats.
- Capital and operating cost analyses of the best two or three thermochemical conceptual plant designs
- Pilot/demonstration plant design and implementation plan for the best one or two solar-powered thermochemical cycles.

Task 2: Metal-Oxide Laboratory Studies

- Design, testing, and evaluation of a porous-wall reactor concept that prevents reactor wall damage and erosion.
- Comprehensive understanding of the ZnO thermochemical cycle with ancillary benefits to understanding other ultra-high temperature metal oxide cycles.
- Design and optimization of a secondary concentrator system to improve the high temperature operating efficiency of the NREL High Flux Solar Furnace.
- Development of a process flow sheet, including the chemical reaction steps and the power tower field design, to support a plant concept development for the ZnO/Zn cycle under Task 1.

Task 3: Photoelectrochemical Hydrogen Generation

- Establishment of program-wide standardized procedures and protocols.
- Physical, optoelectronic, and performance characterization of PEC materials and devices.
- Demonstration of a PEC solar-hydrogen production system with 2%–4% STH efficiency and 100 hours durability.
- Demonstration of reduced-bandgap WO_3 films attained through film doping and surface modification.
- Examination of the characteristics and performance of combinations of enhanced-performance WO_3 compounds.
- Exploration of alternative oxide-based material systems.
- Identification and characterization of durable PEC materials and interfaces.
- Identification and characterization of reduced-bandgap materials needed to approach the DOE performance goal of ~10% STH efficiency.
- Demonstration of large-area fabrication for hybrid photoelectrode devices.
- Design, fabrication, and performance characterization of a hybrid photoelectrode device with STH efficiency approaching or exceeding 10%.

Solar Technology Center

Performing Organization: University of Nevada Las Vegas (UNLV)

Key Technical Contact: Tom Williams, UNLV Research Foundation, 702-895-2833, thomas.williams@unlv.edu

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

FY 2005 Budget: $744K (DOE), $744K (UNLV cost share)

Objectives

- Develop a solar and renewable energy information center in the Eldorado Valley Energy Zone near existing and planned solar projects.
- Provide public exposure to real world solar and other renewable energy technologies operating in a high desert setting.

Accomplishments

- Award was issued in September 2005.

Future Directions

- Determine feasibility of the project.
- Construct the project (pending the outcome of the feasibility study and an acceptable National Environmental Policy Act determination).

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1. Introduction

The UNLV Research Foundation, in cooperation with the City of Boulder City and private entities engaged in solar and other renewable energy technologies, proposes to develop a solar and renewable energy information center. The Solar Technology Center will be developed on a 40-acre site leased by the foundation in the Boulder City-owned 3,000-acre Eldorado Valley Energy Zone near existing and planned solar projects.

The center is planned to ultimately provide public information services on both current and emerging solar and other renewable energy technologies and energy projects that are expected to be located in the Energy Zone. When completed, the center will include a suitable building for public exhibits and tours. The center will provide its own electric service derived from its operating solar systems. Walking tours will be offered to nearby solar facilities. Broadband Internet and data-monitoring communications will be available to allow monitoring of site activities from off-site locations. The completed project is expected to provide public exposure to real world solar and other renewable energy technologies operating in a high desert setting.

2. Technical Approach and Planned FY 2006 Activities

Phase I will include all activities necessary to determine feasibility of the project, including but not limited to design and engineering, identification of land access issues and permitting necessary to determine project viability without permanently disturbing the project site, and completion of any National Environmental Policy Act (NEPA) actions necessary to obtain a NEPA determination prior to any construction activities. Opportunities to team with private entities, utilities, and government agencies will be explored as state and local interest in renewable energy topics and the Energy Zone continues to advance. The labor-intensive fieldwork, design, and engineering will be contracted out following the competitive contract award processes established by the foundation.

Phase II will consist of project construction. A decision to proceed to Phase II will depend on the results of Phase I and an acceptable NEPA determination. Support from nearby energy projects; local utilities; city, state, and federal energy offices; and the laboratory network will be considered in the decision to proceed.

2.1 Phase I: Project Site Development Work

Project Coordination and Oversight:

- Prepare project proposal with budget and schedule and coordinate with funding entity.
- Coordinate with Boulder City to maintain the lease performance requirements.
- Coordinate with concerned Nevada entities to affirm project features and approach.
- Coordinate with other entities in the Energy Zone.
- Conduct competitive architect and engineering subcontract process.
- Oversee selected architect and engineering performance.
- Track project schedule and budget and report to funding entity as necessary.

Project Development Work:

- Conduct survey and staking of 40-acre site.
- Perform all necessary land access activities.
- Conduct NEPA process.
- Design features of project necessary for initial operation.
- Identify and prepare applications for all needed permits.
- Determine availability and cost of utility services (electric power, water, natural gas, telephone, and broadband communications).
- Support foundation efforts to identify partnership opportunities with cost-share potential.
- Assemble complete project site design specifications and drawing package.
- Identify potential Engineer, Procure, Construct (EPC) contractors for site preparation and construction of all project site features.
- Prepare Phase I report identifying estimated project construction cost and schedule, proposed operating plan, and assessment of merits of proceeding with Phase II.

<u>Estimated Outcome of Phase I:</u> The report provided on completion of Phase I efforts will identify all issues pertinent to proceeding with construction of the project. Utility infrastructure, site physical issues, and site security considerations will be addressed. All permitting and federal, state, and local environmental requirements will be addressed. A detailed budget and schedule will be provided to support the necessary additional project funding.

2.2. Phase II: Project Construction

Project Coordination and Oversight:

- Maintain budget and schedule coordination with funding entity.
- Coordinate with Boulder City to maintain the lease performance requirements.
- Coordinate with concerned Nevada entities.
- Coordinate with other entities in the Energy Zone.
- Conduct competitive Engineer, Procure, Construct (EPC) subcontract process.
- Oversight of selected EPC contractor performance during site preparation and construction of all necessary project features including building, pavement, parking areas, walk trails and test pads and fencing.
- Track project schedule and budget and report to funding entity as necessary.

Project Development Work:

- Submit all needed permits with fees.
- Apply for Desert Tortoise remediation permit with fee.
- Apply for all necessary utility services (electric power, telephone, water, and natural gas).
- Arrange construction of all features of the project.
- Arrange for delivery and set up of solar and other apparatus on test pads.
- Arrange electrical and mechanical integration of all systems necessary for initial operations.

<u>Expected Outcome of Phase II:</u> An EPC subcontractor will be selected to secure permits and construct the project. The project will be constructed according to the design and specifications determined in Phase I.

The completed Solar Technology Center will provide schools and the interested public a practical means of observing solar and other renewable energy apparatus in the natural environment contiguous to large solar and other power-production facilities. Opportunities to demonstrate renewable energy technologies will be provided to private entities, Nevada energy utilities, elements of the University of Nevada system, and federal laboratories.

Sustainable Buildings Using Active Solar Power

Performance Organization: University of Louisville Research Foundation (ULRF), Kentucky

Key Technical Contact: Kim Lalley, Director of Sponsored Programs Development, 502-852-6512, Kalall01@louisville.edu

DOE HQ Technology Manager: Glenn Strahs, 202-586-2305

FY 2005 Budget: $397K (DOE), $346K (ULRF cost share)

Objectives

- Install solar technologies, and through technology diffusion, demonstrate to public officials, developers, commercial establishments, industries, and citizens the economic, social, and environmental benefits of using them.

Accomplishments

- Award was issued in September 2005.

Future Directions

- Establish an energy center with the mission of providing technical assistance to facility managers at the University of Louisville, local school district, and Louisville Metro government on ways to incorporate solar energy into building design.
- Conduct five demonstration projects that feature solar energy.

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1. Introduction

The partners will collaborate to establish an energy center with the mission of providing technical assistance to facility managers at the University of Louisville (U of L), local school district, and Louisville Metro government on ways to incorporate solar energy into building design.

2. Technical Approach

The center will be part of the Partnership for a Green City effort, and will be affiliated with the Kentucky Institute for the Environment and Sustainable Development (KIESD). An advisory group composed of the KIESD, the Kentucky Pollution Prevention Center, the Partnership for a Green City (including facility managers from Metro Louisville, Jefferson County Public Schools, and the University of Louisville), Kentucky Solar Partnership, and engineering and architectural firms experienced in solar applications will assist the principal investigator in the implementation of the proposed project. An organizational chart for the project is shown in Fig. 1.

The energy center will have the responsibility of assessing solar heating and lighting technologies to ascertain their economic viability for buildings owned, or being built, by the three institutions. The Center will provide assistance in the assessment of alternative technologies, developing bid specifications, reviewing project proposals, developing training programs, conducting project assessments, conducting applied research as requested, and publishing project evaluations. Assessment will be conducted on each of the proposed projects to assess their efficiency; maintenance and operational requirements; and economic, social, and environmental benefits.

3. Results and Accomplishments

The award was issued in September 2005.

4. Planned FY 2006 Activities

The partners have agreed to conduct five demonstration projects, as described in the following.

4.1 Churchill Park School Swimming Pool Solar Heating Project. Churchill Park School is a rehabilitation school within the Jefferson County Public School (JCPS) system. The pool is used for therapeutic purposes and is maintained at

90^{o}F. The pool is currently heated using a 4-year-old, 250,000-Btu Lochnivar pool heater. The project would include the installation of solar panels, heat exchanger, pumps/plumbing, and engineering and installation costs. The pool may be modified to eliminate the deep end. The school's roof will be rehabilitated as part of the project to ensure compatibility with the installation of solar panels.

4.2. Elementary Schools at Billtown and Aiken Road Solar Water Heating Project

Two new 650-student elementary schools are being planned by the Jefferson County School District. The schools will use solar water heating to meet all hot water demands. The project will include solar panels, storage tank, heat exchanger, pumps/plumbing, engineering, and installation costs.

4.3 Elementary Schools at Billtown and Aiken Road Solar Lighting Project

The new elementary schools will incorporate into their design interior light shelves to enhance natural lighting in up to 32 classrooms. The light shelves shade the rooms from direct sunlight and will reflect sunlight on to enhanced ceiling tiles for deeper, more uniform light distribution. Rooms will be equipped with electronic dimming ballasts to reduce electrical costs. The project would include light shelves, dimming ballasts, ceiling tiles, design, and installation costs.

4.4 Photovoltaic Streetlight Project

The Louisville Metro Government Cabinet for Public Works and Services will conduct a pilot project with solar-powered streetlights. The pilot will include three to four streetlights to be installed in locations deemed critical in the event that the electrical grid were disrupted, and in locations where access to the grid are costly or impractical. The project will include the streetlights, light poles, and installation.

4.5 Residential Solar Hot Water Project

The Kentucky Solar Partnership, with support from the Mountain Association for Community Economic Development, will offer a grant ($500) and low-interest loan (3% for 6 years) to homeowners in 51 counties in eastern Kentucky. The project goal is to increase the number of homes with installed solar water heaters. A total of 25 installations will be conducted during the project period. The project would include the grants and an assessment of the performance of the installed water heaters. Homeowners would not receive the $500 grant unless they agreed to allow the project partners to obtain energy use data, pictures, and testimony on heater performance and agreements to use recipients' information in publications on the project.

As part of the technology diffusion process, the project will include training for operations and maintenance of technologies associated with each of the above projects. Training will be specified in RFPs for each project to have vendors and/or manufacturers provide training of operations and maintenance staff. Prior to issuing bid requests for the projects, training will be available for contractors in Louisville and eastern Kentucky interested in bidding on and installing technologies for all of the projects (except the PV streetlights, which will be installed by Louisville Metro employees). The Kentucky Solar Partnership will coordinate the contractor training programs.

Monitoring and evaluation of each of the projects will be conducted by the center to prepare project reports that will be shared with the Partnership for a Green City and through a workshop on solar opportunities. The workshop will he held at the U of L and will include discussions of solar opportunities in Kentucky and tours of the projects. Speakers from DOE, state solar centers, solar industry representatives, and engineering firms will be invited to participate. Also, as part of this project, the center will establish and maintain a Web site with information on solar energy, a directory of attendees of the solar contractor training, project descriptions, and product information. The Web site will be developed and maintained by the U of L.

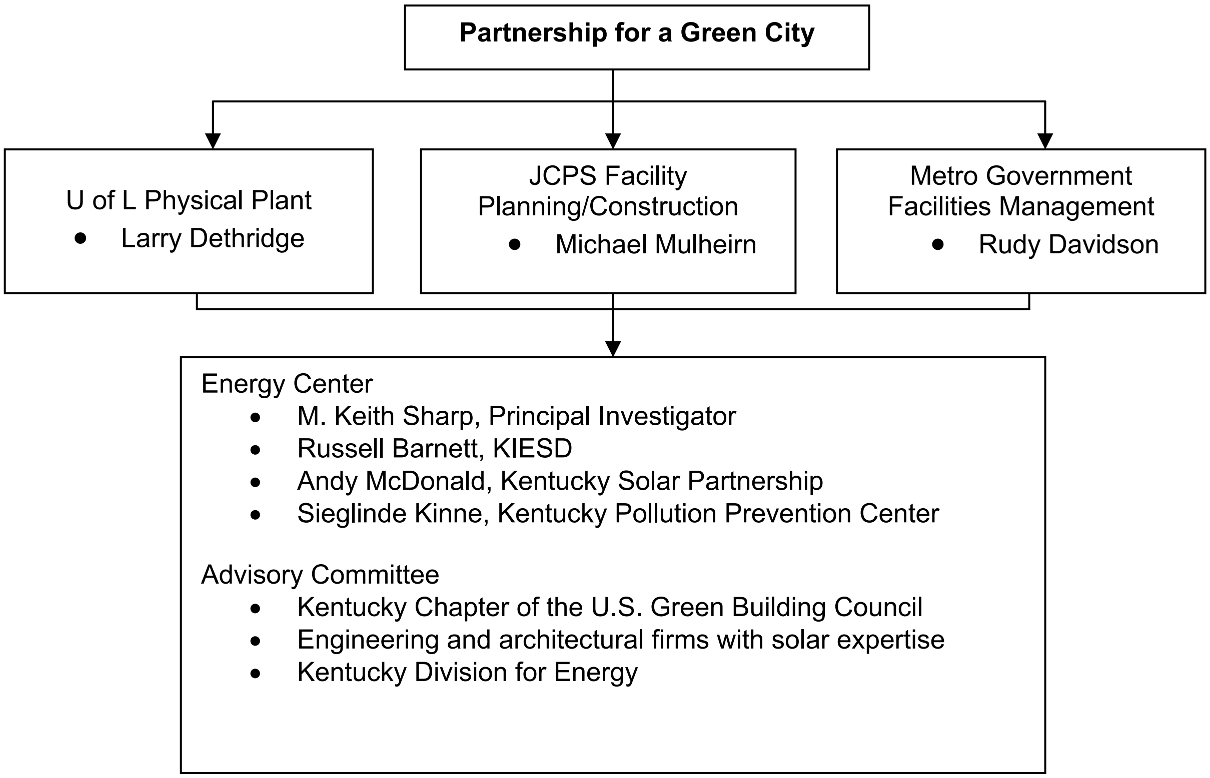


Fig. 1. Organizational chart for the Partnership for a Green City project.

Performing Organizations By Name

Performing Organizations By State/Country

Acronyms and Abbreviations

A2LA	American Association for Laboratory Accreditation
AC	alternating current
AES	Auger electron spectroscopy
ALO	Albuquerque Operations Office (U.S. Department of Energy)
AOP	Annual Operating Plan
APS	Arizona Public Service
AR	antireflection
ASES	American Solar Energy Society
ASHRAE	American Society of Heating, Refrigeration, and Air-conditioning Engineers
a-Si	amorphous silicon
ASOS	Automated Surface Observing System
ASRC	Atmospheric Sciences Research Center (at State University of New York)
ASRM	advanced solar reflective mirror
ASSET	Analysis of State Energy Tradeoffs Databank
ASTM	American Society for Testing and Materials
ASU	Arizona State University
BES	Basic Energy Sciences (within U.S. DOE Office of Science)
BEW	Behnke, Erdman & Whitaker Engineering
BIPV	building-integrated photovoltaics
BLM	Bureau of Land Management
BNL	Brookhaven National Laboratory
BOS	balance of systems
BSC	Basic Sciences Center (within the National Renewable Energy Laboratory)
BSF	back-surface field
Btu	British thermal unit
BU	Boston University
CAD	computer-assisted design
Caltech	California Institute of Technology
CBD	chemical bath deposition
CdTe	cadmium telluride
CEC	California Energy Commission
CET	Center for Ecological Technology
CIGS	copper indium gallium diselenide
CIGSS	copper indium gallium sulfur selenide
CIS	copper indium diselenide
CL	cathodoluminescence
CNT	carbon nanotube
COP	coefficient of performance
COSE	cost of saved energy
COTS	commercial off the shelf
CPS	Corporate Planning System
CPUC	California Public Utilities Commission
CPV	concentrating photovoltaics
CRADA	Cooperative Research and Development Agreement
C_{save}	cost of saved energy
c-Si	crystalline silicon
CSR	Climatological Solar Radiation (model developed by NREL)
CSS	close-spaced sublimation
CU	University of Colorado
CVD	chemical vapor deposition
CY	calendar year
CZ	Czochralski

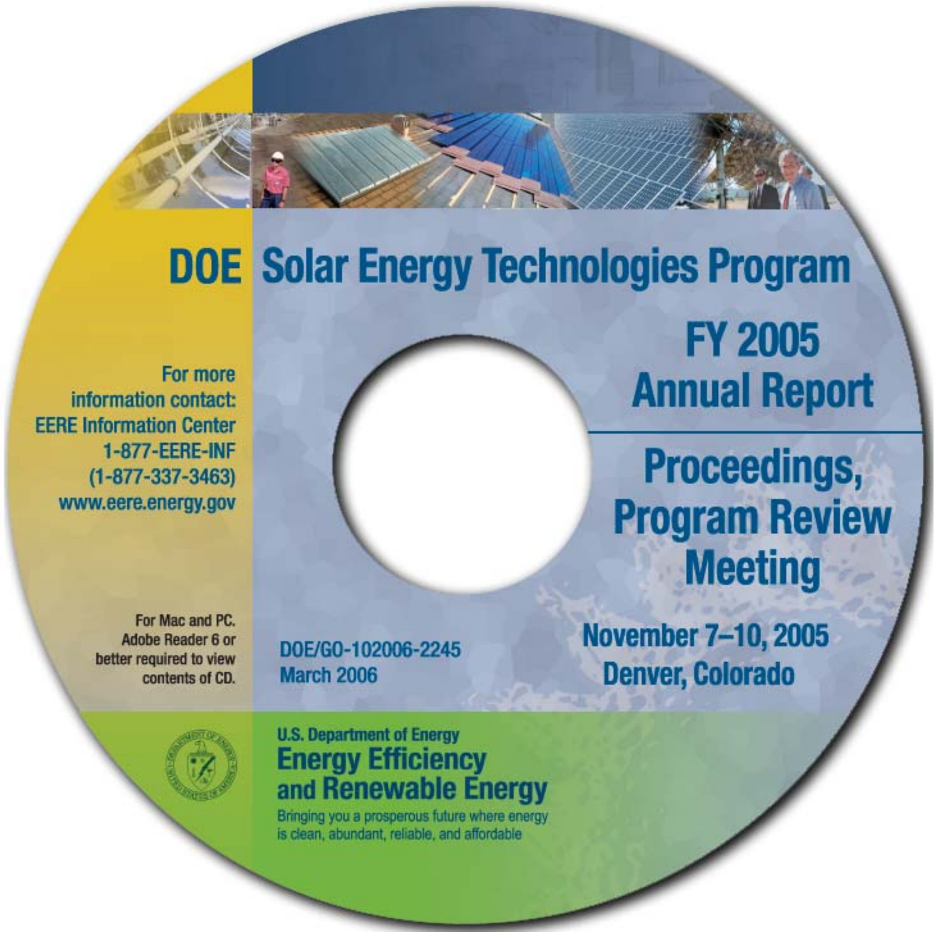
DC	direct current
DEG/SE	Davis Energy Group/SunEarth
DETL	Distributed Energy Technologies Laboratory (at Sandia National Laboratories)
DFMA	design for manufacturing and assembly
DFMECA	design failure mode effects and criticality analysis
DFR	design for reliability
DJ	dual junction
DLR	German Aerospace Center
DLTS	deep-level transient spectroscopy
DMA	dynamic mechanical analysis
DNI	direct normal incident
DoD	Department of Defense
DOE	Department of Energy
DSC	differential scanning calorimetry
DSP	digital signal processing
EAO	Energy Analysis Office
EERE	Energy Efficiency and Renewable Energy (U.S. Department of Energy office)
EFG	Edge-defined, Film-fed Growth
EH&S	environmental health and safety
EIA	Energy Information Administration
EM&D	Electronic Materials and Devices
EPA	Environmental Protection Agency
EPC	Engineer, Procure, Construct
EPS	environmental portfolio standard
EPV	Energy Photovoltaics
EUL	enhanced use leasing
EVA	ethylene vinyl acetate
EVMS	Earned Value Management System
FF	fill factor
FSEC	Florida Solar Energy Center (at University of Central Florida)
FY	fiscal year
GB	grain boundary
GE	General Electric
GIS	geographical information system
GO	Golden Field Office (U.S. Department of Energy)
GOES	Geostationary Operational Environmental Satellite
GPRA	Government Performance and Results Act
GPS	Global Positioning System
GSE	Global Solar Energy
GW	gigawatt
HALT	highly accelerated lifetime testing
HBCU	Historically Black Colleges and Universities
HEM	heat exchanger method
HFSF	High-Flux Solar Furnace
HFSS	High-Flux Solar Simulator
HQ	headquarters
HRII	High-Reliability Inverter Initiative
HRTEM	high-resolution transmission electron microscopy
HSL	hybrid solar lighting
HVAC	heating, ventilating, and air-conditioning
HWCVD	hot-wire chemical vapor deposition
IBAD	ion-beam-assisted deposition
ICS	integral collector storage
IDIP	In-Line Diagnostics and Intelligent Processing
IEA	International Energy Agency
IEC	Institute of Energy Conversion (at University of Delaware)

IEEE	Institute of Electrical and Electronics Engineers
IEP	Independent Energy Producer
IPP	Independent Power Producer
IR	infrared
IREC	Interstate Renewable Energy Council
IRR	internal rate of return
ISES	International Solar Energy Society
ISET	International Solar Electric Technologies
ISIS	Integrated Surface Irradiance Study
ISO	International Standards Organization
ISP	Institute for Sustainable Power
IST	Industrial Solar Technology
ITN/ES	ITN Energy Systems
JGCRI	Joint Global Change Research Institute
J_{sc}	short-circuit current
J-V	current-voltage
KIESD	Kentucky Institute for the Environment and Sustainable Development
kW	kilowatt
kWhe	kilowatt hour electric
kWht	kilowatt hour thermal
LACSS	large-area, continuous-solar simulator
LBNL	Lawrence Berkeley National Laboratory
LCA	life-cycle analysis
LCOE	levelized cost of energy
LD	laser diode
LED	light-emitting diode
LIPA	Long Island Power Authority
LOI	letter of interest
MBE	molecular beam epitaxy or mean bias error
MBMDPE	metallocene-based multi-density polyethylene
MDC	McDonnell Douglas Corporation
MEG	multiple exciton generation
MLTE	module long-term exposure
MOCVD	metal organic chemical vapor deposition
MPP	model power plant
MPPT	maximum power point tracking
MSR	Million Solar Roofs
MTBF	mean time between failure
MURA	Minority University Research Associates
MW	megawatt
MYPP	Multi-Year Program Plan
MYTP	Multi-Year Technical Plan
NABCEP	North American Board of Certified Energy Practitioners
NAHB	National Association of Home Builders
NASA	National Aeronautics and Space Administration
NCPV	National Center for Photovoltaics
nc-Si	nanocrystalline silicon
NEC	National Electrical Code
NEMS	National Energy Modeling System (of the International Energy Agency)
NEPA	National Environmental Policy Act
NETL	National Energy Technology Laboratory
NGO	non-governmental organization
NIR	near infrared
NIST	National Institute of Standards and Technology
NMSU	New Mexico State University
NRCC	Northeast Regional Climate Center

NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Data Base
NSTTF	National Solar Thermal Test Facility (at Sandia National Laboratories)
NTUA	Navajo Tribal Utility Authority
NWS	National Weather Service
NYSERDA	New York State Energy Research and Development Authority
O&M	operations and maintenance
OATS	Outdoor Accelerated-weathering Testing System
ORC	Organic Rankine Cycle
ORNL	Oak Ridge National Laboratory
OTF	Outdoor Test Facility (at National Renewable Energy Laboratory)
OWIP	Office of Weatherization and Intergovernmental Programs
PAE	planning, analysis, and evaluation
PBA	Office of Planning, Budget, and Analysis
PC	polycarbonate
PCU	power conversion unit
PEC	photoelectrochemical
PECVD	plasma-enhanced chemical vapor deposition
PERT	Performance and Energy Ratings Testbed
PI	principal investigator
PIER	Public Interest Energy Research (program of the California Energy Commission)
PMMA	polymethyl methacrylate
PNNL	Pacific Northwest National Laboratory
PTL	Photovoltaic Testing Lab (at Arizona State University)
PV	photovoltaics
PVD	physical vapor deposition
PVME	polyvinylmethylether
PVMR&D	PV Manufacturing R&D
PVPS	Photovoltaic Power Systems Programme (of the International Energy Agency)
PVSAM	PV Systems Analysis Model
PVSC	Photovoltaic Specialists Conference
PVSOL	PV System Optimization Laboratory (at Sandia National Laboratories)
QD	quantum dot
QDLED	quantum dot light-emitting diode
QE	quantum efficiency
QSSPC	quasi-steady-state photoconductance
R&D	research and development
RCPCD	resonant-coupled, photoconductive decay
REAP	Renewable Energy Academic Partnership
REC	renewable energy certificate
RES	Regional Experiment Station
RFP	request for proposal
RFQ	request for qualifications
RITH	roof-integrated thermosiphon
RMOTC	Rocky Mountain Oilfields Testing Center
RMSE	root mean square error
RO	reverse osmosis
ROI	return on investment
ROWPU	reverse osmosis water purification unit
RPS	renewable portfolio standard
RT	room temperature
RUS	Rural Utilities Service (of the U.S. Department of Agriculture)
S&TF	Science and Technology Facility
SAIC	Science Applications International Corporation
SAM	Solar Advisor Model
SBC	systems benefit charge

SBIR	Small Business Innovation Research
SDA	Systems-Driven Approach
SDHW	solar domestic hot water
SEGS	Solar Energy Generating Systems
SEIA	Solar Energy Industries Association
SEM	scanning electron microscope
SEPA	Solar Electric Power Association
SERES	Southeast Regional Experiment Station (at University of Central Florida)
SERF	Solar Energy Research Facility (at National Renewable Energy Laboratory)
SES	Stirling Energy Systems
SHC	solar heating and cooling
SHGR	Solar Hydrogen Generation Research
SHJ	silicon heterojunction
SHW	solar hot water
SIMS	secondary ion mass spectrometry
SKPM	scanning Kelvin probe microscopy
SMUD	Sacramento Utility District
SNL	Sandia National Laboratories
Solar PACES	Solar Power and Chemical Energy Systems
SolarDS	Solar Deployment Systems (model)
SPC	solid-phase crystallized
SPIE	International Society for Optical Engineering
SRCC	Solar Rating and Certification Corporation
SRP	Salt River Project
SSE	Surface Meteorology and Solar Energy (a NASA project)
SSI	Shell Solar Industries
STCH	solar thermochemical hydrogen
SUNY	State University of New York
SURFRAD	Surface Radiation Budget Network
SWH	solar water heating
SWRES	Southwest Regional Experiment Station (at New Mexico State University)
SWTDI	Southwest Technology Development Institute (at New Mexico State University)
TA	technical assistance
TBD	to be determined
TCC	transparent conductive coatings
TCO	transparent conducting oxide
TEM	transmission electron microscopy
TEP	Tucson Electric Power
TES	thermal energy storage
TIO	Technology Improvement Opportunity
TMY	typical meteorological year
TOU	time of use
TPD	temperature-programmed desorption
TVA	Tennessee Valley Authority
U of L	University of Louisville
UHV	ultra-high vacuum
UL	Underwriters Laboratories
ULRF	University of Louisville Research Foundation
UN	United Nations
UNLV	University of Nevada Las Vegas
UPS	ultraviolet photoelectron spectroscopy
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
UV	ultraviolet
VB	valence band
VBM	valence band maximum

V_{oc}	open-circuit voltage
VSHOT	Video Scanning Hartmann Optical Test
WGA	Western Governors' Association
WIP-I	Weatherization and Intergovernmental Program-International
WMO	World Meteorological Organization
WOM	WeatherOmeter
WREC	World Renewable Energy Congress
WRR	World Radiometric Reference
XPS	X-ray photoelectron spectroscopy
YDR	yield, durability, and reliability
ZEH	zero energy homes



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