DOE Solar Energy Technologies Program

FY 2004 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

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Introduction to the Solar Energy Technologies Program

Ray Sutula, Manager, DOE Solar Energy Technologies Program

The Solar Energy Technologies Program, located within the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, 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.

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 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 four 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. We will focus our efforts on realizing the benefits identified for EERE in the Government Performance and Results Act (GPRA) of 1993. The principal metric is gigawatts (GWs) 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 GWs. And, we must meet levelized energy cost goals that will open those markets.

We will use analytical techniques, based on the Systems-Driven Approach, 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 GWs installed. We will factor risk into this analysis, and we will use outside experts to ensure our analysis is robust.

Our multi-year technical plan, annual operating plan, and subcontracts will contain robust milestones, as defined in the stage-gate model for both commercialization and research paths. With the assistance of external experts, we will 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. We will rigorously apply the stage-gate process 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 2004 Solar Program Review Meeting is also included in 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, CO, and Sandia National Laboratories (SNL), in Albuquerque, NM. 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, CO, and the Albuquerque Operations Office (ALO), in Albuquerque, NM, 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 a current $.24/kWh to $.18/kWh. 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

In the area of basic research, the university contracts that support crystalline silicon research were recompeted, with a focus on innovative silicon crystal growth methods that improve throughput, conversion efficiency, and lower energy and material costs. In FY 2004, the high-performance advanced research area achieved the following record efficiencies: 37.3% for a 3-junction terrestrial concentrator cell and 19.5% for a thin-film cell. Present efforts are directed toward choosing and improving materials and processes that can maximize performance and have the potential for low-cost manufacturing.

The Thin Film PV Partnership received a 2004 R&D 100 Award, its seventh joint R&D 100 Award. In addition, NREL-supported thin-film technologies are resulting in significant acceleration in thin-film manufacturing and sales. Another milestone achieved in the thin-film R&D area was the recompetition of the Thin Film Partnerships in the summer of 2004, in time for contract awards in FY 2005. The new solicitation will seek a whole-system approach to reducing costs by increasing the manufacturability, efficiency, and reliability of systems by working with industry in a 50/50 cost-shared partnership.

The advanced manufacturing R&D area in FY 2004 achieved major technical progress in implementing an in-situ, on-line measurement tool to characterize the bottom and middle component cells of the triple junction; fabrication and testing of prototype automated string inspection system for solar cells; and installation of modules utilizing "faster-curing" and "flame-retardant" EVA-based encapsulant systems.

The Solar Decathlon, one of the program's most successful outreach efforts, will be back again in September 2005 with even more teams and an even more challenging competition. Eighteen teams, including the University Polytechnica de Madrid in Spain and Concordia University in Canada, have qualified and will be competing in 10 contests to see which school can design and build the most effective solar-powered house.

In modeling of the Systems-Driven Approach, a beta version of a PV systems performance and cost model was developed. In the next fiscal year, the program will begin expanding the sensitivity model to include solar thermal technologies.

Groundbreaking for a new Science and Technology Facility at NREL occurred late this summer, with the grand opening of the completed facility expected early in 2007. The new facility will provide 71,000 square feet of office and laboratory space. The facility 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.

A Growth Industry

This year the world PV market grew at a rate of more than 50%. For the past decade, the average growth exceeds 25%, which makes the PV industry one of the most consistent high-growth industries in the world. 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 safety and health.

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. The new PV Science Initiative started in FY 2003 is used to more fully develop the concepts and methods that can replace conventional technologies with a new generation of lower-cost, easier-to-manufacture technologies. In support of thin films, a clearer understanding of polycrystalline thin films using CdTe and $CuInSe_2$ (CIS) alloys is also being pursued. This research will lead to improved methods for addressing stability and degradation issues associated with fabricating thin-film materials on a larger scale.

Fundamental research is key to the continued advancement of photovoltaic technology necessary to meeting the long-term goal of achieving $0.06/kWh battery-free, grid-tied distributed 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 2004 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.
- Obtained ISO 17025 accreditation for secondary cell calibration under ASTM and IEC standards.

Electronic Materials and Devices

- Demonstrated important improvement in new and conventional devices with several record efficiencies: 18.5% in $Cu(In,Ga)Se_2$ solar cells using ZnS(OH) alternative buffer layers; 16.5% in 1-µm-thick CIGS absorbers; 19.5% 3-stage-grown CIGS; and 14.4% in CdTe devices on soda lime glass.

PV Exploratory Research

- Achieved 5.9%-efficient organic (plastic) solar cell.
- Identified and characterized metallic defects affecting most commercially available c-Si solar cells.

High-Performance Photovoltaics

- With Boeing Spectrolab, achieved a record efficiency of 37.3% for a 3-junction terrestrial concentrator cell—the highest NREL-confirmed efficiency yet measured for a PV device.

Solar Resource Characterization

- Wrote data management software for producing and managing a National Solar Radiation Data Base.

Environmental Health and Safety

- Analyzed life-cycle impact of cadmium in CdTe PV and the environmental impact of the production of elements in CIGS.

Measurements and Characterization

Performing Organization: National Renewable Energy Laboratory

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

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

FY 2004 Budget: $7,280K

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, universities, and NREL.
- Obtained ISO 17025 accreditation for secondary cell calibration under ASTM and IEC standards.
- Completed investigation of the microstructure and electrical properties of the c-Si/a-Si interface in Si HIT cells.
- Organized the 14th Workshop on Crystalline Silicon Solar Cell Materials and Processes.
- Completed design and construction of a RCPCD apparatus with auto-tuning as a diagnostic for large-area Si wafers produced in a manufacturing environment.
- Reached the 90% completion point for the International Module Intercomparison study.
- Completed study of the growth morphology, defect structure, and compositional uniformity of dilute nitride alloys targeted for multijunction III-V devices.
- Completed a study of CdTe back-contact chemistry aimed at achieving better process control, reproducibility, and reliability.
- Validated the surface analysis test platform for process integration.
- Completed preliminary design specifications of the process integration platform to facilitate seamless integration of deposition, processing, and characterization tools.

Future Directions

- Obtain ISO 17025 accreditation for secondary *module* calibration under ASTM and IEC standards using the large-area, continuous-solar simulator (LACSS).
- Complete International Module Intercomparison study (complete data analysis and publish final technical report).
- 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 multicrystalline Si wafers 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 to device performance.

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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 energy cost 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 five core competency research tasks and a management/coordination task. The five research tasks are Analytical Microscopy, Cell and Module Characterization, Electro-optical Characterization, Surface Analysis, and Process Integration. The major *non-support* research activities pursued in FY 2004 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 2004 priority milestones in each task are listed below.

2.1 Analytical Microscopy Task

- Complete study of the growth morphology, defect structure, and compositional uniformity of dilute nitride alloys.
- Investigate the microstructure and electrical properties of the c-Si/a-Si interface in Si HIT cells.

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

2.2 Cell and Module Performance Task

- Obtain ISO 17025 Accreditation for secondary cell calibration under ASTM and IEC standards.
- Reach the 90% completion point for the International Module Intercomparison study; Initiate outline of technical report due FY 2005.

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

2.3 Electro-Optical Characterization Task

- Complete detailed DLTS studies of the defect content of GaAsN materials to identify the impurities or defects that degrade PV device performance.
- Organize the 14th Workshop on Crystalline Silicon Solar Cell Materials and Processes.
- Complete design and construction of a RCPCD apparatus with auto-tuning as a diagnostic for large-area wafers produced in a manufacturing environment.
- Complete development of a high-speed, non-contact. wafer-thickness measurement and mapping system and apply this method to Si wafers used by the PV industry.

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

2.4 Surface Analysis Task

- Validate surface analysis test platform for process integration.
- Complete a study of the CdTe back contact chemistry aimed at achieving better process control, reproducibility, and reliability.

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

2.5 Process Integration Task

- Complete preliminary design specifications of the process integration platform to facilitate seamless integration of deposition, processing, and characterization tools.

A summary of progress on this milestone is outlined in section 3.5.

Budget allocations by task are provided below.

Task Title	FY 2004 Budget ($K)
Analytical Microscopy	1,468
Cell and Module Performance	1,168
Electro-Optical Characterization	1,787
Surface Analysis	1,201
Process Integration	523
Mgmt./Maintenance/HiPerPV	1,133

3. Results and Accomplishments

Research results outlined in this section address only FY 2004 priority 3 and 4 milestones, and therefore, this report 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, along with the corresponding link in the *DOE Solar Program Multi-Year Technical Plan* (MYTP), are outlined below.

3.1 Analytical Microscopy Task

Growth morphology, defect structure, and compositional uniformity of dilute nitride alloys (MYTP CPV M-2, T-1): In collaboration with NREL's III-V Group, MOCVD-grown GaNP and GaNPAs epitaxial layers on Si substrates were investigated by TEM and CL. These structures are being developed for multijunction devices on Si. Particular emphasis was placed on the initiation of growth on Si substrates as that determines the structural quality of the device. GaNP layers grown on Si substrates (annealed prior to growth under PH_3) and a thin GaP buffer layer contained a high density of threading dislocations and antiphase domains. The antiphase domains were confined in the region close to the substrate/layer interface. In addition to the above defects, transmission electron diffraction revealed evidence of weak CuPt-type ordering in the GaNP alloys. To investigate the origin of defects and antiphase domains in MOCVD GaNP and GaP layers grown on Si substrates, a series of thin GaP layers grown on Si, using different substrate annealing and growth conditions, were examined. The growth conditions for achieving the lowest density of dislocations and antiphase domains were ascertained.

Microstructure and electrical properties of the c-Si/a-Si interface in HIT Si cells (MYTP M-12, T-2): In collaboration with NREL's Si group, the microstructure and interface properties of HIT cells were investigated. Such cells have recently demonstrated world-record efficiency on single-side, untextured Si HIT structures. The microstructure of these record-efficiency cells and other Si HIT cells with lower efficiency was investigated using high-resolution and analytical-electron microscopy. We found that thinner n-layer and a high-quality heterojunction are two critical parameters for achieving high efficiency.

The Si HIT cells with record efficiency exhibited almost perfect c-Si/a-Si interfaces and a thin, but uniformly n-type, a-Si layer, as shown in Fig. 1. The cells with lower efficiency (e.g., low V_{oc}) always showed either an imperfect c-Si/a-Si interface or a too-thick n-layer. The structure of some textured Si HIT cells has also been investigated. We found that the quality of the texture (i.e., the uniformity) directly affects cell performance.

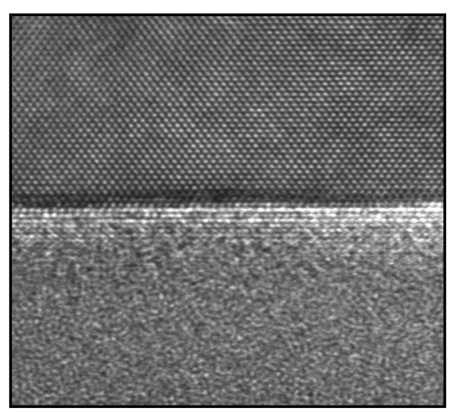

Fig. 1. TEM micrograph of a c-Si/a-Si interface of a high-performance Si HIT cell

In addition, we measured the spatial distribution of the electrical potential on cross sections of HIT Si cells using scanning Kelvin probe microscopy (SKPM). Because SKPM measures the distribution of surface potential, which is influenced by surface charges, we measured the potential changes induced by an external-bias voltage (V_b), which is equivalent to the potential change in the bulk. In this way, we were able to avoid the effect of surface charges or the surface Fermi-level pinning and obtained the V_b-induced potential changes in the bulk. We found that with a small V_b of $\sim \pm 0.2$ V, the electrical junction coincides with the metallurgical interface of crystalline/amorphous Si within the resolution and statistical error of the measurement. The location of the electrical junction with the small V_b should be close to that of the "intrinsic" electrical junction without a V_b.

Role of local built-in potential on grain boundaries in Cu(In,Ga)Se_2 thin films and its effects on device photoconversion efficiency: Using SKPM, we observed that a local built-in potential exists on grain boundaries (GBs) in CIGS films. The SKPM potential image taken on samples that produced record-efficiency devices clearly showed a higher potential or a smaller work function on the GB than on the grain surface. The built-in potential on the GB was caused by positive charges trapped at the GB, and the potential can be expected to attract electrons and repulse holes and thus help in the collection of minority carriers. Further, we carried out detailed experimental work to determine whether such built-in potential on the GBs benefits device performance. This was done by varying the Ga content in the CIGS films and examining how the potential on the GBs changes with the Ga content. We have demonstrated that the local built-in potential on GBs of CIGS films indeed plays a significant role in photoconversion efficiency of the device.

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 attaining ISO 17025 accreditation for secondary-cell calibration under ASTM and IEC standards. The American Association for Laboratory Accreditation (A2LA) awarded the accreditation to NREL on September 14, 2004 (see Fig. 2).

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.

American Association for Laboratory Accreditation
Corporate SEAL 1978 District of Columbia
A2LA

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. 2. A2LA ISO 17025 accreditation certificate

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 same companies rely on NREL for secondary-cell calibrations of the reference cells they use to measure their products. 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.

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 has 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, Sandia, Arizona State Photovoltaic Testing Laboratory, Florida Solar Energy Center, 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. We are currently on schedule to complete this study, and a final report will be complete in FY 2005 as planned.

3.3 Electro-Optical Characterization

Deep-level transient spectroscopy (DLTS) of GaAsN alloys used in multijunction solar cells (MYTP CPV M-2, T-1): The characterization and understanding of electronic defects in PV materials is vital to the advancement and use of PV materials and devices. This milestone focuses on the investigation of defects detrimental to the material and device quality of epitaxial GaAsN. This material system is a key component of the effort to achieve new world-record efficiencies for multijunction III-V solar cells. An electron trap in p-type GaAsN alloy material was detected when N was added to GaAs epilayers. This electron trap increased in concentration with increased N content for small concentrations (less then 0.6%). A bandgap reduction to approximately 1 eV would be required for certain solar cell configurations, requiring over 2% N. With less than 1% N added to GaAs epilayers, the material's bandgap decreased only slightly, however, we found that the solar cell's open-circuit voltage (V_{oc}) decreased substantially. This decrease in V_{oc} also corresponded to the appearance of the DLTS electron trap. A model that used a fit of the electron trap's activation energy as a function of N content and proposed that the quasi-Fermi levels be pinned by the large number of these electron traps was shown to reasonably explain the decreased V_{oc} values that were measured. Besides correlating the electron trap and its activation energy to the amount of decreased V_{oc}, the appearance of the electron trap itself was characterized and modeled. Experimental results closely followed this model and showed that for such values of Schottky barrier, trap energy, capture rate, and trap concentration, electron traps could be detected in p-type material using only reverse bias.

14th Crystalline Si Workshop (MYTP M-9, T-1 and M-11&12, T-2): Bhushan Sopori organized the 14th Workshop on Crystalline Silicon Solar Cells and Modules: Materials and Processes*,* which was held in Winter Park, Colorado, August 8–11, 2004. In attendance were 118 scientists and engineers from 28 international PV and semiconductor companies and 22 research institutions. The theme of the workshop, *Crystalline Silicon Solar Cells: Leapfrogging the Barriers,* reflected progress in Si-PV technology over the past three decades, despite a host of barriers and bottlenecks. This workshop provides an invaluable opportunity to learn about current trends in both the European and Asian Si PV communities.

Auto-tuning RCPCD apparatus development (MYTP M-22&25, T-6): A new, contactless measurement technique was developed based on the RCPCD technique. This technique, which has been applied to silicon wafers and several other materials, has generated several external publications. The sensitivity of minority-carrier lifetime allows the characterization of material quality by using non-destructive and contactless photoconductive decay. Although capable of measuring many types of materials, the resonant-coupled, photoconductive-decay (RCPCD) technique is particularly applicable to indirect-bandgap (Si) and small-bandgap materials (InGaAs). The present system requires pre-measurement tuning by simultaneously adjusting multiple components. A system expert can easily make point measurements, but continuous tuning to measure multiple samples or map multiple points on a single-large sample would be tedious and time consuming. An automated system has been constructed that can perform the following functions: 1) move stage to load position for initial placement of sample; 2) move stage to measurement position; 3) auto-tune multiple controls to find the most sensitive measurement condition; and, 4) fit photoconductive decay curve, returning a decay time constant or lifetime value. This demonstrates all elements necessary for a manufacturing-friendly diagnostic tool.

Complete development of a high-speed, non-contact wafer thickness measurement and mapping system and apply this method to Si wafer used by the PV industry (MYTP M-22&23, T-6): A new diagnostic for rapidly mapping the thickness of antireflection (AR) coatings was developed and tested in FY 2004. This technique uses an imaging approach obtained by fitting the previously developed PV Reflectometer with a CCD camera and a band-pass filter so that a spatial-reflectance image of a sample can be obtained. In the resulting image, the local values of the intensity are inversely proportional to the AR coating thickness. This proportionality allows an easy conversion of reflectance image into a thickness image. With this modification, the Reflectometer can be operated in either the spectrum or imaging mode. In the spectrum mode, the reflected light is directed to a diode array spectrometer to rapidly measure "average" parameters of the entire wafer/cell (for process monitoring). In the imaging mode, the reflected light is filtered and directed to a camera to generate an image of the AR-coated wafer. This technique is also applicable for mapping wafer thickness and meets an important FY 2004 Division milestone.

Figure 3 shows AR thickness images of two samples from the same batch of production wafers (textured and AR-coated) from a solar cell manufacturer. The maps show the wafer-to-wafer variation caused by deposition system inconsistencies. Also shown are horizontal and vertical line profiles along the center of each wafer.

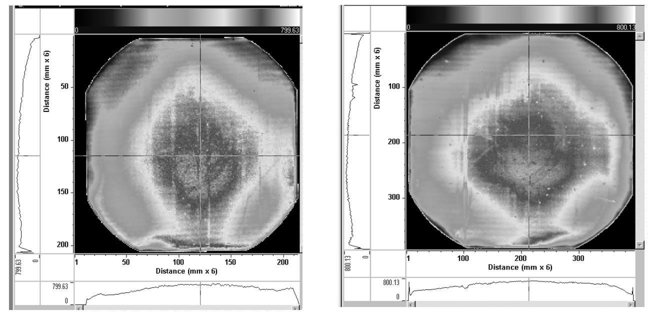

Fig. 3. AR coating thickness maps from two wafers from the same batch, showing AR coating thickness uniformity.

3.4 Surface Analysis

Process integration tool development (MYTP M-5, T-1): During FY 2004, we completed construction and testing and began regular operation of the surface analysis test platform for process integration, also referred to as the cluster tool. This project involved integrating the team's x-ray and ultraviolet photoelectron and Auger electron spectrometers (XPS/UPS, AES) together with a deposition system and nitrogen-purged glove box (see Fig. 4). All four stations are connected through an ultra-high vacuum (UHV) transfer system. This new capability allows us to study controlled surfaces, with and without exposure to atmosphere, ultimately leading to better fundamental understanding of PV materials and device properties.

Fig. 4: Photograph of the surface analysis process integration tool completed in FY 2004

In FY 2004, we initiated several major experiments (described in the following) that demonstrate the utility of this system.

An XPS and UPS investigation of CBD-related CIGS surface chemistry was initiated. CIGS films were exposed to both partial electrolyte and full chemical bath depositions in the glove box. Processed films were transferred *in situ* to the XPS for analysis. High-resolution, core-level spectra show removal of contaminants, as well as the depletion of Ga and In from the surface due to ammonium hydroxide exposure (partial electrolyte). XPS and UPS measurements on these surfaces show the presence of a Cu^{+1}, consistent with the formation of a detrimental layer of Cu_2Se at the surface. Measurements made after controlled air exposures of the treated surface show that this state disappears in minutes. This experiment would be impossible without the cluster tool. This work was presented at the IEEE PV Specialists Conference, January 2005.

A unique photoemission study was completed investigating doping mechanisms in p-type nitrogen-doped ZnO thin films. By making use of *in-situ* ion-implantation and characterization techniques in the XPS, it was possible to quantify and identify for the first time four different nitrogen chemical environments in ZnO. Systematic differences in abundances of these nitrogen chemical states were observed between films grown via MOCVD and reactive sputtering. The data have led to new explanations for poor nitrogen electrical activity normally found in N-doped ZnO and the realization that MOCVD films grown with diethylzinc have significant levels of carbon contamination. Based on the results, recommendations were made for changes in growth methods that should lead to improved nitrogen doping of ZnO. This study would not have been possible without the ability to create and study clean surfaces in the cluster tool. This work has been accepted for publication in the *Journal of Applied Physics* in early 2005.

Improvements were made to the standard chemical-bath deposition process for CdS window-layer growth on CIGS by adding a non-interfering nonionic surfactant to the bath. The surfactant eliminates bubble formation, thereby improving coating uniformity. Devices made with the new CdS had a 23% efficiency gain relative to devices with standard CBD-grown CdS, which is due primarily to an average increase of 93 mV in V_{oc}. Experiments using the cluster tool show that carbon and oxygen are incorporated during normal CBD growth and are not from the surfactant.

Complete a study of the CdTe back contact chemistry, aimed at achieving better process control, reproducibility, and reliability (MYTP M-19-21, T-5): During FY 2004, we made important advances toward understanding the chemistry between Cu and CdTe. Cu is a critical component in most thin-film CdTe back contact schemes. The major points are summarized below. All of these results have important ramifications for fabricating stable back contacts to CdTe, and none could have been obtained without the capabilities provided by the cluster tool.

We measured the reaction kinetics of Cu with the CdTe(111)-B surface by *in-situ* deposition of Cu on clean CdTe followed by temperature-programmed desorption (TPD) experiments. The TPD experiments show the rate of reaction for Cu with CdTe is zero order, or independent of concentration.

We observed a temperature-reversible surface-segregated Cu-phase on CdTe(111)-B surfaces by using *in-situ* temperature-programmed XPS measurements. The Cu segregates in a monolayer thick phase at the surface of the CdTe at lower temperatures and diffuses into the bulk as the temperature is raised. Cu will reversibly re-segregate as the temperature is lowered. The transition temperature for this change is 250°–300°C. XPS shows that the Cu and Cd concentrations are complementary, implying Cu displaces Cd in the surface phase.

We observed a metastable Cu_xTe bulk phase at the CdTe(111)-B surface after experiments involving deposition of Cu and heating to 250°–300°C (temperatures well within the processing range of CdTe devices). Although it appears in the same temperature range, this phase is separate from the surface-segregated phase identified above. The bulk Cu_xTe phase inhibits faceting of the surface (see Fig. 5). High-resolution Auger microscopy shows that flat areas contain Cu and no Cd, whereas triangular pit regions are free of Cu and contain Cd.

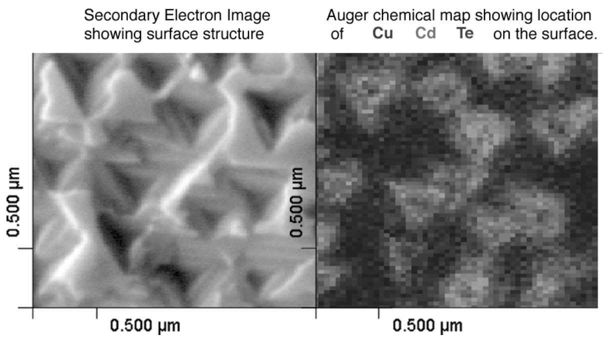

Fig. 5: Secondary electron micrograph and corresponding Auger map of a CdTe(111)-B surface after experiments involving deposition of Cu and heating to 250°–300°C.

Through UPS measurements, we observed that Cu changes the near-surface, valence-band (VB) structure. For clean CdTe, the VB is about 0.5 eV below the Fermi level, whereas CdTe with surface-segregated Cu has electronics states just below the Fermi level. An experiment to test the significance of this observation was designed and carried out. Au contacts were deposited *in situ* on a clean CdTe surface with and without the surface-segregated Cu phase. The Au/CdTe contact exhibited rectifying Schottky-type behavior, whereas the Au/Cu/CdTe contact was ohmic. Ongoing work will seek to discriminate between doping by diffused Cu and the surface-segregated phase.

We studied the chemical changes at the CdTe surface that result from steps used by a particular manufacturer in its process. This work mimicked a wet chemical step used to treat the back surface of CdTe devices. Samples were treated in a N2-purged glove box and then transferred directly to vacuum, via the cluster tool, for analysis. We have shown that this part of the process removes oxide and carbonaceous contaminants from the CdTe surface and also preferentially removes Cd, leaving a thin, beneficial Te layer. This work was extremely significant for the manufacturer.

3.5 Process Integration Task

Complete preliminary design specifications of the process integration platform to facilitate seamless integration of deposition, processing, and characterization tools (MYTP M-5, T-1): A contract was awarded to Transfer Engineering to develop detailed engineering drawings for the prototype process-integration tool that is based on a detailed set of design specifications (25-page statement of work) developed by the NCPV design team. Issuing the contract to complete engineering services marks a significant milestone in the process-integration project. The contract includes the following scope:

- Full-design engineering of a prototype tool, such that the final design package can be sent out for bid to a tool fabrication company
- Engineering design to incorporate the following elements into the prototype tool:
  - Sample platen designs that can accommodate several substrate configurations
  - A transport pod to provide a means of moving sample platens between future tools
  - A dock to provide an interface between the transport pod and the tool chamber and house the sample transfer mechanisms
  - A thermal test chamber to test out heater designs for heating uniformity, and other tests, and expansion for PVD applications.
  - A transfer mechanism to reliably move the platen between various system components.

NREL will own these designs, allowing us to incorporate the design into future tools. Many groups within the NCPV are currently using these ideas and incorporating them into their next generation tools so they will be prepared to make the best possible purchases as capital equipment funds become available. Once the design is finalized, a separate RFQ will be prepared for the fabrication of the prototype tool.

4. Planned FY 2005 Activities

A list of selected FY 2005 planned activities is given below. A more complete list of planned activities and milestones can be found in the Measurements and Characterization FY 2005 Annual Operating Plan. In FY 2005 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.
- Complete International Module Intercomparison study. Complete data analysis and publish final technical report.
- Obtain ISO 17025 accreditation to secondary module calibration under ASTM and IEC standards using the large-area, continuous-solar simulator.
- Develop a prototype minority-carrier lifetime measurement system capable of accurately measuring both crystalline and multicrystalline Si wafers in an in-line manufacturing environment.
- Conduct experiments to examine the structural, chemical, and electrical properties of the crystalline Si/amorphous Si interface in HIT cells and correlate these properties to device performance.
- 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 of facilitating 25-year module warranties.
- Organize the 15th Workshop on Crystalline Silicon Solar Cell Materials and Processes.

5. Major FY 2004 Publications

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Electronic Materials and Devices

Performing Organization: National Renewable Energy Laboratory

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FY 2004 Budget: $9,245K

Objectives

- Initiate research on high-performance heterojunction silicon solar cells.
- Develop high-throughput materials research using combinatorial processes for deposition, diagnostics, and data analysis.
- Test intrinsic device stability under water vapor and selected spectral and thermal stresses for CdTe cells.
- Demonstrate a >13% CdTe cell fabricated with the simplified process.
- Evaluate optimized cells grown by MBE to assess GaInAsN for multiple-junction cells.
- Select *in situ* diagnostic tool and control system design for CIGS deposition system upgrade.

Accomplishments

- Increased V_{oc} to 628 mV in amorphous silicon on p-type silicon heterojunction solar cells.
- Installed and evaluated single-wavelength optical reflectance spectroscopy to be used as an *in situ* diagnostic of thin-film growth.
- Demonstrated power of combinatorial diagnostic tools for rapid screening of materials properties.
- Established operational laboratory for evaluation of intrinsic device stability and initial linkage between device design/processes and stability.
- Demonstrated important improvement in new and conventional devices with several record efficiencies, including:
    - 18.5% efficiency in $Cu(In,Ga)Se_2$ solar cells using ZnS(OH) alternative buffer layers
    - 16.5% efficiency in 1-µm-thick CIGS absorbers
    - 19.5% efficiency in 3-stage-grown CIGS
    - 14.4% efficiency in CdTe devices processed on soda lime glass.
- Achieved quantum efficiencies >90% in dilute nitride 1-eV cells.
- Demonstrated functional GaNPAs/Si multiple-junction solar cell.

Future Directions

- Advance the understanding and performance of heterojunction silicon devices.
- Explore new concepts aimed toward preparation of crystalline silicon films on glass.
- Establish new capabilities in combinatorial deposition, diagnostics, and data mining.
- Push thin-film technologies toward higher throughput by increasing deposition rates and reducing thickness.
- Improve the understanding and performance of heteroepitaxial III-Vs on silicon.

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1. Introduction

The Electronic Materials and Devices Project carries out research in semiconductor materials, device properties, and fabrication processes to improve the efficiency, stability, and cost of photovoltaic solar energy conversion. This research can be characterized in three forms. First, we apply our capabilities to assist industry and the National Research Teams in addressing current problems. Second, we explore specific techniques and processes to develop and transfer technology improvements that industry will soon need. Finally, we seek to create new technologies and lead the development of the knowledge base and tools for the future of PV. Through these activities, the project supports both flat-plate and concentrator PV technologies at the cell and module level, in all of the application targets and time frames identified in the *DOE Solar Program Multi-Year Technical Plan*. Our work spans all of the major PV technologies, from silicon wafers through organic nanocomposite films. Our work is best known for the world-record efficiencies we have achieved in each of the materials systems under investigation. These accomplishments are the result of continuous improvement in the quality of our materials and innovation in design of device structures. During 2004, we continued to increase our emphasis on innovation in materials processing. This is opening new opportunities to accelerate the pace of research and the potential for technology transfer, with the targets of simplicity, high throughput, and improved source utilization and yield.

2. Technical Approach

The project is composed of four primary research tasks and management. The management task coordinates project planning and operations within the PV program 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 Silicon Materials

- Amorphous/crystalline silicon heterojunctions
- Ta-wire HWCVD a-SiGe:H low-gap cells
- Film crystalline Si on glass
- Optical/capacitive spectroscopy of defects in PV cells.

2.2 Process and Advanced Concepts

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

2.3 Thin-Film Polycrystalline Compounds

- Wide-bandgap absorbers for polycrystalline thin-film tandem solar cells
- Comparative study of the junction and interface formation and properties in CdTe/CdS and the Cu-chalcopyrite system
- TCOs for thin-film solar cells
- Develop simplified and improved processes for CdTe and CIS manufacture
- Thinfilm intrinsic device stability.

2.4 Concentrator Crystalline Cells

- Dilute nitrides for 4-junction GaInP/GaAs/GaInAsN/Ge or similar cell
- Multijunction GaNP on silicon
- Novel lattice-mismatched cell.

Budget allocations by task are provided below.

Task Title	FY 2004 Budget ($K)
Silicon Materials	1,994.8
Process and Advanced Concepts	1,896.8
Thin-film Polycrystalline Compounds	3,069.7
Concentrator Crystalline Cells	1,940.0
Electronic Materials Management	343.7

David Ginley, task leader for Process and Advanced Concepts, created a contractual mechanism for all of NREL through which we are able to engage students from local universities in collaborative research. This University Collaboration program provides a blanket subcontract that allows investigators from NREL to identify a topic of investigation of importance to an NREL project and suitable for thesis research for a student. The student then works primarily on site at NREL with both campus and NREL advisors. The professor participates in project meetings at NREL and is engaged in the NREL work. Obviously, the EM&D project takes full advantage of this innovative mechanism. In FY 2004, six students and postdocs from the Colorado School of Mines were supported for PV research through this program.

3. Results and Accomplishments

The a-Si:H/c-Si heterojunction (SHJ) solar cell opens opportunities for low-temperature junction formation and higher device performance. Avoiding the high-temperature diffusion process should improve the minority-carrier lifetime in conventional c-Si wafers and may be a critical enabling technology for thin-film crystalline silicon-on-glass solar cells.

Research on SHJ cells was initiated in 2004 in collaboration with the Center of Excellence at the Georgia Institute of Technology (GIT). Our work has focused on understanding and controlling the interface between the deposited silicon film and crystalline wafer. At this time, devices are simple planar junctions prepared at NREL on wafers processed by GIT using a screen-printed back contact. These have achieved V_{oc} of 628 mV, exceeding our 620-mV project milestone.

We use HWCVD to deposit low-temperature hydrogenated silicon thin films as the emitter and back-surface field (BSF) layers on p-type c-Si wafers. As the bulk of silicon PV production makes use of p-type wafers, this direction may speed industrial adoption. HWCVD could prove superior to the commonly used PECVD for SHJ solar cells because of simplicity of the system, reduced ion bombardment, low powder formation, and high densities of atomic hydrogen (H) generation, which may passivate the wafer interface region.

The crystallinity of the deposited Si layer is found 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. We have found that epitaxy is more likely on a (100) substrate than on a (111) substrate, even at temperatures as low as 200°C. When we lower the substrate temperature to 100°C, abrupt amorphous silicon growth is obtained, even on a (100) wafer, yielding a V_{oc} greater than 620 mV. Figure 1 illustrates V_{oc} as a function of the substrate temperature for HWCVD of the amorphous silicon heterojunction layers.

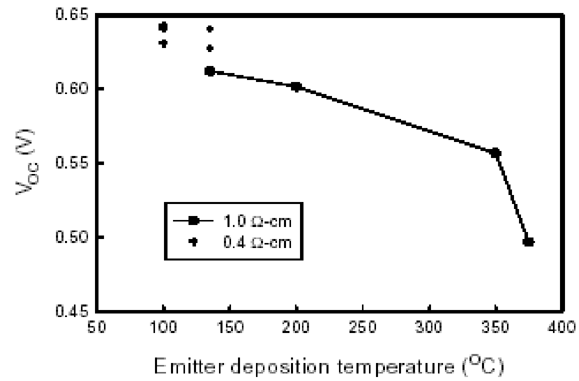

Fig. 1. V_{oc} vs. HWCVD amorphous silicon deposition temperature

The Silicon Materials and Devices Group is also active in using its resources to help solve near-term problems. For example, Solaicx is a PV start-up company that found help at NREL in testing prototypes for production. As part of the company's plan to provide high-quality, low-cost silicon wafers to the photovoltaic industry, Solaicx researchers are investigating new ceramics-based crucibles designed to have longer usable life and also produce high-lifetime Czochralski silicon. They contacted our group to assist in testing the crucibles. Growth was complicated by differences in radio-frequency (rf) coupling compared with conventional quartz crucibles housed in a graphite susceptor. We modified a rf-heated crystal puller and used the Solaicx experimental crucibles to successfully grow two crystal ingots, which are now being tested at Solaicx.

Assistance is of little value if results are not delivered in a quality and pace that exceed expectations. Another recent example of rapid problem solving involved collaborating with a thin-film PV company that sought to understand a new class of transparent conducting oxides. Their interest was piqued by a singular result of titanium doping in indium oxide. We applied our still developing capability in combinatorial deposition and film analysis to quickly screen the properties of alloys of InO_2 and TiO_2 over the full range of composition. The entire experiment, which could have takes months using conventional methods, was completed in a few weeks. The results (shown in Fig. 2) quickly guided further research to compositions of around 20% Ti.

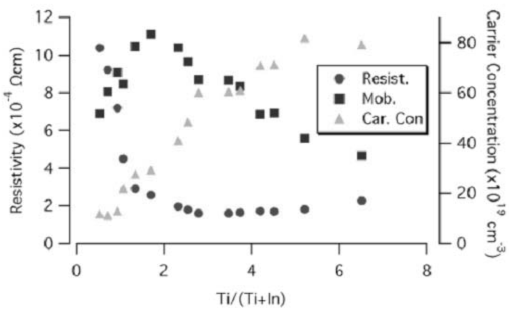

Fig. 2. Electronic properties of $InTiO_x$

One of the most important developments in the thin-film technologies is demonstrated in the 18.5% record efficiency achieved for Cu(In,Ga)Se_2-based solar cells that incorporate a zinc sulfide (ZnS) compound as an alternative to the cadmium sulfide (CdS) layer in its device structure. Not only does the compound avoid perceived problems in the use of Cd, but its wider bandgap may enhance current generation and therefore improve performance. The wider bandgap value should in principle lead to additional current generation in the device, because additional photons, those no longer screened by the CdS layer, would now contribute to the overall photocurrent. The cell J-V parameters are as follows:

V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)
670	35.11	78.78	18.5

These J-V parameters are indeed very comparable to the current world-record devices that incorporate CdS (19.5% efficiency as we previously reported). High-efficiency CIGS cells have been fabricated without the need to do multiple coatings or extensive post-anneals, cumbersome processes required in earlier work. At this early stage of research, the ZnS layers can perform as well as CdS layers, and they represent another option to achieve >20% conversion efficiencies with further optimization.

Research targeting mid- or long-term applications engages collaborators just as described in the near-term problem-solving realm. For example, our work toward understanding the basic mechanisms involved in the formation of photovoltaic junctions in CIGS solar cells has been done in conjunction with the CIS National Team and several industrial partners. This model produced an early success with results for the cadmium partial electrolyte (Cd PE) treatment. This was developed on NREL absorbers and extended to Shell Solar Industries (SSI) absorbers. During the current period, we were involved in a joint experimental study with the absorber and junction subteams of the national team. The absorber team attempted to find a "figure of merit" that will enable us to distinguish a "good absorber" from a "bad absorber." NREL absorbers and devices were provided for this study to serve as a benchmark for comparisons with other devices. Correlations between deep-level density and device performance was established. An unexpected (and possibly more interesting and useful) outcome of this exercise was the remarkable difference in the performance of solar cells fabricated from SSI absorbers where the window layers were processed at SSI and NREL.

High-efficiency devices are gaining increased attention as novel concepts are proposed to push efficiencies above 50%. Much of this would be summarily dismissed, were it not for the very real achievement of 37% efficiency in III-V multiple-junction devices. Building from NREL's 1985 invention of the dual-junction GaInP/GaAs tandem cell, all of the present 3-, 4-, and 5-junction designs drop from optimum performance because of the absence of a good option for a device at 1.0-eV bandgap. The dilute nitride systems hold the greatest promise for meeting this need, but to date have not delivered the high quantum efficiency needed to match the current of the rest of the structure. One way to accomplish an increase of current from the GaInNAs junction is to employ a p-i-n structure with a wide, intrinsic base layer. We have succeeded in growing GaInNAs solar cells with depletion widths ~3 µm by MBE, a hydrogen- and carbon-free growth technique, which minimizes impurities and the formation of associated point defects. For comparison, GaInNAs grown by MOCVD typically shows background carrier concentrations near 10^{17} cm^{-3}, with corresponding depletion widths of ~0.2 µm as-grown. These new MBE-grown cells, most with bandgaps near 1.3 eV, show greatly enhanced short-circuit currents and QEs compared to reports in the literature. In addition, recent cells with Eg~1.15 eV show no degradation in depletion width or QE compared to samples with higher bandgaps. Figure 3 shows the QE measurements of three GaInNAs solar cells, displaying the difference between wide and narrow depletion widths at Eg~1.3 eV, as well as the QE from a cell with Eg~1.15 eV. This basic cell structure does not employ a BSF, and has no window layer and no way to remove the contact layer after processing. This leads to recombination of carriers at the front surface and the associated poor blue response. The QEs for the samples with the wide depletion widths are, to our knowledge, the best reported for a GaInNAs sample.

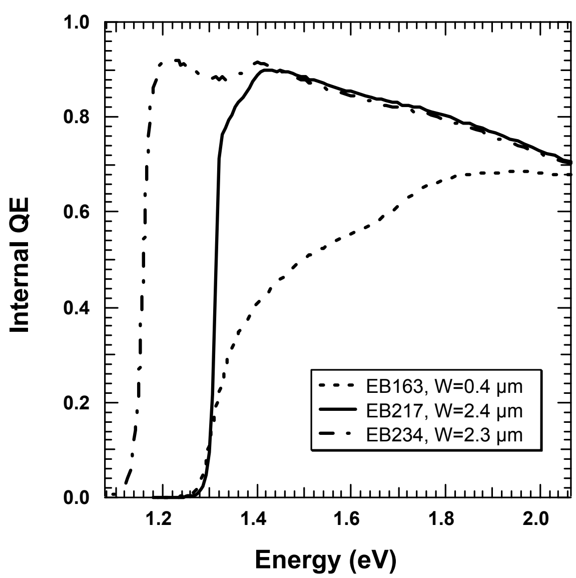

Fig. 3. Comparison of QEs for similar samples with wide and short depletion widths

High-efficiency skeptics will level their first criticism of the technologies at the cell manufacturing costs. With widespread use of comparable technologies in light-emitting diodes for traffic signs and other illumination applications, along with continued development of satellite power, the devices are easily compatible with cost targets for concentrating PV systems. Further improvements may well need to target the substrates used for manufacture of these thin-film cells. The present technology using germanium wafers faces barriers in reducing the cost of the substrate and production efficiency limited by the relatively small area of current substrates. Development of technology to build high-performance devices on silicon substrates would address both of these barriers. NREL's work in this area during 2004 shows some substantial progress. Again, the properties of dilute nitride are exploited to minimize change in the lattice constant of the alloy while engineering the desired bandgap. In this case, the GaNPAs alloy is explored to produce a top cell for use on silicon. Figure 4 displays the quantum efficiency for a GaAsNP and silicon junctions. These were assembled along with a tunnel-junction interconnect to make the first functioning GaAsNP/Si tandem cell.

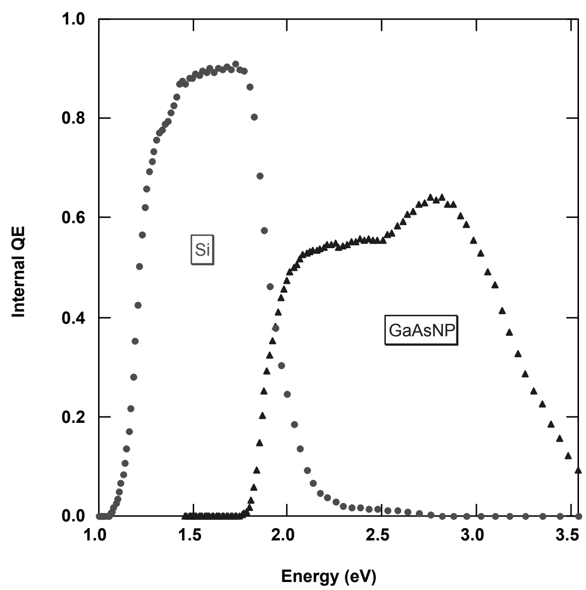

Fig. 4. Quantum efficiency measurement of the component junctions of a III-V-on-silicon tandem solar cell

4. Planned FY 2005 Activities

Our activities in FY 2005 will predominantly continue the avenues pursued in the current year. As described above, we will move more resources toward exploration of new processes and diagnostics. Some notable examples in the coming year will be the exploration of much thinner devices, plasma-enhanced chemical vapor deposition of polycrystalline semiconductors, evaluation of multiple-wavelength optical reflectance as an in-situ diagnostic, and completion of a micro-Raman spectrometer for combinatorial materials analysis.

The major objectives of this project are to:

- Advance the understanding and performance of heterojunction silicon devices.
- Explore new concepts aimed toward preparation of crystalline silicon films on glass.
- Establish new capabilities in combinatorial deposition, diagnostics, and data mining.
- Demonstrate ink-jet writing of contacts for silicon solar cells, achieving 10% efficiency.
- Push thin-film technologies toward higher throughput by increasing deposition rates and reducing thickness.
- Fabricate dual-junction polycrystalline thin-film cell of 14% efficiency,
- Improve the understanding and performance of heteroepitaxial III-Vs on silicon.

5. Major FY 2004 Publications

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.

Y. Xu, A.H. Mahan, L.M. Gedvilas, R.C. Reedy, and H.M. Branz, "Deposition of Photosensitive Hydrogenated Amorphous Silicon-Germanium with a Ta Hot-Wire," *Thin Solid Films,* in press.

M.P. Taylor, D.W. Readey, C.W. Teplin, M.F.A.M. van Hest, J.L. Alleman, M.S. Dabney, L.M. Gedvilas, B.M. Keyes, B. To, P.A. Parilla, J.D. Perkins, and D.S. Ginley "Combinatorial Growth and Analysis of the Transparent Conducting Oxide ZnO:In (IZO)," *Macromolecular Rapid Communications* **25**, 344 (2004).

C.W. Teplin, T. Kaydanova, D.L. Young, J.D. Perkins, D.S. Ginley, A. Ode, and D.W. Ready, "A simple method for the preparation of transparent p-type Ca-doped $CuInO_2$ films: pulsed-laser deposition from air-sintered Ca-doped $Cu_2In_2O_5$ targets," *Applied Physics Letters* **85**, 3789 (2004).

Xuanzhi Wu and Jie Zhou, "High Efficiency CdTe solar cells on Commercial SnO_2/Soda Lime Glass Prepared by Novel Manufacturing Process," *Proceedings of the 19th European Photovoltaic Energy Conference,* June 2004, Paris, in press.

Xiaonan Li, Timothy Gessert, and Timothy Coutts, " The properties of Cadmium Tin Oxide Thin Film Compounds Prepared by Linear Combinatorial Synthesis," *Applied Surface Science* **223** (2004) 138-143.

Kannan Ramanathan, Glen Teeter, James Keane, and Rommel Noufi, "Properties of High Efficiency $CuInGaSe_2$ (CIGS) Thin Film Solar Cells," *Thin Solid Films, Proc. 2004 E-MRS Meeting,* Strasbourg, France, in press.

D.J. Friedman, J.F. Geisz, and A. Ptak, "Photovoltaics applications of dilute nitrides," published in "Physics and applications of dilute nitrides," 371-393 (2004).

J.F. Geisz, J.M. Olson, and D.J. Friedman, "Toward a monolithic lattice-matched III-V on silicon tandem solar cell." *Proceedings of the 19th European PV Solar Energy Conference and Exhibition,* Paris, France (2004).

6. University and Industry Partners

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
Colorado School of Mines R. Collins, D. Wood, and D. Readey	Golden, CO rtcollins@mines.edu	University Collaboration Program investigation of TCOs and CIGS at NREL	97.1
University of Colorado C. Rogers	Boulder, CO charles.rogers@colorado.edu	University Collaboration Program investigation of nanocomposite cells.	12.7

PV Exploratory Research

Performing Organizations: National Renewable Energy Laboratory
DOE Golden Field Office

Key Technical Contacts: Robert McConnell (NREL, Primary Contact), 303-384-6419, robert_mcconnell@nrel.gov
Glenn Doyle (DOE/GO), 303-275-4706, glenn.doyle@go.doe.gov

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

FY 2004 Budgets: \$5,400K (NREL), \$950K (DOE/GO)

Objectives

- 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
- Fundamental research on perplexing issues within—and generation of innovative concepts for—current technologies
- Fundamental understanding and implementation of performance-enhancing features of low-cost, high-efficiency crystalline silicon (c-Si) solar cells
- DOE/GO-based cooperative agreement award supporting the Center of Excellence for optimizing solar cells through university/industry collaborations on production processes
- Scientific and technical research opportunities for minority undergraduate and graduate students in solar energy technologies via the Minority University Research Associates (MURA) project.

Accomplishments

- Achieved 18%-efficient GaAs on Si/Ge buffer-layered (low-cost) silicon substrate (Ohio State).
- Achieved 5.9%-efficient organic (plastic) solar cell (there is a strong market interest in plastic solar cells) (Princeton).
- Measured extremely high quantum yields of 300% (3 excitons per photon) via efficient multiple-exciton generation.
- Achieved highest independently verified III-V (GaAs) single-junction cell on Si PV cell efficiency: 18.1% AM1.5 with 10% grid coverage (~19% with 4.5% conventional metal coverage) (Ohio State).
- Developed theory for the operational characteristics of grain boundaries in CIGS.
- Identified and characterized metallic defects affecting most commercially available c-Si solar cells (UC Berkeley).
- Demonstrated a correlation between in-plane stresses in Si sheet, cell processing, and the critical issue of wafer breakage (Georgia Tech, U. of South Florida).
- Achieved a number of record high efficiencies (≥18% on 4 cm^2 photolithography cells and manufacturable screen-printed cells on low-cost materials) (Georgia Tech).
- Achieved first proof of concept of strong light-bending using silicon textured with a photonic crystal backside.
- Achieved first III-V dual junction (DJ) solar cell on Si using SiGe; first transition from our record material quality for III-V on Si by ANY means, from single to multijunction cell (Ohio State).
- Achieved first high-performance DJ cell on Si with a V_{oc} of 2 volts (Ohio State).

Future Directions

- Study and mitigate factors limiting the high-yield manufacturing of cost-effective PV devices.
- DOE/GO activities: finalize current research and development on high-efficiency, low-cost crystal Si production processes and recompete current Center of Excellence award.
- Manage MURA summer program to include REAP review meeting and summer internship program. Partner with similar programs at other minority universities in the REAP Conference.
- Facilitate 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.

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1. Introduction

A guiding principle for the U.S. Department of Energy's Solar Energy Technologies Program has always been to support high-risk, potential high-payoff PV technologies requiring innovative long-term R&D. The provisions of the *DOE Solar Program Multi-Year Technical Plan* (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. This exploratory R&D project covers a wide spectrum of fundamental PV research, ranging from synchrotron studies of atomic-level c-Si defects at UC Berkeley to c-Si manufacturing research at Georgia Tech, from fundamental research on tandem organic solar cells at Princeton to PV power distribution and management at Howard University, with student education at the core of every project along the continuum.

The rationale for this Exploratory Research Project is simple: providing options for solar electric technologies. Research that is "plausibly possible" is led by groups whose initial proposal withstood the rigors of a peer review process. This project is a portal into the R&D of very new and different technologies that are "beyond the horizons" of our current technologies. It would be imprudent to maintain that the menu of PV possibilities has already been established, and it is now just a matter of fine-tuning existing recipes. In fact, one would better bet on just the opposite—that the most important discoveries are likely beyond the horizon of today's technologies. The other part of project's initial charter is to conduct fundamental research on problems existing within current material systems that are yet to be solved.

There are three general categories within the PV Exploratory Research Project: 1) the exploratory research conducted by NREL's in-house Basic Sciences Center (BSC), funded by DOE's Basic Energy Science (BES) division, and the subcontracted Future Generation research; 2) a strong crystalline silicon effort; and 3) an effective minority universities-based research and PV education project.

Beyond the fundamental research into other material systems, there are essentially three independent DOE c-Si PV research efforts, namely, the NREL-managed University Crystalline Silicon Research Project, the DOE/GO-managed Center of Excellence for PV Research, and the newly expanding NREL in-house c-Si research group. Given the near-term release of a new university c-Si research RFP and the near-term DOE review of Georgia Tech's 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 the program in light of new possibilities and new thinking (e.g., using the System-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 2005.

2. Technical Approach

The PV Exploratory Research Project has a Minority University Research Associates (MURA) task that provides scientific and technical research opportunities for minority undergraduate students to work on various solar energy technology projects. The task for NREL's Basic Sciences Center supports exploratory research in quantum dot, organic, and "third generation" solar cells; theoretical studies of c-Si solar cells and dye-sensitized solar cells; and specialized characterization of high-efficiency III-V solar cells.

These tasks are well leveraged by related science supported by DOE's Office of Science, Basic Energy Sciences. The task for the Georgia Tech Center for Excellence in Silicon Photovoltaics advances the current state of c-Si solar cell technology to make it more competitive with conventional energy. It will emphasize fundamental and applied research appropriate for education and advanced degrees, while also performing industry-relevant research. The University Crystalline Silicon Research task supports exploratory research in c-Si on six research topics determined by the PV industry.

These topics include development of improved silicon nitride hydrogenation, methods for handling and processing thin wafers with high yield, neutralization of bad regions in wafers, rear-surface passivation, hybrid heterojunction emitters, and innovative c-Si technologies. The Future Generation II PV Project funds university teams developing high-risk innovative concepts such as organic solar cells and novel solar conversion processes having potential for ultra-high efficiency (>50%, i.e., third-generation cells) and very low cost. It is worth noting that what is generically referred to as Future Generation PV consists of the first Future Generation Project (5/99–7/02) arising out of an international workshop on Future Generation PV in 3/97 in Denver, CO, then a follow-on exploratory research project entitled Beyond the Horizon (6/01–8/04), and now a new Future Generation II Project (9/04–11/07), with all three predicated on exploratory PV research.

Involving 34 subcontracted projects and 7 in-house projects, the PV Exploratory Research Project consists of the following major tasks.

Task Title	FY 2004 Budget ($K)
Future Generation/ Beyond the Horizon	1,375
NREL Basic Sciences Center*	1,950
University c-Si PV Research	950
DOE/GO Center of Excellence	950
MURA	425
Project management	700

*See Table 1 for research activities.

3. Results and Accomplishments

3.1 Basic Sciences Center

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 in quantum dots [nanocrystals]) and developed a totally new theory to explain this phenomenon; and observed optoelectronic properties of individual grain boundaries in CdTe with submicron resolution. BSC researchers also achieved an unprecedented measurement of luminescence from a single isolated impurity center; developed a new theory for doping using large size-mismatched impurities; developed a theory of CIGS grain boundaries; and developed a quantitative assessment of the probability of 1) carrier multiplication and 2) hot electrons in quantum dots for solar cells.

Table 1. NREL Basic Sciences Center Activities

Principal Investigator	Title/Research Activity
Arthur Frank	EERE/OS Dye Cell Research
Arthur Nozik	Quantum Dots
Angelo Mascarenhas	Solid State Spectroscopy
Angelo Mascarenhas	Grain Boundary Studies
Su-Huai Wei	Computational Materials Science
Alex Zunger	Solid State Theory
Satyen Deb	Basic Sciences Center Management

3.2 Beyond the Horizon
This project, which was completed in FY 2004, featured many accomplishments: successful 3-year layer transfer and bonding work "graduated" to High-Performance Project for high-efficiency, low-cost concentrator cells (Caltech); successful 3-year buffer layer work graduated to High-Performance Project for high-efficiency, low-cost concentrator cells (Ohio State); and development of new organic solar cell structures leading to high efficiency (5.9%) and "best of the best in Beyond the Horizon" and new follow-on Future Generation PV subcontract (Princeton).

3.2 DOE's Center of Excellence for Photovoltaic Research, Education, and Collaboration Program
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 (15.9%–18.1%). Also developed screen-printed contacts on textured high-resistance emitters, resulting in 1.2% efficiency enhancement.

3.3 University c-Si Research Project
Continued targeting c-Si research toward industry needs, as identified at the DOE/NREL Crystalline Silicon Workshop; revealed defect passivation in SiN_x films via the growth of high [H] content SiN_x films by HWCVD (Caltech, 6/04); increased the lifetime in ribbon silicon materials 100-fold using a 1-s process (Georgia Tech, 3/04); and identified and characterized the metallic defects affecting a wide range of commercially available solar cell materials using synchrotron-based analytical techniques (UC Berkeley, 8/04). This project also achieved the first quantitative detection of hydrogen introduced into bulk c-Si by the post-deposition annealing of a SiNx AR coating (Texas Tech, 1/04); proved a correlation between in-plane stresses in silicon sheet, cell processing, and the serious problem of wafer breakage (Georgia Tech, 3/04); and achieved the first proof of concept of strong light-bending using textured silicon with a photonic crystal backside (MIT, 7/04).

Minority University Research Associates: As a result of the RFPs in the fall of 2003, eight minority-serving universities were awarded subcontracts (six HBCUs, 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 (U. 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 11–14, 2004, at the Florida Solar Energy Center in Cocoa, Florida.

PV Exploratory Research Project Management: 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.

4. Planned FY 2005 Activities

- Conduct peer reviews of: 1) Georgia Tech Center for Excellence in Crystalline Silicon research, 2) Minority University research projects, 3) Basic Sciences and new Future Generation PV research, and 4) proposals for new c-Si research projects.
- DOE-GO activities: 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.
- Pursue exploratory research into third-generation solar cells: dye-sensitized cells, quantum dots, multiple-exciton emission, nanostructures, intermediate-band solar cells, and plastic/organic solar cells.
- MURA: Ensure progress on projects currently under way and invite additional universities to

participate in the REAP Conference through partnerships with other similar programs.

- Target 10% efficiency for organic solar cells.
- Pursue R&D of ultra-high efficiency solar cells targeting >50% efficiency.

5. Major FY 2004 Publications

R. McConnell and R. Matson, "Next-Generation Photovoltaic Technologies in the United States," *Proceedings of the 19th European Photovoltaic Solar Energy Conference and Exhibition,* Paris, France, June 5-13, 2004.

6. University and Industry Partners

These organizations partnered in the Project's research activities during FY 2004 (no cost share).

Fundamental and Exploratory Research: Beyond the Horizon Project

University/Organization Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
University of Arizona Neal Armstrong	Tucson, AZ nra@u.arizona.edu	Liquid Crystal-Based Photovoltaic Technologies	84
Iowa State University Vikram Dalal	Ames, IA vdalal@iastate.edu	Novel Group IV Materials for Photovoltaic Applications	63
University of California Susan Carter	Santa Cruz, CA sacarter@cats.ucse.edu	Polymer Hybrid Photovoltaics	78
United Solar Systems Corp. Jeffrey Yang	Troy, MI jyang@uni-solar.com	Microcrystalline Solar Cells	127
Princeton University Steve Forrest	Princeton, NJ forrest@ee.princeton.edu	Double Heterostrucure and Tandem Organic Solar Cells with Integrated Concentrators	98
Ohio State University Steve Ringel	Columbus, OH ringel.5@osu.edu	GeSi Buffer layers on Si Substrates for III-V Solar Cells	118
University of Illinois Angus Rockett	Urbana, IL arockett@uiuc.edu	Low-Temperature Processing for CIGS Solar Cells	53
Iowa State University Rana Biswas	Ames, IA biswasr@iastate.edu	Nanoscale Design of Thin-Film Heterogeneous Silicon Solar Cells	24
Caltech Nathan Lewis	Pasadena, CA nslewis@its.caltech.edu	Efficiency Improvements of Dye-Sensitized Solar Cells	137
Johns Hopkins Gerald Meyer	Baltimore, MD meyer@jhu.edu	Electron Transfer in Sensitized TiO_2 Photoelectrochemical Cells	71
UNISUN Chris Eberspacher	Newbury Park, CA unisun@aol.com	Non-Vacuum Processing of CIGS Solar Cells	75
Caltech Harry Atwater	Pasadena, CA haa@its.caltech.edu	Layer Transfer Fabrication of High Efficiency Solar Cells	80
University of Michigan Rachel Goldman	Ann Arbor, MI rsgold@engin.umich.edu	Synthesis and Nanometer-Scale Characterization of GaInNAs for High Efficiency Solar Cells	58
United Innovations Ugur Ortabasi	San Marcos, CA uortabasi@unitedinnovations.com	Broad-Band Rugate Filters for High-Performance Solar Electric Concentrators	124

Future Generation Project II (one month's funding in FY 2004)

University/Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 $K
Princeton University Steve Forrest	Princeton, NJ forrest@ee.princeton.edu	Approaching 10% Efficient Cells Using Tandem Organic PV Cell with Enhanced Optical Coating	25
Univ. of Colorado-Boulder Josef Michl	Boulder, CO michlj@colorado.edu	Ultra-High Efficiency Excitonic Solar Cells	40
Northwestern University Tom Mason	Evanston, IL tmason@northwestern.edu	Interface and Electrodes for Next-Generation Organic Solar Cells	42
University of Delaware Christiana Honsberg	Newark, DE honsberg@ee.udel.edu	Theoretical and Experimental Investigation of Approaches to >50% Efficient Solar Cells	18

University c-Si PV Research Project

University/Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
Caltech Harry Atwater	Pasadena, CA haa@caltech.edu	Si Passivation and CVD of Si Nitride	69
UC Berkeley Eicke Weber	Berkeley, CA weber@gsonet.org	Efficiency Improvement of Si Solar Cells	150
Georgia Tech Ajeet Rohatgi	Atlanta, GA ajeet.rohatgi@ee.gatech.edu	Fundamental R&D for Improved Crystalline Solar Cells	150
Texas Tech Stefan Estreicher	Lubbock, TX Stefan.estreicher@ttu.edu	Hydrogen Passivation of Si Solar Cells	149
NCSU George Rozgonyi	Raleigh, NC rozgonyi@ncsu.edu	Improved Efficiency and Yield R&D	111
Georgia Tech Steven Danyluk	Atlanta, GA steven.danyluk@ma.gatech.edu	Birefringence of Stresses in Thin Si Sheet	150
MIT Lionel Kimerling	Cambridge, MA lckim@mit.edu	Super Reflector for Thin Crystalline Si Cells	124

DOE Center of Excellence in Crystalline Silicon Project

University/Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
Georgia Tech Ajeet Rohatgi	Atlanta, GA ajeet.rohatgi@ee.gatech.edu	University Photovoltaic Research, Education, and Collaboration Program	950

Minority University Research Associates Project

University/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
So. Univ. and A&M College Rambabu Bobba	Baton Rouge, LA Rambabu@grant.phys.subr.edu	Student research projects related to energy conversion and storage devices	63
Univ. of Texas, El Paso Gregory Lush	El Paso, TX glush@gerdau.com	Investigation, fabrication, characterization, and modeling of solar cells	38
Fisk University Richard Mu	Nashville, TN rmu@fisk.edu	Development of Si Q-dots for advanced solar cells with maximum efficiency	77
Howard University J.M. Momoh	Washington, DC jmomoh@msn.com	Developing automation/strategies to improve power management and distribution of renewable energy resources	37
N. Carolina Central Univ. Joe Dutta	Durham, NC jmd@nccu.edu	Fabricating and characterizing bulk and non-phase PV materials for student research.	35
Univ. 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.	50
N. Carolina A&T State Univ. G. Shahbazzi	Greensville, NC ash@ncat.edu	Modeling performance of a grid-connected PV system in a residential area.	58
Central State University Clark Fuller	Wilberforce, OH cfuller@prodigy.net	Renewable energy technology and technology transfer in developing countries.	44

High-Performance Photovoltaics

Performing Organization: National Renewable Energy Laboratory

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@hq.doe.gov

FY 2004 Budget: $2,800K

Objectives

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

- Developing thin-film tandem cells and modules toward 25% and 20% efficiencies, respectively
- Developing multijunction pre-commercial concentrator modules able to convert more than one-third of the sun's energy to electricity.

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. Near-term milestones for the polycrystalline thin-film tandems and III-V multijunction concentrator R&D are listed in the *DOE Solar Program Multi-Year Technical Plan* (MYTP) and will be discussed in future sections.

Accomplishments

- Fourteen groups, selected competitively, were involved in negotiations for the HiPerf PV Phase IB, "Accelerating and Exploring Ultimate Pathways." All awards have been completed and all activities have commenced.
- The Polycrystalline Thin-Film PV Group at NREL has demonstrated that a surface-modified CGS top cell exhibits the following NREL-confirmed device operating parameters: V_{oc} = 0.82, J_{sc} = 18.61 mA/cm^2, fill factor = 66.8%, and total-area efficiency = 10.2%.
- Solar cells were fabricated at IEC using the structure glass/Mo/Cu(InGa)$(SeS)_2$/CdS/ZnO/ITO with Ni-Al collection grids and total area, defined by mechanical scribes, of 0.47–0.51 cm^2. The best cell from one run had an efficiency = 10.9% with V_{oc} = 0.826 V, J_{sc} = 20.4 mA/cm^2, and fill factor = 64.5. From the other run, the best cell had an efficiency = 10.9% with V_{oc} = 0.836 V, J_{sc} = 20.4 mA/cm^2, and fill factor = 64.
- Boeing Spectrolab has achieved a record efficiency of 37.3% for a 3-junction terrestrial concentrator cell. This is the highest NREL-confirmed efficiency yet measured for a PV device.
- Amonix has been working toward the design of a greater than 33%-efficient high-concentration module. Recently, they completed a prototype package for testing including a sun shield, sun-shield base, substrate, diode, and multijunction cell.

Future Directions

- The current Phase IB, "High-Performance PV—Exploring and Accelerating Ultimate Pathways," is a continuation of Phase I and addresses exploring and accelerating ultimate pathways to reach the project's long-term goals. Several promising approaches will be explored in each category during this phase, which will lead to Phase II, "Implementation of Pathways."

- Continue development of wide-bandgap material, tunnel junction, and bottom cell toward a 25%-efficient tandem cell.
- Demonstrate a 41% III-V multijunction solar cell incorporated into a high-concentration module.

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1. Introduction

The HiPerf PV Project aims to explore the ultimate performance limits of existing PV technologies, approximately doubling their sunlight-to-electricity conversion efficiencies during its course. This work includes bringing thin-film tandem cells and modules toward 25% and 20% efficiencies, respectively, and developing multijunction pre-commercial concentrator modules able to convert more than one-third of the sun's energy to electricity.

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. Near-term milestones for the polycrystalline thin-film tandems and III-V multijunction concentrator R&D under the project follow and are listed in the Solar Program's 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.

2. Technical Approach

The project consists of three phases that focus on a specific approach to solving the challenges associated with high efficiencies. The second HiPerf PV subcontract solicitation was recently completed and allows the NCPV to provide 3 years of funding to the top-ranked companies and universities. The first phase is critical, as it provides a means to accelerating toward the most promising paths for implementation, followed by commercial-prototype products.

Fourteen groups, selected competitively, were involved in negotiations for the HiPerf PV Phase IB, "Accelerating and Exploring Ultimate Pathways." All awards have been completed and have begun activities (see section 6 below).

Budget allocations by task for the HiPerf PV Project are shown below.

Task Title	FY 2004 Budget ($K)
High-Performance PV Management	400
Thin-Film Polycrystalline Tandems	1,050
III-V Multijunction Concentrators	1,350

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 developed plans for the Implementation Phase. (09/04), MYTP: Task 1 of Section 4.1.2

Completed all awards (14) under the new solicitation: "Exploring and Accelerating Pathways towards High-Performance PV: Phase I-B." Award length is for 3 years with a maximum amount of $300K/year. These subcontracts are exploring and accelerating issues that will lead into the implementation phase.

3.2 Thin-Film Polycrystalline Tandems

- Identified device design in terms of monolithic/mechanical structure, as well as various bandgap combinations. (09/04), MYTP: Task 1 of Section 4.1.1.5.

It was found that there are benefits to a monolithic and/or monolithic approach, and that both designs would be pursued in parallel. Subcontractors, as well as internal NREL researchers, are addressing both approaches. Focus remains on the wide-bandgap material of the tandem cell.

The Polycrystalline Thin-Film PV Group at NREL has demonstrated that a surface-modified CGS top cell exhibits the following NREL-confirmed device operating parameters: V_{oc} =

0.82, J_{sc} = 18.61 mA/cm^2, fill factor = 66.8%, and total-area efficiency = 10.2%.

Solar cells were fabricated at IEC using the structure glass/Mo/Cu(InGa)$(SeS)_2$/CdS/ZnO/ITO with Ni-Al collection grids and total area, defined by mechanical scribes, of 0.47–0.51 cm^2. The best cell from one run had an efficiency = 10.9% with V_{oc} = 0.826 V, J_{sc} = 20.4 mA/cm^2, and fill factor = 64.5.

3.3 III-V Multijunction Concentrators

- Optimized MBE-grown GaInNAs cell and evaluated future options for this approach. (09/04), MYTP: Task 1 of Section 4.1.2
- Demonstrated a 37.3%-efficient III-V multijunction cell under concentration. (09/04), MYTP: Task 1 of Section 4.1.2

The III-V Multijunction Concentrator Group at NREL has focused on the addition of a 1-eV GaInAsN junction to a GaInP/GaAs/Ge cell. This structure has the potential of reaching efficiencies in the 35%–40% range. Evaluation has taken place for the assessment of the viability of GaInNAs.

Boeing Spectrolab achieved a record efficiency of 37.3% for a 3-junction terrestrial concentrator cell, which is the highest NREL-confirmed efficiency yet measured for a PV device. This record used 3-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. The device was processed at Boeing Spectrolab.

Amonix has been working toward the design of a greater than 33%-efficient high-concentration module. Recently, the company completed a prototype package for testing, including a sun shield, sun shield base, substrate, diode, and multijunction cell.

4. Planned FY 2005 Activities

The planned activities directly support the Solar Program's MYTP under Tasks 1, sections 4.1.1.5 and 4.1.2.5. Implementation efforts under the project are expected to be a result of the subcontracts and in-house R&D under the FY 2005 activities.

- Continue awards under "Exploring and Accelerating Pathways towards High-Performance PV: Phase I-B" though FY 2006.
- Demonstrate 14%-efficient polycrystalline thin-film tandem.
- Demonstrate a 38%-efficient III-V multijunction cell under concentration.
- Address the operating issues assessed for high-efficiency multijunction cells under a Fresnel lens.
- Begin implementation efforts of Phase II, High Performance PV, addressing critical cell and receiver components.

5. Major FY 2004 Publications

M. Symko-Davies, "Progress in High Performance PV: Polycrystalline Thin Film Tandems," *International PVSEC-19*, Paris, France, 2004.

R. McConnell, L. Ji, J. Lasich, and R. Mansfield, Concentrator Photovoltaic Qualification Standards for Systems Using Refractive and Reflective Optics," *International PVSEC-19*, Paris, France, 2004.

M. Symko-Davies, Rommel Noufi, S. Kurtz, and T. Coutts, National Renewable Energy Laboratory. "High Performance PV: Exploring and Accelerating Ultimate Pathways," presented in Italy Nov. 2003.

R. McConnell, Solar Concentrator International Conference CD, Alice Springs, Australia, 2004.

M. Symko-Davies, High-Performance PV Review Meeting CD, Denver, Nov. 2004.

6. University and Industry Partners

The following subcontracts were awarded in FY 2004 and continue into FY 2006.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share ($K)
Task 2. 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	178	0
University of Delaware Bill Shafarman	Newark, DE wns@udel.edu	High-Performance PV–Polycrystalline Thin-Film Tandem Cells	266	0
University of Toledo Alvin Compaan	Toledo, OH adc@physics.utoledo.edu	Sputtered II-VI Alloys and Structures for Tandem PV	260	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	75	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	150	0
Oregon State University Douglas Keszler	Corvallis, OR Douglas.keszler@orst.edu	Novel Materials Development for Polycrystalline Thin-Film Solar Cells	210	0
LightSpin Technologies David Salzman	Bethesda, MD salzman@lightspintech.com	Novel Polycrystalline Thin-Film Solar Cells	100	0
Task 3: III-V Multijunction Concentrators				
Spectrolab, Inc. Raed Sherif	Sylmar, CA rsherif@spectrolab.com	Ultra-High-Efficiency Multijunction Cell and Receiver Module	280	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	270	40
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	175	0
JX Crystals Lew Fraas	Issaquah, WA lfraas@jxcrystals.com	Toward 40% Efficient Mechanically Stacked III-V Terrestrial Concentrator Cells	150	0
University of Delaware Christiana Honsberg	Newark, DE honsberg@ece.gatech.edu	Novel High Efficiency PV Devices Based on the III-N Material System	75	0
Ohio State Steve Ringel	Columbus, OH ringel@ee.eng.ohio-state.edu	Optimized III-V Multijunction Concentrator Solar Cells on Patterned Si and Ge Substrates	150	0
Concentrating Technologies Steven Kusek	Huntsville, AL kusek@bellsouth.net	A Scaleable High-Concentration PV System	150	0

Solar Resource Characterization

Performing Organization: National Renewable Energy Laboratory

Key Technical Contacts: Dave Renné, 303-384-7408, david_renne@nrel.gov
Steve Wilcox, 303-384-7785, stephen_wilcox@nrel.gov

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

FY 2004 Budget: $590K

Objectives

- Investigate feasibility of producing an updated National Solar Radiation Data Base (NSRDB) for 1991–2000.
- Evaluate candidate models for modeling solar radiation, including satellite-based model.
- Improve estimates for aerosols, water vapor, and ozone.
- Produce a test-year database to develop production methods and procedures.
- Develop a Work Plan and Annex for a proposed International Energy Agency Task: "Solar Resource Knowledge Management."

Accomplishments

- Acquired input meta data for 1999 and 2000.
- Used satellite and ground-based data to create a gridded dataset of aerosols, water vapor, and ozone for the United States.
- Produced hourly data for 1999 and 2000 using four candidate models.
- Wrote data management software for producing and managing an NSRDB.
- Developed a Work Plan for the IEA Solar Resource Knowledge Management task.
- Submitted a draft Annex to the SHC ExCo for the Solar Resource Knowledge Management task.

Future Directions

- Develop recommendations for producing an NSRDB update (1991–2000).
- Seek feedback from NSRDB stakeholders.
- Develop an NSRDB update plan.
- Produce a ten-year NSRDB update (1991–2000).
- Create additional solar resource products (e.g., buildings data manual, TMYs).
- Develop method for annual NSRDB updates.
- Implement the Solar Resource Knowledge Management task and begin benchmarking satellite-derived solar resource data sets from around the world.

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1. Introduction

This project addresses solar resource assessment, access to data, and characterization of the solar resource, as well as the needs of designers, modelers, and resource assessment interests. The project focuses on both domestic and international data sets. Further, the project breaks new ground with the incorporation of satellite imagery in the modeling of our domestic solar resource assessment data.

The efforts described here contribute toward two goals: 1) an update of the 1961–1990 National Solar Radiation Data Base; and 2) benchmarking, access, and improvement in the way various international organizations (including NREL) develop satellite-derived solar resource data. For the first goal, we produced a small-scale evaluation database, enabling us to investigate database production issues, assess input data availability and quality, and develop modeling alternatives. This forms the groundwork necessary for a report of recommendations on the feasibility of and preferred methods for producing an updated database. That report will provide the U.S. Department of Energy and other interests with the information necessary to allocate resources for a full-scale NSRDB update.

For the second goal, we have assembled a team of international experts to develop a formal Annex proposal and Work Plan called "Solar Resource Knowledge Management," which has been submitted to the International Energy Agency's Solar Heating and Cooling Programme. This task will support efforts to benchmark solar resource data sets developed by different international organizations (including NREL), provide improved mechanisms to access the data, and undertake critical R&D (particularly in the area of solar resource forecasting) that can be shared by all institutions.

2. Technical Approach

For Goal #1, the project acquired all necessary solar, satellite imagery, and meteorological input files necessary for model runs and evaluations to:

- Acquire and quality-assess available measurements of solar irradiance data for validation
- Research data-filling methods (for missing periods of input meteorological data)
- Modify the METSTAT solar model inputs for automated meteorological data and satellite cloud product
- Evaluate the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) model (using automated and satellite cloud inputs)
- Produce a gridded solar product using State University of New York at Albany (SUNYA) satellite model
- Investigate feasibility of new clear-sky algorithms for solar models
- Develop improved atmospheric aerosol and water-vapor estimates
- Quantify differences between the original NSRDB methods and update methods.

For Goal #2, technical meetings on international experts were convened in Washington, DC, and in Madrid, Spain, to develop a work plan for the proposed IEA Solar Resource Knowledge Management task. These plans have been submitted to the IEA and to the Solar Heating and Cooling Executive Committee for formal approval. NREL would serve as the Operating Agent for this task.

3. Results and Accomplishments

METSTAT Model. The recent switch to automatic weather service stations eliminated the human-observed total and opaque sky cover amounts used for inputs to the METSTAT model. The approach used for this year's work derived equivalent sky cover inputs (total and opaque cloud cover) from a combination of Automated Surface Observing System (ASOS) and ASOS supplemental cloud measurements. ASOS detects clouds to 12,000 feet, whereas the ASOS supplemental cloud measurements provide information about clouds for heights above 12,000 feet. The ASOS supplemental cloud measurements are derived from GOES (Geostationary Operational Environmental Satellite) data.

ASHRAE/NRCC Model. ASHRAE and the Northeast Regional Climate Center (NRCC) have developed a solar radiation model for applications in the architectural community. Their approach was to modify a model developed for estimating global horizontal radiation for the northeast region of the United States.

Essentially, the model consists of closed-form transmittance equations for Rayleigh, gas, and water vapor transmission (estimated from dew point), and a look-up table of empirical expressions for aerosol transmission and cloud transmissions to computed global and direct irradiance. Diffuse irradiance is computed from these two estimated components.

SUNYA Satellite Model. One goal of the updated NSRDB is a spatial resolution greater than the ancillary interpolated products that were later produced based on the 239 NSRDB meteorological stations. Toward that end, we are considering using a model that estimates solar radiation from satellite imagery. The Atmospheric Sciences Research Center (ASRC) at SUNYA has been developing such a model, which 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 SUNYA model has been refined to take into account anomalous ground conditions that occur either geographically (specular reflections from bright sand or water) or with time (snow cover). Perez et al. have shown that the refined model, when compared with 13 ground measurement stations, has an average mean bias error (MBE) in global irradiance of 3 W/m^2 (less than 1% of the average irradiance) and an average root mean square error (RMSE) of 54 W/m^2 (14%). The errors for direct normal estimates are an MBE of 4 W/m^2 (1%) and RMSE of 137 W/m^2 (30%).

Analysis. The three models described above have been run using the available input data to produce modeled solar radiation data for the 33 station test sites. The resulting output data set holds a total of 396 station months, or 245,909 daylight station hours available, for comparison with the measured data in the test sites. Because the objective of the project is to produce a data base of solar radiation with the same statistical properties as the measured data, our primary focus for model performance is not on hour-by-hour comparisons of model and measured data, but comparison of appropriate statistics for the measured and modeled data. This was the objective of the original NSRDB: the philosophy being that even if there were great discrepancies in hour-by-hour modeled data with respect to measured data (if it were available), if the model data set provided the correct statistics (mean, variance) for monthly solar radiation data, then hourly simulations using these data over periods of a month to a year to many years would result in correct computation of simulation results.

Preliminary investigations will look at the clear-sky envelopes, which are the basis of the model computations, in comparison with measured clear-sky data to discern possible inherent biases between the models. We will then investigate MBE, RMSE, scatter plots, and correlations between measured and modeled data, the difference between measured and modeled data as a function of measured irradiance, and as cumulative probability functions as in Fig. 1.

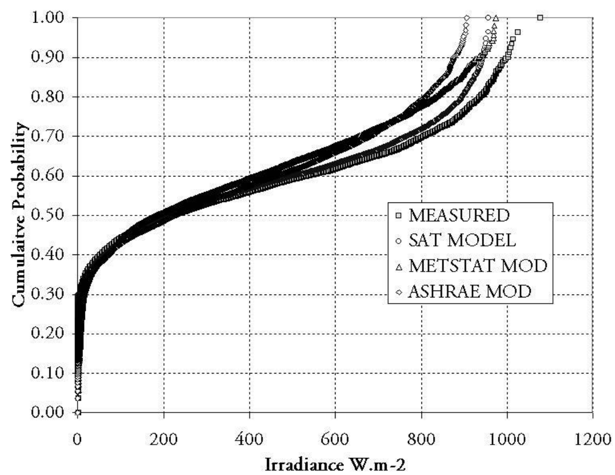

Fig. 1. Preliminary cumulative probability plots for two years of hourly measured global horizontal (squares) and three model data sets (satellite, circles; METSTAT, triangles; ASHRAE: diamonds) for a single test site.

We will intensively investigate the hypothesis that the difference between monthly means of daily total and hourly average modeled and measured solar radiation is zero.

For the proposed Solar Resource Knowledge Management task, meetings of technical experts were held in Washington, DC, in December 2003 and in Madrid, Spain, in February 2004. A draft work plan for the task was developed at these meetings and formally submitted to the Solar Heating and Cooling Program Executive Committee (ExCo). The work plan was presented at their semi-annual meeting in Helsinki in May, and the ExCo then directed the NREL Task Organizer to prepare a formal annex to submit to the IEA and to the ExCo for formal approval. The annex will be reviewed at the next ExCo meeting in Costa Rica in November 2004. NREL will serve as Operating Agent for this task and has secured an agreement for minimal collaboration by both the IEA Photovoltaic Power Systems (PVPS) and the Solar Power and Chemical Energy Systems (Solar PACES) Executive Committees.

4. Planned FY 2005 Activities

With the work accomplished in FY 2004, we are now in a position to evaluate model performance and quantify the feasibility of producing an updated NSRDB. By examining tools, input data availability, processing constraints, and uncertainties of the output product, we will be able to develop a NSRDB update plan. Toward that end, we will work on the following:

- Complete model evaluation and make recommendations on which model to use.
- Develop recommendations for NSRDB update methods.
- Solicit input from NSRDB stakeholders.
- Develop an NSRDB update plan.
- Produce the ten-year NSRDB update.
- Implement the Solar Resource Knowledge Management task through international technical collaboration and a technical meeting to be held in conjunction with the Solar World Congress in Orlando, FL, August 6–12, 2005.

5. Major FY 2004 Publications

S. Wilcox et al., "Progress on an Updated National Solar Radiation Data Base," *Proceedings of the American Solar Energy Society, July 2004, Portland, OR*.

R. Perez et al., "Status of High Resolution Solar Irradiance Mapping from Satellite Data," *Proceedings of the American Solar Energy Society, July 2004, Portland, OR.*

C. Gueymard, "High Performance Model for Clear-Sky Irradiance and Illuminance," *Proceedings of the American Solar Energy Society, July 2004, Portland, OR.*

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
State University of New York, Albany Richard Perez	Albany, NY perez@asrc.cestm.albany.edu	Make improvements to satellite model for producing hourly solar estimates on a 10-km grid.	50
Solar Consultant Services Chris Gueymard	New Myrna Beach, FL Chris@SolarConsultingServices.com	Developed methods for estimating aerosols from MISR satellite data and ground-based AERONET data.	20
University of Oregon Frank Vignola	Eugene, OR fev@uoregon.edu	Developed recommendations for correcting data from rotating shadowband radiometers for use in NSRDB.	20

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@hq.doe.gov

FY 2004 Budget: $440K

Objectives

- Assist in preserving the safe and environmentally friendly nature of PV and minimize 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 photovoltaic materials, processes, or applications and define strategies to overcome such barriers.
- Maintain the Center as the world's best source on PV-EH&S, providing accurate information related to EH&S issues and perceptions.

Accomplishments

- Analyzed life-cycle impact of cadmium in CdTe PV; received high praise from journal reviewers.
- Analyzed environmental impact of the production of elements in CIGS PV production.
- Started experimental research on CdTe PV recycling, and optimized Phase I, leaching of metals.
- Made major contributions to European Commission Workshop on life-cycle analysis (LCA) and recycling.
- Answered many requests for EH&S information and cleared up some misperceptions.

Future Directions

- Conduct LCA of PV technologies.
- Conduct and coordinate LCA-based comparisons of PV with other energy technologies.
- Reach out to industry with guidance on hazard analysis and other EH&S issues.
- Communicate to the public, technical community, business partners, and policy makers.
- Guide the management of waste from 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 outreach, and technical communications. The overall goal is to preserve the safe and environmentally friendly nature of PV and minimize EH&S risks and associated costs, to ensure the public support and economic viability of PV systems. Minimization of EH&S risks and costs is paramount for achieving the DOE Solar Program's goal of $0.06/kWh 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 Partnership and other NREL projects.

2. Technical Approach

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

Task 1: Identification and characterization of EH&S issues. In FY 2004, we conducted research on the life-cycle impacts of cadmium in CdTe PV and on the environmental impacts of the production of materials used in CIGS PV.

Task 2: Hazard Management. In FY 2004, we initiated experimental research on recycling of CdTe PV.

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 2004 Budget ($K)
Hazard Identification/ Characterization	134
Hazard Management/Recycling	157
Industry Outreach/DOE/NCPV	75
Information Dissemination	74

3. Results and Accomplishments

- Task 1. We completed a comprehensive Life-Cycle Impact Analysis of cadmium in CdTe PV, which was published in *R&S Energy Reviews* and was presented in several symposia.
- Task 2. We optimized leaching of the metals from CdTe modules (02/04) and advanced the metal separation in solution (09/04).
- Task 3. We provided facility-specific assistance to Uni-Solar, First Solar, and DayStar Tech. We provided the Thin Film PV Partnership with data and assessments to use in a new Website, and guided NREL EH&S on sulfuric/acid/hydrogen peroxide incompatibilities. We also assisted DOE with SBIR solicitations and with starting an IEA PV-EH&S task.
- Task 4. We answered about 40 requests for EH&S information from different agencies, business partners, citizen organizations, and the media.

4. Planned FY 2005 Activities

1. Hazard Identification/Characterization
   - Fire-simulating tests on CIGS PV samples
   - Environmental inventory analysis of metals in PV modules
   - LCA) of CdTe PV
   - LCA-based comparisons of PV (x-Si, a-Si, CIGS, and CdTe) with conventional energy technologies.
2. Hazard Management/Recycling
   - Advance CdTe Recycling
   - Start CIGS Recycling Research
3. Industry Outreach/Support to DOE & NCPV
4. Information Dissemination

5. 5. Major FY 2004 Publications

Fthenakis V. Life Cycle Impact Analysis of Cadmium in CdTe PV Production, Renewable & Sustainable Energy Reviews, 8, 303-334, 2004

Fthenakis V. and Bulawka A., Photovoltaics, Environmental Health and Safety Issues, Chapter in the Encyclopedia of Energy, Academic Press, 2004

V.M. Fthenakis, M. Fuhrmann, J. Heiser, A. Lanzirotti, J. Fitts and W. Wang. Emissions and Encapsulation of Cadmium in CdTe PV Modules During Fires, Submitted to Progress in Photovoltaics: Research and Applications.

Fthenakis V.M. and Wang W. Kinetics Study on Separation of Cadmium from Tellurium in Aqueous Solutions Using Cation Exchange Resins, Submitted to the Journal of Hazardous Materials.

Fthenakis V.M., Life Cycle Impact Analysis of Cadmium in CdTe PV Modules, Proceedings 19th European Photovoltaic Energy Conference, Paris June 2004.

Fthenakis V.M., Heiser J. and Fuhrmann M. and Wang W., Experimental Investigation of Emissions and Redistribution of Elements in CdTe PV Modules During Fires, Proceedings 19th European Photovoltaic Energy Conference, Paris June 2004.

Fthenakis V. and Alkons F., EH&S Considerations for Large Chemical Systems in Hundred-Megawatt Photovoltaic Cell Manufacturing, BNL Draft Report, November 2003, Brookhaven National Laboratory, Upton, NY.

Wang W. and Fthenakis V.M., Leaching of Cadmium, Tellurium and Copper from Cadmium Telluride Photovoltaic Modules, Recycling Task - Progress Report I, February 3, 2004.

Wang W. and Fthenakis V.M., Separation of Cadmium from Cadmium-Tellurium-Containing Waste Streams, Recycling Task -Progress Report II, April 19th, 2004.

V. Fthenakis and W. Wang, Advances in cadmium telluride photovoltaic module recycling, presented at the DOE Solar Program Review Meeting, Denver, CO, October 25-28, 2004 (oral presentation).

V. Fthenakis and W. Wang, Environmental Impact Assessment for Elements used in $Cu(InGa)Se_2$ Photovoltaics, poster presented at the DOE Solar Program Review Meeting, Denver, CO, October 25-28, 2004.

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.

Achievements in FY 2004 include the following.

Thin Film PV Partnership

- Shared an R&D 100 Award (Global Solar Energy and NREL) for the development of flexible CIS modules on stainless steel (the seventh such award for the Partnership).
- Carried out the Thin Film PV Partnership recompetition.
- Made major advancements in first-time manufacturing of all three thin films, with technology partners taking fiscal year U.S. production levels up from about 12 MW in FY 2003 to about 20 MW in FY 2004:
    - Shell Solar and Global Solar sold about 3 and 1 MW of CIS modules, respectively.
    - First Solar sold about 4 MW of CdTe modules.
    - Uni-Solar Ovonic sold about 12 MW of a-Si modules.

PV Manufacturing R&D

- Completed renewal for active "In-Line Diagnostics and Intelligent Processing" subcontracts.
- Completed LOI review, source selection, and initiated negotiations for awards under "Large-Scale Module and Component Yield, Durability, and Reliability" solicitation.

PV Module Reliability R&D

- Continued an intensive effort in support of NREL's thin-film module hot and humid, long-term outdoor reliability-testing program. NREL and SNL provided detailed baseline characterizations of more than 180 modules from 4 manufacturers prior to field deployment at the hot and humid test sites (Florida and Texas).
- Evaluated more than 20 module backsheet and encapsulant materials for their moisture-barrier and adhesion properties and reported results to industry.

Thin Film PV Partnership

Performing Organizations: National Renewable Energy Laboratory
DOE Golden Field Office

Key Technical Contacts: Ken Zweibel (NREL, Primary Contact), 303-384-6441, ken_zweibel@nrel.gov
Glenn Doyle (DOE/GO), 303-275-4706, glenn.doyle@go.doe.gov

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

FY 2004 Budgets: $10,321K (NREL), $140K (DOE/GO)

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

- The new effort to stress prototype commercial thin-film modules outdoors in hot and humid climates began with testing at FSEC and Texas A&M of CIS, CdTe, and a-Si modules.
- The Thin Film PV Partnership recompetition was carried out via LOI RXL-4-44205.
- A report ("Study of Potential Cost Reductions Resulting from Super-Large-Scale Manufacturing of PV Modules") by an expert from Hewlett Packard (HP) in large-volume manufacturing indicated large potential cost reductions for thin-film modules from economies of scale and make/buy decisions (NREL/SR-520-36844). The report once more confirms that the long-stated DOE cost goals for thin-film modules are reasonable.
- A publicly accessible Website on cadmium issues in PV (http://www.nrel.gov/cdte/) was developed and posted live with the help of BNL and became a major resource for the global ES&H community; based on this Website, we were invited to participate in a key EU rulemaking workshop on PV issues and were able to provide favorable input (March 2004).
- Major advancements were achieved in first-time manufacturing of all three thin films, taking fiscal year U.S. production levels up from about 12 MW in FY 2003 to about 20 MW in FY 2004:
  - In CIS, Technology Partners Shell Solar and Global Solar sold about 3 and 1 MW of CIS modules, respectively.
  - In CdTe, Technology Partner First Solar sold about 4 MW of CdTe modules.
  - In a-Si, Technology Partner Uni-Solar Ovonic sold about 12 MW of a-Si modules.
- Despite a mandated 20% reduction in FY 2004 funds from the expected level, (1) all milestones were met and (2) the budget within the Thin Film Partnership was managed within +0.006% of the required lower level by adjusting most ongoing subcontracts downward and canceling others. This new, lower level was then incorporated in the levels planned for subcontract emerging from the recompetition LOI.

- GSE and NREL shared an R&D 100 Award for the development of flexible CIS modules on stainless steel (the seventh for the Partnership, three in the last three years); a 10.1% commercial prototype was measured at NREL.

Future Directions

In FY 2005, the project management will address changes resulting from the recent recompetition and the lower levels of funding, number of subcontractors, and National Team participation. Subcontracts that are ending will be extended on an as-needed basis to assure completion of graduate student thesis work, where possible. In terms of technical progress, the Partnership will continue to address key issues supporting the transition to successful first-time manufacturing of each thin film. These will be especially critical in FY 2005, which is expected to be a key turn-around year in thin films, with U.S. production rising from about 12 MW in CY 2003, to 24 MW in CY 2004, and to more than 50 MW in CY 2005. Any setbacks in manufacturing yield or outdoor reliability could lead to multi-year setbacks or even technology abandonment in extreme cases.

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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 cross-cutting teams in Thin Film Module Reliability and EH&S (the latter with BNL). 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 34 subcontracts (see below) during FY 2004, with a recompetition under way to fund new contracts starting in FY 2005. The subcontract areas were broken down as shown following table.

Task Title	FY 2004 Budget ($K)
Project Management and Team Coordination	853
Thin Film Center of Excellence	868
Amorphous and Thin Film Silicon	2,882
Polycrystalline Thin Films	5,516
Hot and Humid Testing	202
NIST (DOE/GO)	140

Of these, five were major, Technology Partner contracts: Shell Solar, EPV, and Global Solar in CIS; First Solar in CdTe; and United Solar Ovonic (Uni-Solar Ovonic) 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.

In addition, the Partnership is making an in-depth study of its priorities based on the Systems-Driven Approach. Initial insights were reported at the 2004 Solar Program Review Meeting. The key conclusions are that efforts must be made as follows:

1. Champion cell and module efficiencies must be moved to production in the form of typical commercial module efficiencies.
2. Each technology must demonstrate reliability, with the special assistance of new, accelerated testing at the cell and encapsulated-module levels.
3. Thinner CIS and CdTe layers (while maintaining high efficiencies) should be pursued with greater priority, because such

thinner layers would: reduce materials availability issues for Te and In; reduce materials costs for these costly elements; and allow faster deposition times, reducing capital, maintenance, energy input, and equipment footprint costs.
4. Single-junction a-Si efficiency and deposition rates should be enhanced to provide support to the aggressive "factories of factories" approach given in the HP-Keshner (2004) study for multi-GW thin film manufacturing.
5. Lower-cost CIS processing methods should receive greater emphasis.
6. Low-cost barrier layers to protect semiconductors should be investigated to reduce encapsulation costs.
7. Materials utilization rates should be a priority when expensive elements such as Te and In are used.
8. Temperature-resistant, non-conductive substrates should be investigated if they can provide an alternative for roll-to-roll deposition and simultaneously act as encapsulation (e.g., such as glass does now).

Our FY 2005 subcontract activities are already being modified to reflect these more precise priorities.

3. Results and Accomplishments

The Thin Film PV Partnership supported the transition to successful first-time manufacturing of key thin-film technologies during the fiscal year. This is our most important activity in the short term, because it will help establish thin films in the marketplace; improve their chances of future growth and success; and help define the transition of technologies that have been successfully developed by DOE funding to the private sector. This evolution has been over two decades in the making and is not yet accomplished. However, with the substantial growth in CY 2004 to about 20 MW (from only 12 MW in the United States in the prior year), thin films are entering this important transition. Based on surveys of the Partnership's Technology Partners, it is expected that this may again double in CY 2005 to about 50 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). These would be major accomplishments.

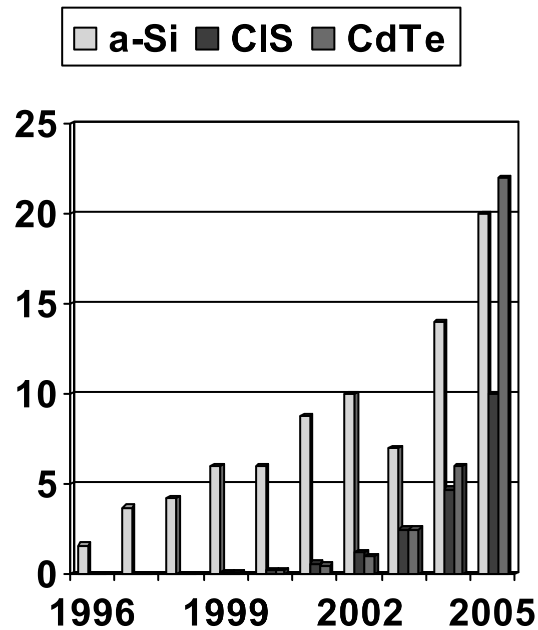

Fig. 1. Megawatts of PV module manufacturing in the United States, broken down by thin-film technology. A survey of the Partnership's Technology Partners suggests that U.S. thin-film manufacturing is going through a major growth period, and new thin films are joining amorphous silicon in the marketplace (FY 2004 is preliminary data; FY 2005 is planned sales).

The Partnership had several management accomplishments of note during the fiscal year. The most important was our Partnership subcontract recompetition LOI. We received 47 proposals and presently plan to fund about 20 (down from 34 in past years). The lower level is due to our expected reduced levels of funding availability. In addition to handling the recompetition in a timely manner, we reduced our existing subcontract spending rates to meet DOE guidance, despite having to act within the limitations of contractual agreements. This approximate 20% reduction was achieved such that by year-end we had managed our lower budget within +0.006% of the required lower level. We also participated in ongoing ES&H challenges that affect our technologies, especially those with cadmium and selenium. We worked with BNL to develop and then post live a Website (http://www.nrel.gov/cdte/) devoted to cadmium issues in PV. This site is now accessed frequently by companies and regulators concerned with this issue. We maintain that no issue of any substance stands in the way of the manufacture, use, or disposal of Cd-containing PV modules. Establishing this in the mind of key policy-makers and the public could be crucial to the survival and success of CdTe PV technology. Our insights were heavily used in a mid-year review of ES&H issues in Belgium, sponsored by the EU. Without our inputs, U.S. exports to the EU markets could have been stopped. We also worked on finishing a report on the effects of manufacturing thin films in super-large volumes with HP expert, Marvin Keshner. This report concludes that scaling up thin-film technologies will result in strong cost reductions that will allow systems under $1/Wp to be installed. The report is now available and is being requested frequently. Finally, we started the now ongoing testing of prototype thin-film modules in extremely hot and humid climates in Texas and Florida to discover vulnerabilities and try to feed back information on an ongoing basis to module suppliers so that modules can be fixed.

In CdTe, the fiscal year saw progress in manufacturing, exclusively at First Solar. Company personnel installed almost an entire second generation of equipment at the Perrysburg, OH, plant, including cadmium chloride heat treatment, lamination, and scribing. They are also performing shakedown tests on their second-generation semiconductor coater. The coater is designed to improve uniformity and allow for higher materials utilization. During the year, First Solar has (1) continued to ramp up production and remains on track to produce over 20 MW in CY 2005 (6 MW in CY 2004); (2) continued outdoor and accelerated tests of CdTe modules to improve module designs and reliability; and (3) stated aggressive plans to replicate their successful 25-MW facility worldwide once it has reached a proper degree of reproducibility. They continue to sell a large fraction of their output to the German market, where they have been especially active in markets that demand the lowest cost systems per kWh of output—a major attainment for them and for thin films, in general, because most people's recent perceptions of thin films (based on a-Si history) has been that they are for niche markets. Yet the goal of the Thin Film Partnership is energy significance, and niche markets can only be minor stepping stones to that achievement. It is important that a thin film has broken into large, distributed, and utility markets the way First Solar CdTe has done.

As predicted by theory, the CdTe modules deployed by First Solar have better outdoor performance per installed watt-peak than c-Si systems, which is due to their reduced sensitivity to high operating temperatures. In addition, they seem to display a better low-light-level performance. The result is that their so-called performance ratio (kWh/kWp) is about 80% (Table 1)—a very high level.

Table 1. First Solar CdTe Performance Ratios

Location/ Type	System Size (kW)	Start Date	Performance Ratio (PR)	
			Current Month	Total
AZ-USA Field mounted	126.5	Jun-03	81.5%	81.0%
AZ-USA Field mounted	129.0	Jul-03	84.7%	83.8%
Perrysburg EZ-Mount	24.7	Sep-03	86.2%	84.1%
San Diego EZ-Mount	36.0	Jul-03	79.0%	79.9%
Phoenix EZ Mount	3.0	Jan-04	87.7%	86.0%
Phoenix EZ Mount	23.9	Apr-04	79.4%	80.6%
Germany Roof Mount	17.9	Oct-03	80.8%	82.3%
Germany Field Mount	105.7	Jan-04	85.5%	86.1%
Germany Field Mount	97.0	Jun-04	85.9%	86.5%
Germany Roof Mount	21.0	Oct-03	80.5%	74.9%
Germany Roof Mount	28.5	Jun-04	87.7%	87.7%

Our biggest concern with First Solar will be outdoor reliability, based on the paucity of data and the need for correlating accelerated tests with real performance. Because these remain challenges, we will maintain a high level of research focus on them.

Significant progress has been made in the area of thin-film copper indium diselenide ($CuInGaSe_2$, CIS) and related materials. For small-area laboratory devices, total-area conversion efficiency of 19.5% has been achieved by NCPV scientists. Using a ZnS buffer layer, a total-area conversion efficiency of 18.5% has also been achieved by NCPV scientists. For more details, refer to the Electronic Materials and Devices report. In a joint collaborative research effort between International Solar Electric Technology (ISET) and the NCPV, an NREL-verified, total-area conversion efficiency of 13.3% has been achieved using ISET's patented ink-based nanotechnology process for the absorber formation. The National CIS R&D Team held its team meeting focusing on key CIS research issues such as grain boundaries. Progress has also been made in the area of thin-film CIGS module fabrication in the past year. Global Solar Energy (GSE), Tucson, AZ, along with ITN Energy Systems (ITN/ES), Littleton, CO, fabricated a thin-film CIGS module with an aperture-area conversion efficiency of 10.1% and a power output of 71.2 W, the highest output for any CIS-based module made by a U.S. company. Improvements in thickness, uniformity, stoichiometry, and yield over a 1000-foot-long stainless steel (ss) web resulted in these improvements. ITN/ES assisted GSE in intelligent processing and in-situ diagnostics, which resulted in better stoichiometry and uniformity control of the ss web. NREL, GSE, and ITN/ES were the joint winners of the prestigious R&D100 Award for 2004 for the development of lightweight, flexible thin-film CIGS modules. This is the seventh R&D 100 Award won by the Thin Film PV Partnership Program. Shell Solar Industries, Camarillo, CA, installed two of the world's largest installations of CIS-based PV modules. A 245-kW rooftop solar electric array was installed in Camarillo, CA, atop the company's solar cell manufacturing facility; and an 85-kW building integrated PV (BIPV) thin-film, CIS-based facade was deployed in North Wales, U.K. Energy Photovoltaics (EPV) fabricated a 7.5% thin-film CIGS module using the hybrid sputtering-evaporation process. A recent press release indicated that a major investment (to the tune of about $90 million) will be made in a U.S.-based CIS nano-ink company in the very near future. This company has been part of our development program for more than a decade (although its current contract will not be renewed in FY 2005 because of our budget shortfall).

The biggest developments in FY 2004 thin-film amorphous and crystalline Si films were significant production increases at Uni-Solar Ovonic and the bankruptcy of AstroPower, Inc., and subsequent sale of its assets to GE Energy. Uni-Solar Ovonic reported that it produced 1.5 MW_p of product on its 30-MW manufacturing line during June 2004. Further increases of this manufacturing rate are expected for FY 2005. Also remarkable is that a significant fraction of Uni-Solar Ovonic products were shipped as roofing laminates rather than as standard modules, which marks the first time that a thin-film PV manufacturer has been successful in penetrating the BIPV market (i.e., developed a unique product for a unique application).

AstroPower had been working under subcontract on a thin-film solar cell cell prepared by melt-recrystallizing a CVD-deposited (~50–100-μm–thick "growth" layer) on a ceramic substrate. Then, active solar cell layers were deposited epitaxially by CVD. Small-area solar cells were prepared by this method with efficiencies as high as 9.2%. A serious drawback to the approach was the low recrystallization speed of the first CVD seed layer (less than 1 cm/min). Based on the limited potential of this method for near-term commercialization, and because of the December 2003 decrease in the FY 2004 thin-film PV budget and the bankruptcy of AstroPower, it was decided to eliminate the third planned phase of this project.

Much of the R&D effort in amorphous silicon was geared toward developing low-temperature-deposited nanocrystalline (nc-Si) film as a replacement for the narrow-bandgap a-SiGe:H cell currently used in spectrum-splitting multijunctions. This approach had received significant attention in Europe and Japan. Several subcontractors (Uni-Solar Ovonic, EPV, and MVSystems) achieved respectable cell results, suggesting that U.S. entities also have the know-how for making such state-of-the-art solar cells. The work confirmed the general observation that best cell results are obtained with mixed-phase, small-grained absorber layers, in a deposition regime called "near the edge." The best cells were produced by Uni-Solar Ovonic employing grading of hydrogen dilution during deposition, a process that can be understood in terms of film growth as measured by spectroscopic ellipsometry (Penn State results). The stability of these cells was assessed in light-soaking experiments. Although the behavior is not perfectly stable, as claimed in some scientific publications, the light-induced losses are smaller than those observed in a-SiGe:H cells. Uni-Solar Ovonic was able to prepare tandem and triple-junction cell structures with an nc-Si:H bottom cell (replacing the a-SiGe:H cell) with performance levels comparable to an all-amorphous-cell structure (both near 12% stabilized efficiency), but these champion cells required very low deposition rates for the nc-Si layers, with corresponding deposition times of about 5 hours. To implement this new technology into manufacturing, even higher cell efficiencies and deposition rates for the nc-Si layer must first be achieved. This is consistent with our expectations and the state of the art in nc-Si throughout the world.

5. Major FY 2004 Publications

M. Keshner and R. Arya (2004). *Study of Potential Cost Reductions Resulting from Super-Large-Scale Manufacturing of PV Modules: Final Report, Sept. 30, 2004*; NREL Report No. SR-520-36844.

B. von Roedern (2004), "Physics of PV Materials," *Encyclopedia of Energy*, Elsevier, Inc., V. 5.

H. S. Ullal (2004), "Polycrystalline Thin-Film PV Technologies: Progress and Technical Issues," 19th European PVSEC, Paris, France, June 7-11, 2004.

K. Zweibel, H. S. Ullal, B. Von Roedern (October 2004), "Finally: Thin Film PV!" in *Photon International*, M. Schmela (ed), p. 48-56.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share ($K)
Colorado State University Jim Sites	Ft. Collins, CO sites@lamar.colostate.edu	Analysis of CIS and CdTe devices	101	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	233.3	0
Colorado School of Mines Tim Ohno	Golden, CO tohno@mines.edu	Characterization and analysis of CdTe cells	171.5	0
University of Toledo Al Compaan	Toledo, OH ADC@physics.utoledo.edu	CdTe cells made by sputtering	202.5	108
PNNL Larry Olsen	Richland, WA Larry.Olsen@pnl.gov	Barrier coatings for thin-film cell protection	185	0
University of South Florida Chris Ferekides	Tampa, FL ferekide@eng.usf.edu	High-efficiency CdTe cells by CSS	172	6.75
U. of Delaware, Institute of Energy Conversion Robert Birkmire	Newark, DE rwb@strauss.udel.edu	Thin Film Center of Excellence	827	0
Pennsylvania State U. Chris Wronski	University Park, PA crwece@engr.psu.edu	Phase-engineered a-Si:H-based multifunction solar cells	181.4	3.1
Florida Solar Energy Center Neelkanth Dhere	Cocoa, FL dhere@fsec.ucf.edu	CIGSS solar cells by selenization and sulfurization	99	16.9
University of Toledo Xunming Deng	Toledo, OH dengx@physics.utoledo.edu	High-efficiency, triple-junction a-Si-H- and nc-Si-based solar cells	167	62.4

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share ($K)
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	140	0
University of Florida Tim Anderson	Gainesville, FL tim@nersp.nerdc.ufl.edu	Characterization of the reaction chemistry of CIGS solar cells	257	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	287.8	72
United Solar Ovonic Subhendu Guha	Auburn Hills, MI sguha@uni-solar.com	High-efficiency a-Si-alloy-based solar cells and modules	529.5	343
University of Oregon Dave Cohen	Eugene, OR dcohen@oregon.uoregon.edu	Electronic properties relevant to improving performance and stability of a-Si PV cells	119.1	0
Syracuse University Eric Schiff	Syracuse, NY easchiff@syr.edu	Transport, Interfaces and Modeling in a-Si:H-based solar cells	154.7	8.1
University of Utah Craig Taylor	Salt Lake City, UT craig@physics.utah.edu	Characterization of advanced amorphous silicon materials and PV devices	84	0
California Institute of Technology Harry Atwater	Pasadena, CA haa@daedalus.caltech.edu	Thin–film Si solar cells on low-cost substrates	48.5	0
University of Illinois Angus Rockett	Urbana, IL arockett@uiuc.edu	Understanding the structural and chemical basis of chalcopyrite solar cells	56.9	0
Colorado School of Mines Don Williamson	Golden, CO dwilliam@mines.edu	Structure of silicon-based thin-film solar cell materials	39.3	0
AstroPower, Inc. Jim Rand	Newark, DE jim.rand@ps.ge.com	Thin-film crystalline Si solar cells on ceramic substrates	809	814
Energy Photovoltaics Yuan-Min Li	Lawrenceville, NJ y.li@epv.net	Advanced deposition techniques for microcrystalline silicon solar cells and modules	165	71.7
MVSystems, Inc. Arun Madan	Golden, CO ArunMadan@aol.com	Narrow-gap, high-efficiency solar cells and tandem-junction a-Si:H-based devices	96.9	34.7
Iowa State University Vik Dalal	Ames, IA vdalal@iastate.edu	High-efficiency, narrow-gap, and tandem-junction devices	116.3	0
Case Western Reserve University Frank Ernst	Cleveland, OH fxe5@po.cwru.edu	Liquid-phase deposition of α-CIS thin layers	68.7	0
Florida Solar Energy Center Neelkanth Dhere	Cocoa, FL dhere@fsec.ucf.edu	Module reliability testing in hot and humid climate	7	0
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	140	0
Shell Solar Industries Dale Tarrant	Camarillo, CA Dale.tarrant@shellsolar.com	Process R&D for CIS-based thin-film PV	853	853
First Solar, LLC Rick Powell	Perrysburg, OH rcpowell@firstsolar.com	Research leading to high-throughput processing of thin-film CdTe PV technology	847	847
Global Solar Energy Markus Beck	Tucson, AZ mbeck@globalsolar.com	Tolerance of three-stage CIGS deposition to variations imposed by roll-to-roll processing	325	325
Energy Photovoltaics Alan Delahoy	Lawrenceville, NJ a.delahoy@epv.net	Advanced CIGS photovoltaic technology	807	242

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share ($K)
International Solar Electric Technologies Vijay Kapur	Inglewood, CA vkkapur@isetinc.com	Lab to large-scale transition for non-vacuum thin-film CIGS solar cells	365	36.5
ITN Energy Systems Ingrid Repins	Littleton, CO irepins@itnes.com	Plasma-assisted co-evaporation of S and Se for wide-bandgap chalcopyrite photovoltaics	319	32
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	0	0

PV Manufacturing R&D

Performing Organization: National Renewable Energy Laboratory

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

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

FY 2004 Budget: $9,264K

Objectives

Assist the U.S. PV industry by:

- 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

- Completed analysis of FY 2003 U.S. PV industry cost/capacity/recapture data and reported progress.
- Completed renewal for active "In-Line Diagnostics and Intelligent Processing" subcontracts.
- Completed LOI review, source selection, and initiated negotiations for awards under "Large-Scale Module and Component Yield, Durability, and Reliability" solicitation.
- Shell Solar Industries implemented bar-code scribing on its CIS manufacturing line, leading to increased capacity, improved yield, and significant cost reductions in manufacturing process.
- AstroPower achieved a 40% reduction in silicon feedstock used on Silicon-Film wafer production with a molded-wafer formation process.
- BP Solar demonstrated production-scale slicing and processing of ultra-thin (110 micron thick) polycrystalline silicon wafers into cells and modules.
- PowerLight achieved a 20% reduction in labor required for PowerGuard, Gen II tiles along with improving its "design for manufacturability," reducing per-watt cost by 18%.
- ITN Energy Systems demonstrated process improvements on the Global Solar production line, including significant improvements in CIGS uniformity, thickness control, yield, and throughput.
- Sinton Consulting developed the in-line, minority-carrier monitoring tool for process control during fabrication of crystalline silicon cells with measurements as fast as 0.6 s/measurement, and actual data acquisition, analysis, and logging requiring less than 0.4 s.
- Evergreen Solar developed the Project Gemini dual-ribbon growth production system, resulting in dramatic cost reduction based on dual output capacity.
- Energy Photovoltaics increased the throughput of deposition system by 20%, reduced per-watt module cost by 25%, and increased the stabilized module power output of a-Si modules by 20%.
- Xantrex Technology developed three advanced, high-impact PV inverter products for grid-tied applications and reduced weight, size, cost, and conversion losses of new inverters.
- RWE Schott Solar completed development of prototype, large-diameter EFG furnace and laser-cutting station for production of 12.5-cm x 12.5-cm wafers.
- Specialized Technology Resources developed formulation and optimized extrusion for super-fast-cure and flame-retardant EVA-based encapsulants.

Future Directions

- Complete award of eligible subcontracts under the "Yield, Durability, and Reliability Manufacturing Scale-Up" solicitation.
- Conduct an analysis of the FY2004 U.S. PV industry cost/capacity/recapture data to identify capacity-weighted average module manufacturing costs and manufacturing capacity.
- Complete renewal of remaining subcontracts under the "In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up" solicitation.
- Complete development of at least three in-line diagnostic processes initiated in the FY 2002 awards from "In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up" subcontracts.
- Complete an assessment and determination of the need for additional Manufacturing R&D Project work and select areas for elimination or support.

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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 DOE and members of the U.S. PV industry. Subcontracted research under this project 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 FY2004 work effort was divided into three areas: (1) Project Management and Support; (2) FY 2001 competitively solicited subcontracts for "In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up" (IDIP); and (3) evaluation and competitive selection of research subcontracts under FY 2003 solicitation, "Large-Scale Module and Component Yield, Durability, and Reliability" (YDR).

Task Title	FY 2004 Budget ($K)
PV Manufacturing R&D Management	775
In-Line Diagnostics and Intelligent Processing	6,511
Yield, Durability, and Reliability	1,978

2.1 PV Manufacturing R&D Management

The Project Management and Support subtask addresses: (1) the management of the PVMR&D project; (2) the management of subcontracts awarded under the IDIP procurement; (3) the selection and management of subcontracts under the YDR procurement; (4) coordination of NREL in-house activities in support of the PVMR&D industrial partners; and (5) an evaluation of the current trends in the PV manufacturing industry through the collection of data for cost/capacity and recapture of R&D funding.

2.2 In-Line Diagnostics and Intelligent Processing

The IDIP subtask consists of cost-shared PV manufacturing R&D subcontracts awarded under the FY 2000 IDIP competitive solicitation. This solicitation was directed at: the improvement of module manufacturing processes; system and system component packaging; system integration, manufacturing, and assembly; product manufacturing flexibility; and BOS 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.

2.3 Yield, Durability, and Reliability

The YDR subtask consists of cost-shared PV manufacturing R&D subcontracts resulting from the FY 2003 YDR competitive solicitation. It focuses on the improvement of 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 the enhancement of module, system component, and complete system reliability.

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 2004 milestone to "Analyze U.S. PV industry cost/capacity/recapture data and report on progress." 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 2003, data completed in March of 2004, 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 2003 survey of PV module manufacturers. Total PV manufacturing capacity has increased from 14 MW at the Project's inception to 201 MW at the close of 2003. This increase in capacity represents a 25% compound annual growth rate over the 12-year period examined. Direct manufacturing costs, in 2003 constant dollars, declined from $5.55 to $2.49 over the same time period, a 6.5% compound annual reduction.

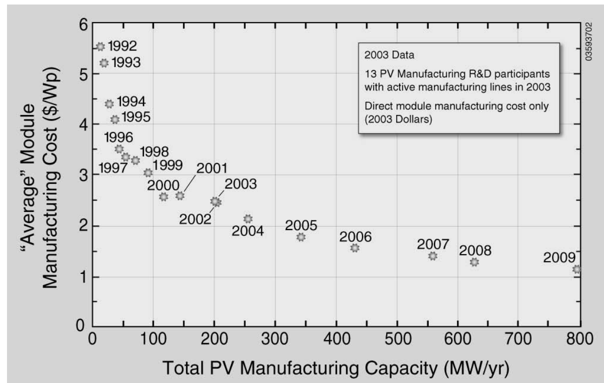

Fig. 1. FY 2003 U.S. PV module manufacturing cost-capacity

In addition, the PVMR&D project tracks the manufacturing cost savings resulting from improvements implemented under project subcontracts (this was completed in May 2004). Public savings (shown in Fig. 2) is calculated based on measurable price reductions, whereas industry savings (shown in Figure 3) is based on the amount retained by the manufacturers. For both the public and private sectors, estimated cost savings exceeded investment during 1998, with a projected discounted-cash-flow rate of return at 40% through 2009.

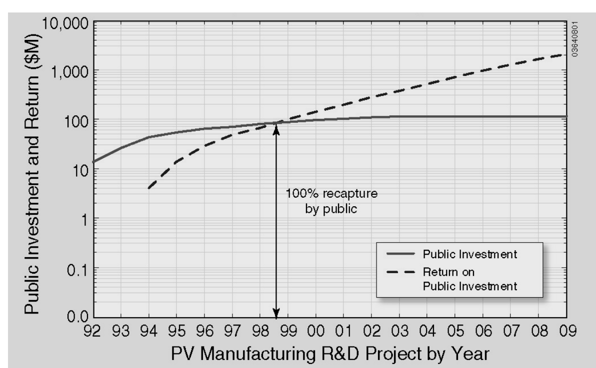

Fig. 2. Recapture of public investment in PVMR&D

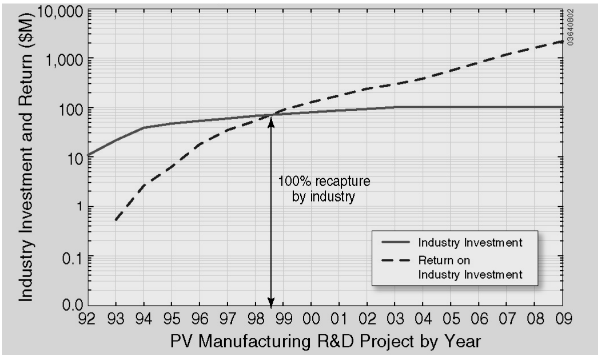

Fig. 3. Recapture of industry investment in PVMR&D

3.2 In-Line Diagnostics and Intelligent Processing
Under this subtask, the PVMR&D milestone for "renewal of remaining IDIP subcontracts" focused on preventing interruptions in the research in IDIP subcontracts, supporting the MYTP Milestone 25, Task 6 (due in FY 2005). This milestone was completed in September of 2004.

Other significant achievements under this subtask were accomplishments by the individual subcontractors, which include the following:

Shell Solar Industries – "PV Manufacturing R&D - Integrated CIS Thin-Film Manufacturing Infrastructure"

- Developed specifications for CIS absorber formation reactors for high-throughput manufacturing levels.
- Implemented bar-code scribing equipment, resulting in increased capacity, improved yield, and significant cost reductions in manufacturing.
- Implemented x-ray florescence feedback control for CIS deposition, leading to increased machine utilization.

RWE SCHOTT Solar, Inc. (formerly SCHOTT Applied Power) – "Plug and Play Components for Building-Integrated Systems"

- Completed optimization of new flat-roof mounting system for commercial PV array installations. Completed improved design of Photovoltaic Source Circuit Protectors and initiated listing process with Underwriters Laboratory.
- Initiated design effort with Phillips Lighting to develop improved SunSine AC module.
- *Evergreen Solar, Inc.* – "Innovative Approaches to Low-Cost Module Manufacturing of String Ribbon Si PV Modules"
- Developed production-ready dual-ribbon growth system known as Project Gemini, resulting in dramatically reduced manufacturing costs from dual output capacity.
- Made progress in developing wrap-around contacts for monolithic modules, achieving a record wrap-around cell efficiency of 13.6%.
- Developed production machine to produce cell contacts using unique contact-printing technology, attaining a gain in yield of 3%, overall efficiency improvement of 0.3% absolute, and throughput increase of 70%.

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

- Demonstrated good yields and cell efficiencies using a mix of 25% solar-grade silicon and 75% intrinsic silicon feedstock.
- Demonstrated slicing of 110-micron-thick wafers.
- Demonstrated 2.5% to 3% increase in module output power using AR-coated glass; qualified glass through environmental testing.
- Built modules using 110-micron-thick silicon cells.

Sinton Consulting, Inc. – "Development of an In-Line Minority-Carrier Monitoring Tool for Process Control During Fabrication of Crystalline Silicon Solar Cells"

- Developed improved, fast-data analysis for multicrystalline wafers, including corrections for trapping, a common artifact in multicrystalline wafer measurements.
- Demonstrated performance measurements as fast as 0.6 s/measurement. Actual data acquisition, analysis, and logging required less than 0.4 s.
- Commercialized prototype through sale of six units to PV manufacturers.

ITN Energy Systems, Inc. – "Trajectory Oriented and Fault Tolerant Based, Intelligent Process Control for Flexible CIGS PV Module Manufacturing"

- Developed physics-based and empirical models for CIGS deposition processing and physics-based model for Mo deposition processing.
- Improved process control through in-situ sensor development, indicating further potential for enhanced status monitoring and control of deposition.
- Demonstrated process improvements, including significant improvement in CIGS uniformity, thickness control, yield, and throughput.

PowerLight Corporation – "PowerGuard Lean Manufacturing"

- Developed new version of PowerGuard, Gen II, in which the cementitious coating on the foam backerboard was replaced by a metal or plastic cover, reducing product lead time.
- Improved manufacturing yield to 99.7%, reduced product lead time, required labor, floor space, and inventory levels, exceeding company goals.
- Achieved 20% reduction in labor required to produce Gen II tiles with improved manufacturing.
- Improved "design for manufacturability," reducing per-watt cost by 18%.

AstroPower, Inc. – "High-Volume Manufacturing of Silicon-Film Solar Cells and Modules"

- Developed and implemented continuous back-metallization, screen-printing, and laser-scribing systems.
- Achieved 40% reduction in silicon feedstock used per wafer following introduction of near net shape wafer-formation process.
- Addressed feedstock supply by developing continuous unidirectional solidification process to upgrade metallurgical-grade silicon to Silicon-Film purity requirements.
- Achieved overall increase of 5% in relative power and nearly 15% in mechanical and visual yield.

Specialized Technology Resources, Inc. – "Development of New Low-Cost, High-Performance PV Module Encapsulant/Packaging Material"

- Completed research under this work effort on thin-film module technology including device performance/failure analysis, glass stability, and device encapsulation for thin-film technologies.
- Developed analytical models for the individual interfacial components for thin-film type modules both "as manufactured" and after field exposure or laboratory aging.
- Completed pre-commercialization activities for the formulation and extrusion optimization for the super-fast-cure and flame-retardant EVA-based encapsulants designed for the PV module market.

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

- Completed installation of second-generation a-Si reflection spectrometer in production equipment.
- Completed fabrication of first-generation closed-loop, thickness-control systems for ITO and ZnO.
- Completed installation of retrofitted component cell PV capacitive diagnostic in production equipment.
- Completed initial investigation of plasma-cleaning parameters and correlation with QA/QC data.

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

- Completed design effort for a large-area, 800-W PV module and associated production line with goal of minimizing total installed-system cost for multi-megawatt, utility-connected brightfield PV arrays.
- Continued development process of an automated cell string inspection process to detect visible and microcrack defects.

RWE SCHOTT Solar, Inc. – "EFG Technology and Diagnostics R&D for Large-Scale PV Manufacturing"

- Completed R&D of prototype, large-diameter EFG furnace and laser-cutting station for producing 12.5-cm x 12.5-cm wafers.
- Completed design and prototypes of reflector module (based on concept of replacing fraction of cells with lower-cost reflecting module backskin), which may result in reduced module costs.
- Demonstrated Computer Management and Maintenance System to improve operation efficiency and reduce overall manufacturing cost.

Energy Photovoltaics, Inc. – "Productivity Enhancement for Manufacturing of Amorphous Silicon PV Modules"

- Completed thorough evaluation of single-junction and tandem a-Si modules to determine the best option, as a function of application, based on EPV's proprietary batch deposition process.
- Reduced a-Si deposition cycle time for tandem devices by 20%.
- Increased the throughput of the deposition system by 20%.
- Reduced per-watt module cost from EPV production line by 25%.
- Increased stabilized module power output of a-Si modules by 20%.

Xantrex Technology, Inc. – "PV Inverter Products Manufacturing and Design Improvements for Cost Reductions and Performance Enhancements"

- Developed three advanced, high-impact PV inverter products for grid-tied applications.
- Reduced weight, size, cost, and conversion losses of new inverters by nearly 50% when compared to current technology.
- Developed DSP-based control boards for each of the three PV inverter topologies that were designed for universal application at virtually any power level for any inverter with the same electrical topology.

3.3 Yield, Durability, and Reliability

The "Large-Scale Module and Component Yield, Durability, and Reliability" LOI 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 2004, the Source Evaluation Board completed an assessment of the 29 responses to the solicitation and determined that 17 responses were in the competitive range. These competitive LOIs represented a wide spectrum of the value chain in the PV industry, ranging from BOS work to PV module manufacturing. The competitive LOIs represent a total of more than $82M, DOE and industry cost share, of research over three years, with a total proposed cost share by industry of nearly 53%.

A milestone under this subtask was to "Initiate new PV Manufacturing R&D projects directed to areas identified in FY 2003 and partners solicited in FY 2004." This milestone supports research advancements to further aid DOE and NREL decision makers in support of the MYTP Go/No Go Decision Point 9, which is due in early FY 2006. The top-ranked responders were contacted and progress has been made in the preparation of subcontract statements of work. Individual subcontract negotiations are under way, with several awards expected in the first few months of FY 2005.

4. Planned FY 2005 Activities

PVMR&D procurements are framed to specifically address milestones under the MYTP. Under the continuing IDIP procurement, PVMR&D focused on integrating state-of-the-art process controls with current production technology in support of MYTP Task I.3, Milestone 14 (Reduce direct module-manufacturing costs to $1.75 and achieve module-manufacturing processes capable of $1.50/watt direct module-manufacturing costs with 500-megawatt production capacity) and Task I.6, Milestone 25 (Complete development [achieve manufacturing-line-ready status] for at least three in-line diagnostic processes initiated in FY 2002 awards from In-Line Diagnostic, Intelligent Processing Solicitation). The focus of the upcoming subcontracts under the FY 2003 YDR procurement will be on enhancing field reliability and durability, as well as manufacturing yield, supporting of MYTP Task I.3, Milestone 14 mentioned above.

The major expected accomplishments of this project during FY 2005 include:

- Analyzing the FY 2004 U.S. PV industry cost/capacity/recapture data to identify the capacity-weighted, industry average (05/05).
- Development of at least three in-line diagnostic processes, initiated in the FY 2002 awards from "In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up" subcontracts (09/05).
- Assessment and determination of the need for additional PV Manufacturing R&D work, and selection of areas for elimination or support (09/05).
- Renewal of remaining subcontracts under the "In-Line Diagnostics and Intelligent Processing in Manufacturing Scale-Up" solicitation (07/05).
- Completion of eligible subcontract awards under the "Large-Scale Module and Component Yield, Durability, and Reliability" solicitation (09/05).

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 selected 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, PV industry participants 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 industry/laboratory/government partnership by implementing multi-year subcontracts which addressing industry-identified problems selected through competitive and fair processes.

5. Major FY 2004 Publications

ITN Energy Systems, Inc.
Simpson, L., "Trajectory Oriented and Fault Tolerant Based Intelligent Process Control for Flexible CIGS PV Module Manufacturing," Phase 1 Final Technical Report–March 2003, NREL/SL-520-35146, February 2004.

First Solar, Inc.
Bohland, J., McMaster, Henson, A. S., and Hanak, J. "Specific PVMaT R&D in CdTe Product Manufacturing," Final Subcontract Report–March 2003, NREL/SR-520-35177, January 2004.

Specialized Technology Resources, Inc.
Agro, S.C., Tucker, R.T., "Development of New Low-Cost, High-Performance, PV Module Encapsulant/Packaging Materials," Annual Technical Progress Report, Phase 1, 22 October 2002–30 September 2003, NREL/SR-520-35683, March 2004.

Xantrex Technology, Inc.
West, R., "PV Inverter Products Manufacturing and Design Improvements for Cost Reduction and Performance Enhancements: Final Subcontract Report," November 2003, NREL/SR-520-35885, April 2004.

BP Solar International, LLC
Wohlgemuth, J., and Shea, S.P., "Large-Scale PV Module Manufacturing Using Ultra-Thin Polycrystalline Silicon Solar Cells," Annual Subcontract Report, 1 April 2002–30 September 2003, NREL/SR-520-35887, April 2004.

Evergreen Solar, Inc.
Hanoka, J.I., "Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules," First Annual Report, 27 September 2002–31 March 2003, NREL/SR-520-36194, May 2004.

RWE Schott Solar, Inc.
Russell, M.C., "Plug and Play Components for Building-Integrate PV Systems," Phase I Final Report, 20 February 2002–19 February 2003, NREL/SR-520-36246, July 2004.

Shell Solar Industries
Tarrant, D.E., Gay R.R., "PV Manufacturing R&D–Integrated CIS Thin-Film Manufacturing Infrastructure," Phase I Technical Report, 2 August 2002–31 October 2003, NREL/SR-520-36247, June 2004.

Energy Conversion Device, Inc.
Ellison, T., "Implementation of a Comprehensive On-Line Closed-Loop Diagnostic System for Roll-to-Roll Amorphous Silicon Solar Cell Production," Phase I Annual Subcontract Report, 23 April 2003–31 August 2003, NREL/SR-520-36610, August 2004

Sinton Consulting, Inc.
Sinton, R.A., "Development of an In-Line Minority-Carrier Lifetime Monitoring Tool for Process Control during Fabrication of Crystalline Silicon Solar Cells," Annual Subcontract Report, June 2003, NREL/SR-520-35884, April 2004.

Evergreen Solar, Inc.
Hanoka, J.I., "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.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004.

Organization/ Principal Investigator	Location/e-mail	Description/ Title of Research Activity	FY 2004 ($K)	Cost Share
Shell Solar Industries Dale Tarrant	Camarillo, CA dale.tarrant@shell.com	PV Manufacturing R&D–Integrated CIS Thin-Film Manufacturing Infrastructure	100	205
AstroPower, Inc. James Rand	Newark, DE jimrand@astropower.com	High Volume Manufacturing of Silicon-Film Solar Cells and Modules	0 137*	0 261*
BP Solar International, LLC John Wohlgemuth	Frederick, MD john.wohlgemuth@bp.com	Large-Scale PV Module Manufacturing Using Ultra-Thin Polycrystalline Silicon Solar Cells	1,130 80*	1,561 110*
PowerLight Corporation Jonathan Botkin	Berkeley, CA Jbotkin@powerlight.com	PowerGuard Lean Manufacturing	0 293*	0 447*
RWE SCHOTT Solar, Inc. Miles Russell	Billerica, MA miles.russell@rweschottsolar.us	Plug and Play Components for Building-Integrated Systems	40 123*	55 167*

* Funded with prior year (FY 2003)
** Award pending

Organization/ Principal Investigator	Location/e-mail	Description/ Title of Research Activity	FY 2004 ($K)	Cost Share
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	485 90 *	564 110 *
Sinton Consulting, Inc. Ronald Sinton	Boulder, CO Ronsinton@AOL.com	Development of an In-Line Minority-Carrier Monitoring Tool for Process Control During Fabrication of Crystalline Silicon Solar Cells	0 69 *	0 69 *
Evergreen Solar, Inc. Jack Hanoka	Marlboro, MA hanoka@evergreensolar.com	Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules	1,414 80 *	1,415 80 *
Specialized Technology Resources, Inc. Susan Agro	Enfield, CT susan.agro@strus.com	Development of New Low-Cost, High-Performance PV Module Encapsulant/Packaging Material	260 168 *	224 145 *
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	1,240 173 *	1,240 173 *
Spire Corporation Michael Nowlan	Bedford, MA mnowlan@spirecorp.com	Development of Automated Production Line Processes for Solar Brightfield Modules	825 55*	770 53*
RWE SCHOTT Solar, Inc. Juris Kalejs	Billerica, MA juris.kalejs@rweschottsolar.us	EFG Technology and Diagnostics R&D for Large-Scale PV Manufacturing	1,309 100 *	1,869 137 *
Energy Photovoltaics, Inc. Hermann Volltrauer	Lawrenceville, NJ h.volltrauer@EPV.net	Productivity Enhancement for Manufacturing of Amorphous Silicon PV Modules	0 314 *	0 314 *
Georgia Tech Steven Danyluk	Atlanta, GA steven.danyluk@ma.gatech.edu	Stresses and Handling of Thin Silicon Sheet	200	0
TBD (10–12 awards anticipated)	TBD	Subcontracts under "PV Module And Component Yield, Durability, And Reliability" solicitation	1,145 **	1,145 **

* Funded with prior year (FY 2003)
** Award pending

PV Module Reliability R&D

Performing Organizations:	National Renewable Energy Laboratory Sandia National Laboratories
Key Technical Contacts:	Roland Hulstrom (NREL, Primary Contact), 303-384-6420, roland_hulstrom@nrel.gov David King (SNL), 505-299-9184, dlking@sandia.gov
DOE HQ Technology Manager:	Jeffrey Mazer, 202-586-2455, jeffrey.mazer@hq.doe.gov
FY 2004 Budgets:	$2,544K (NREL), $965K (SNL)

Objectives

- Isolate, scientifically understand, and help industry mitigate module failure and/or degradation mechanisms.
- Gather and analyze outdoor, long-term, reliability/performance data for all candidate module technologies.
- Use advanced indoor and outdoor accelerated exposure stress testing to discover and/or replicate observed outdoor failures and performance degradation.
- Develop improved module packaging materials and designs that result in at least 25-year service lifetimes, lower costs, and acceptable long-term performance.
- Assist industry with developing and implementing consensus standards and codes for module performance ratings and qualification testing.
- Characterize and provide models for PV module performance and reliability for a range of field/application conditions.

Accomplishments

- Completed accelerated testing program (thermal cycling, UV exposure, humidity-freeze cycling, damp heat, and light-soaking) for several CdTe modules and provided results and conclusions to the manufacturer.
- Completed accelerated testing program (thermal cycling, damp heat, and surface cuts) for a group of advanced prototype crystalline silicon modules and provided results and conclusions to the manufacturer.
- Continued an intensive effort in support of NREL's thin-film module hot and humid, long-term outdoor reliability testing program. NREL and SNL provided detailed baseline characterizations of more than 180 modules from 4 manufacturers prior to field deployment at the hot and humid test sites (Florida and Texas).
- Completed an advanced indoor module light-soaking apparatus and used it to collect and publish data on a-Si and CdTe modules. Capabilities will be used, in collaboration with industry partners, to improve characterization of module light-soaking behavior.
- Evaluated more than 20 module backsheet and encapsulant materials for their moisture barrier and adhesion properties. Several promising packaging material and design candidates were identified, and results were published in a report to industry.
- Developed a new mathematical model to project the time-phased ingress of water vapor (moisture) into module backsheet and encapsulant materials, based on laboratory measurements of material diffusivity and solubility. This model can now be used to predict how long a given module packaging design will prevent moisture from reaching the PV material/absorber.

- Using outdoor PV module performance data dating back to 1991, calculated and published annual module performance degradation rates for both thin-film and c-Si modules. A major conclusion was that a 0.5%/year module performance degradation rate is a reasonable goal for all module manufacturers.

Future Directions

- Continue and expand (if possible) outdoor PV module performance and reliability testing to discover any failures and degradation problems, and to establish accurate performance and reliability characterizations and models in support of PV systems selection and design.
- Improve accelerated testing methods, diagnostics, and modeling for module packaging materials and designs, leading to minimal issues with manufactured modules.
- Improve accelerated testing methods, diagnostics, modeling, and qualification test standards as required to support the industry's continued development and commercialization of advanced module technologies and products.
- Develop module quick-screening stress-testing methods to identify module technologies and designs that should not proceed past the prototype stage.
- Investigate (i.e., module performance and reliability characteristics) lower cost (e.g., $\$/m^2$) alternatives for module packaging designs and/or materials, working with manufacturers to help meet long-term PV cost goals.
- Work with PV module manufacturers to help develop in-line manufacturing diagnostics that are key indicators of module reliability properties.

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1. Introduction

The PV Module Reliability R&D 4Project has been a joint NREL and SNL effort for the past several years. The overall objective is to work with industry to develop PV modules that have 30-year service lifetimes, an annual performance degradation rate of <0.5%, and a $/Wp (as determined by the module efficiency and $\$/m^2$) required to meet the 2020 PV system goal of 5 to 6 ¢/kWh LEC (levelized energy cost). This project also provides critical performance and reliability testing and benchmarking of modules to validate the progress and accomplishments of the DOE Solar Program's investments in PV module technology R&D. Along these lines, we work very closely and collaboratively with the PV Manufacturing R&D and Thin Film PV Partnership Projects.

2. Technical Approach

This project is a key component of the overall Systems-Driven Approach (SDA), as shown in Fig. 1. It is an element of "Components R&D" within the Advanced Materials and Devices segment of the overall PV program. To be viable in various markets, the module component of a PV system has to meet certain performance, cost, and reliability requirements related to both the overall system and specific applications. The Module Reliability R&D project addresses module service lifetime and annual performance degradation as integral requirements along with costs and efficiency. R&D is performed at the module materials and design levels, as well as the complete module.

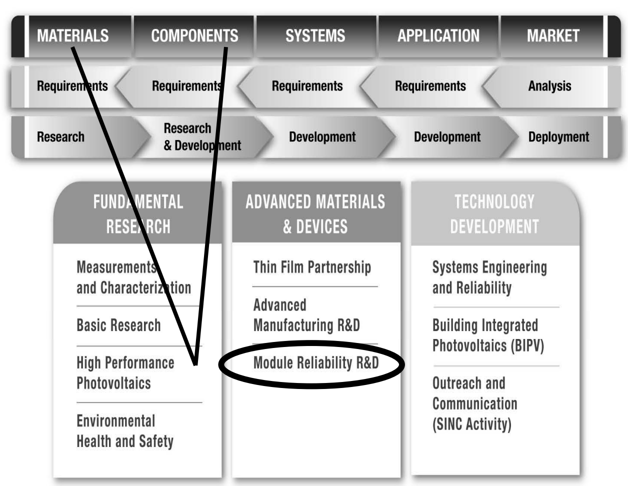

Fig. 1. System-Driven Approach and the Module Reliability Project

The Module Reliability Project consists of the following tasks.

Task Title	FY 2004 Budget ($K)
Exploratory Reliability & Performance (NREL)	1,292
Module Packaging Research and Reliability (NREL)	1,252
Long-term Outdoor Durability Test & Failure (SNL)	462
Module Reliability Characterization (SNL)	110
Module Manufacturing and Process R&D (SNL)	393

The NREL Exploratory Reliability & Performance Task includes accelerated indoor and outdoor environmental stress testing, and long-term outdoor performance and reliability testing and analyses of most (if not all) PV module technologies. The emphasis is on the module technologies being addressed by the NREL PV Manufacturing R&D and Thin Film PV Partnership Projects. The NREL Outdoor Test Facility (OTF) is used for these purposes. Accelerated testing uses specialized environmental chambers and facilities to conduct tests that include thermal cycling, UV exposure, humidity-freeze cycling, damp heat exposure, and light-soaking. Accelerated outdoor testing includes a specialized apparatus called the Outdoor Accelerated-weathering Testing System (OATS), which allows module exposure to solar irradiance at an intensity of nearly 3 suns. The long-term module performance and reliability uses a specialized test bed called the Performance and Energy Ratings Testbed (PERT). This test bed holds up to 45 PV modules that are kept at maximum power; it periodically (every 15 to 30 minutes) measures full I-V curves, along with other measurements such as incident solar irradiance, outdoor temperature, and module temperature. These data are used to determine performance ratings (e.g., $kWhr_{dc}/Wp$) and performance degradation rates for several module technologies and manufacturers.

The NREL Module Packaging Research and Reliability Task includes efforts to address the long-term reliability aspects of module packaging materials (e.g., encapsulants) and designs. Module-level packaging R&D includes:

- Alternatives to double glass for thin films (soft backsheets and hard-coat barrier films)
- EVA substitutes that are cheaper/better, not requiring transparency.
- Field and stress survival including adhesion, cohesion, and water-diffusion barriers
- Detailed measurements and characterization of moisture transmission properties of polymers and coatings
- Modeling of moisture ingress and egress into module structures.

The SNL tasks include the continued development and use of module-performance characterization methods; and, the collection and performance-degradation rate analyses using long-term exposure data from SNL, the Florida Solar Energy Center (FSEC), and the Southwest Technology Development Institute (SWTDI). SNL uses a module-performance characterization (i.e., calibration) apparatus that is capable of deriving the module power output (i.e., I-V curve) as a function of solar irradiance, optical air mass (i.e., spectral), solar irradiance incident angle, atmospheric temperature, and module temperature. Using this apparatus, SNL provided PV module baseline performance characterizations prior to the deployment of modules at the long-term exposure sites at FSEC, SWTDI, SNL, and NREL. At periodic intervals, SNL repeats such measurements to establish module performance-degradation characteristics. This database was also used to continue the improvement of existing software that accurately models the expected power and energy production from PV systems in site-dependent applications. The SNL tasks also include investigations, jointly with NREL, of observed module field (either at the FSEC/SWTDI and/or from industry sites) failures.

3. Results and Accomplishments

- Completed accelerated testing program (thermal cycling, UV exposure, humidity-freeze cycling, damp heat, and light soaking) for several CdTe modules and provided results and conclusions to the manufacturer.

- Completed accelerated testing program (thermal cycling, damp heat, and surface cuts) for a group of advanced prototype crystalline silicon modules and provided results and conclusions to the manufacturer.
- An intensive effort was continued in support of NREL's thin-film module hot and humid, long-term outdoor reliability testing program. NREL and SNL provided detailed baseline characterizations of over 180 modules from 4 manufacturers prior to field deployment at the hot and humid test sites (Florida and Texas).
- An advanced indoor module light-soaking apparatus was completed and used to collect and publish data on a-Si and c-Si modules. Capabilities will be used, in collaboration with industry partners, to improve characterization of module light-soaking behavior.
- A large number (more than 20) of module backsheet and encapsulant materials were evaluated for their moisture barrier and adhesion properties. Several promising packaging material and design candidates were identified, and results were published in a report to industry.
- A new mathematical model was developed to project the time-phased ingress of water vapor (moisture) into module backsheet and encapsulant materials, based on laboratory measurements of material diffusivity and solubility. This model can now be used to estimate how long a given module-packaging design will prevent moisture from reaching the PV material/absorber.
- Using outdoor PV module performance data dating back to 1991, annual module performance degradation rates were calculated and published for both thin-film and c-Si modules. A major conclusion was that a 0.5%/year module performance degradation rate is a reasonable goal for all module manufacturers.

The following milestones were completed:

- Provided initial baseline (pre-aging) report for group of First Solar CdTe modules (12/1/03).
- Investigated performance loss in Uni-Solar Ovonic a-Si modules in Arizona Public Service system (12/5/03).
- Provided ultrasonic analysis of resistance-welded ribbons for Shell Solar (12/30/03)
- Performed second baseline testing for 12 Uni-Solar Ovonic a-Si modules after 6-year exposure at FSEC and SWTDI (1/30/04).
- Investigated recently discovered field failure mechanism in First Solar CdTe modules (2/1/04).
- Investigated and confirmed solder bond failures in Kyocera modules from 200 NTUA systems in Arizona (3/1/04).
- Conducted SNL/NREL rheometric analysis of multiple polymer materials for edge seal and encapsulation (4/1/04).
- Completed testing agreement with First Solar on CdTe modules delivered in FY 2003 (6/1/04).
- Conducted workshop on the physical properties of PV packaging materials and industry requirements (6/24/04).
- Completed extensive technical report covering water vapor transmission rates, peel strengths, and stress testing of existing and new PV module packaging materials (9/17/04).
- Established archive baseline and subcontractor-delivered data for the thin-film hot and humid experiment (9/29/04).

4. Planned FY 2005 Activities

This project will consist of the following tasks:

- Exploratory Reliability & Performance R&D (NREL)
- Module Packaging Research & Reliability (NREL)
- Module Reliability Characterization (SNL).

The major expected results include the following:

- A technical report/publication addressing the influence of cell edges on cell performance and projected results for module scribe lines
- An overview publication documenting the degradation characteristics of commercial PV modules, using 5 to 15 years of outdoor exposure data for 10 module types.
- Water-resistant formulations and procedures for enhanced adhesion of a production-compatible self-priming PV encapsulation material

- Progress report covering the water vapor ingress properties of several module-packaging materials.

5. Major FY 2004 Publications

B. Marion, S. Rummel, and A. Anderberg, "Current-Voltage Curve Translation Using Bilinear Interpolation," accepted by *Prog. In Photovoltaics: Research Applications,* 2004.

6. University and Industry Partners

The following organization partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
Arizona State University Govindasamy Tamizh Mani	Mesa, AZ manit@asu.edu	Outdoor energy rating measurements and modeling of PV modules	25

Technology Development

The Department of Energy, in cooperation with the U.S. photovoltaics industry, seeks to advance PV performance and systems engineering, improve systems reliability, and develop technology suitable for integration into residential and commercial building structures.

Systems and reliability research focuses on the critical need to improve reliability of the entire PV system, including balance-of-system components such as DC-to-AC current inverters and battery charge controllers. Technology Development 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.

The Technology Development activity involves five activities: systems engineering and reliability; domestic and international market development, BIPV R&D; outreach and analysis, and the Million Solar Roofs Initiative. Outreach and analysis activities are necessary for a national R&D program to remain viable in a rapidly changing energy sector.

FY 2004 accomplishments within this arena follow.

PV Systems Engineering

- Achieved the final approval, after several years of development, of the IEEE Standard 1526 for stand-alone PV system performance testing.

PV System Evaluation and Optimization

- Provided technical assistance to the U.S. Department of Agriculture (USDA), which led to including accepted PV systems on the Rural Utilities Service List of Materials; USDA is the first federal agency to offer direct financing to the 1000+ rural coops that purchase PV from the list.

Inverter and BOS Development

- Phase II contracts with three major resulted in utility-interactive inverters with minimums of 10 years or more mean time before failure.

Domestic PV Applications

- Provided technical support to U.S. Environmental Protection Agency’s Supplemental Environmental Projects.

Building-Integrated PV

- Continued the implementation of the 2005 Solar Decathlon university competition, releasing the final regulations, solidifying sponsors, and supporting teams.

Million Solar Roofs

- Initiated series of state-specific economic analysis briefs, targeted at solar industry distributors and retailers, for their use in marketing their products.

International Solar Technologies

- Helped open markets for U.S. renewable energy companies. A dozen U.S. concerns participated in a China trade mission, resulting in at least six business partnerships.

PV Systems Analysis

- Completed a beta model that offers the user the ability to conduct parametric studies on performance, costs, and financing for a 2.4-kW grid-tied residential PV system.

Regional Experiment Stations

- Performed 20 technical site evaluations for implementation of solar and wind energy projects in rural Brazil.

PV Systems Engineering

Performing Organizations: National Renewable Energy Laboratory
Sandia National Laboratories
DOE Golden Field Office

Key Technical Contacts: Roland L. Hulstrom (NREL, Primary Contact), 303-384-6420, roland_hulstrom@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@hq.doe.gov

FY 2004 Budgets: $1,425K (NREL), $156K (SNL), $200K (DOE/GO)

Objectives

- Determine, characterize, document, and model the near and long-term performance and reliability of candidate, emerging PV technologies in the context of small, grid-connected, systems.
- Provide benchmark-type data and analyses for technical contributions into codes, standards, and certifications to best implement a systems-driven approach for infrastructure building and evolutionary or leapfrog advances of grid-connected and stand-alone PV systems.
- Assist the PV industry and community with the development and implementation of codes, standards, and certification practices to assure safe installations that perform as expected.
- Provide the DOE Solar Program with world-class and traceable solar radiometric capabilities, measurements, and standards.

Accomplishments

- Long-term performance and reliability testing and reporting continued on 10 small (<2 kW), grid-connected PV systems deployed at the NREL Outdoor Test Facility (OTF).
- Mutual site visits with Arizona Public Service and the PowerLight Corporation were conducted to determine and initiate collaborative efforts regarding PV system performance and reliability testing, analyses, and system design/modeling.
- Achieved the final approval, after several years of development, of the IEEE Standard 1526 for stand-alone PV system performance testing.
- Completed draft of *Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems* and submitted to the California Energy Commission for inclusion in its Emerging Renewables Program Guidebook.
- Completed SNL-led industry forum work for the 2005 National Electrical Code with proposals and balloting process for PV system installation updates.
- Enhancements were completed for the NREL PVWATTS PV applications and system model, consisting of improvements in performance, ease of use, and output.
- Completed two rounds of PV installer certification testing, including updating each test and the study guide used by applicants.
- Provided technical review and extensive input to clarify and expand the UL1741 standard for listing inverters for PV and other distributed applications.
- Provided technical review and input to draft IEEE1547.1 standard for interconnecting inverters with the utility grid.
- NREL's optical metrology passed external and internal audit and was deemed suitable for ISO 17025 accreditation of NREL's Photovoltaic Reference Cell Calibration ISO certification.

- Responded to more than 80 requests for technical assistance in radiometry and spectrometry from the PV industry, academia, consultants, and engineering/design firms.

Future Directions

- Install and initiate long-term outdoor system performance and reliability testing for an additional two new technologies at the NREL OTF.
- Increase collaborations with the PV industry and system owners to gather, analyze, and report PV system performance and reliability results for larger (10 kW) systems in various applications.
- Complete the development and validation of NREL's PV system performance analysis software and make it available to the PV and utility industries.
- Enhance PVATTS to allow the user to specify AC of DC power nameplate ratings, along with other user inputs, such as soiling losses, system availability, inverter specifications, geometry of shading objects, and international weather data.
- Submit *Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems* to IEEE to establish a national guideline document to encourage national and state incentive programs that are based on system performance.
- Begin industry forum collaborations for proposed changes to the 2008 NEC code cycle.
- Complete SNL funding support to NABCEP for installer certification program, but continue technical support for the study guide, testing committee, and other technical committees.
- Support IEEE and UL standards writing activities for domestic PV applications.
- Support International Electrotechnical Commission standards writing with guidance that is beneficial to the U.S. PV industry.
- Revise the ASTM calibration standards for pyranometers and pyrheliometers.
- Develop and publish solar radiometry best practices, measurement uncertainties, and applications to PV module and system performance measurement.

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1. Introduction

This PV Systems Engineering Project is integral to the *DOE Solar Program Multi-year Technical Plan* because it provides credible and independent data, systems analyses, and assessments of the performance and reliability metrics that are required in validating, assessing, and benchmarking the candidate technologies and supporting the Program's Systems-Driven Approach to R&D.

The major activity and thrust of this project is the near- and long-term performance monitoring, characterization, and modeling of emerging-technology, grid-connected, prototype systems installed and operating at NREL's Outdoor Test Facility (OTF). Critical to this effort is a supporting task that provides world-class and traceable measurements and instrumentation for solar radiometry. The resultant precision and accuracy of 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 includes very important infrastructure building activities aimed at supporting the development of industry consensus on procedures and the adoption of codes, standards, and certification related to PV systems, components, and installations.

2. Technical Approach

The PV System Performance and Standards Task performs long-term performance and reliability engineering testing and analyses on several small, grid-connected, systems located at NREL's Outdoor Test Facility (OTF). The types of technologies under test include crystalline silicon, amorphous silicon, cadmium telluride, and copper indium diselenide (from several manufacturers). Periods of record date back over 10 years. The analyses include the kWhr(ac)/kWp performance rating as a function of temperature and sun angles, and the annual degradation rate of power output at specific temperatures and incident solar irradiance. For all systems, a quarterly report is generated and provided to the corresponding industry manufacturer and the corresponding NREL technical monitor within the Thin Film PV Partnership Project and/or the PV Manufacturing R&D Project, to help validate and/or guide the technology development R&D. Figure 1 shows a typical analyses product. Results and the experience gained are used to help the industry develop improved standards for performance monitoring, certification, and ratings.

The precise and accurate measurement of the performance (e.g., efficiency, power ratings) demands precise, accurate, and standardized measurements of the incident (i.e., on modules and arrays) solar irradiance. This requires national and internationally recognized and traceable solar radiometry and instrumentation. For several years, NREL has developed, maintained, and used solar radiometric methods and instrumentation to meet these requirements.

The approach to meeting solar research and industry needs in optical calibrations and measurements is to provide data of known uncertainty that is traceable to national standardizing laboratories and internationally recognized reference standards, such as the National Institute of Standards and Technology (NIST) Standard of Spectral Irradiance and the World Radiometric Reference (WRR). We participate with consensus standards organizations such as the American Society for Testing and Materials (ASTM), International Standards Organization (ISO), and International Lighting Commission (CIE) to develop standards assuring high-quality solar energy industry products. The task assures traceable optical radiation measurements of known uncertainty for the NREL Solar Program research community and solar industry partners by participating in the NREL quality system according to the requirements of ISO17025. Reference standard and working instruments and systems are characterized and calibrated with documented procedures against national and international standards with as short a "traceability chain" as possible to accurately quantify and reduce uncertainties. Calibrations, measurements, and technical expertise are provided on programmed and as-requested bases.

Supporting the nation's codes, standards, and certification writing efforts for PV-related components and systems is essential to assuring safe PV installations that perform as expected. The National Electrical Code (NEC) is a consensus document that is revised every three years. SNL, in close collaboration with the Southwest Technical Development Institute, leads an industry forum that consists of more than 90 members from the PV industry, utilities, academia, and government agencies. This forum reviews the existing electrical code for installation requirements and proposes improvements and changes for the next code cycle. The codes work has taken on a new perspective in recent times, in that it must also provide checks to faulted public proposals from uniformed sources.

Certification takes two paths to improve the likelihood of safe, properly designed PV installations. Practitioner certification has been implemented through the establishment of the North American Board of Certified Energy Practitioners (NABCEP). Certification of components is being advanced with the drafting of the *Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic System*. There are currently no national requirements for using certified hardware in PV installations, but it is likely that state agencies will soon require certification of hardware for incentive programs. The PV Systems Engineering Project supports certification, codes, standards efforts that are needed to help remove barriers.

The Project consists of four tasks, shown below.

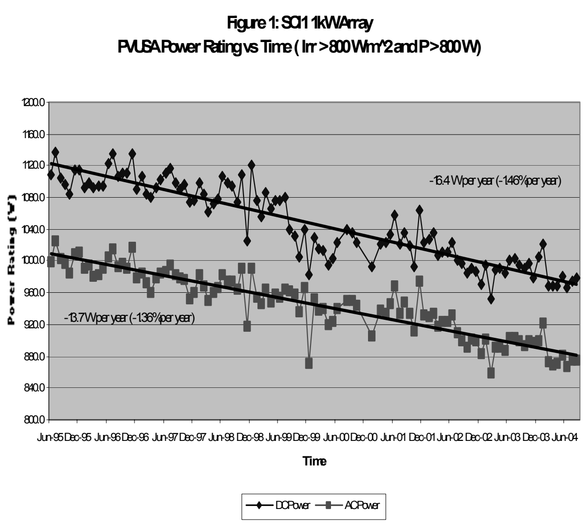
Task Title	FY 2004 Budget ($K)
PV System Performance and Standards (NREL)	800
Solar Radiometry & Metrology (NREL)	625
Codes, Standards, Certification (NREL)	156
Solar Broad Based (NABCEP), (GO)	200

3. Results and Accomplishments

PV system engineering performance and reliability testing, analyses, and reporting continued the long-term testing record at the NREL OTF. A total of eight grid-connected systems were monitored and four quarterly test reports were generated and provided to the corresponding PV industry manufacturers. The systems were the following (record starting dates are shown in parentheses):

- 1.00 kWp CdTe system (June 2003)
- 1.43 kWp x-Si system (Feb. 1995)
- 1.43 kWp CIS system (Dec. 1998)
- 1.20 kWp a-Si system (Sept. 1999)
- 1.00 kWp CdTe system (July 1995)
- 6.00 kWp x-Si system (May 1994)
- 1.80 kWp a-Si system (Jan. 1993)
- 1.00 kWp a-Si system (Oct. 1998)

An example of a long-term performance analysis result is shown in Fig. 1. Each quarterly report, for each system, contains such results.



In September 2004, PVWATTS Version 2 was moved to a higher-speed server and modified to run on ESRI ArcIMS Version 9.0 software. On the map server, PVWATTS is a tool that may be invoked from the top-level "United States Solar Atlas" screen that shows a map of the United States with elevation shading (see Fig. 2).

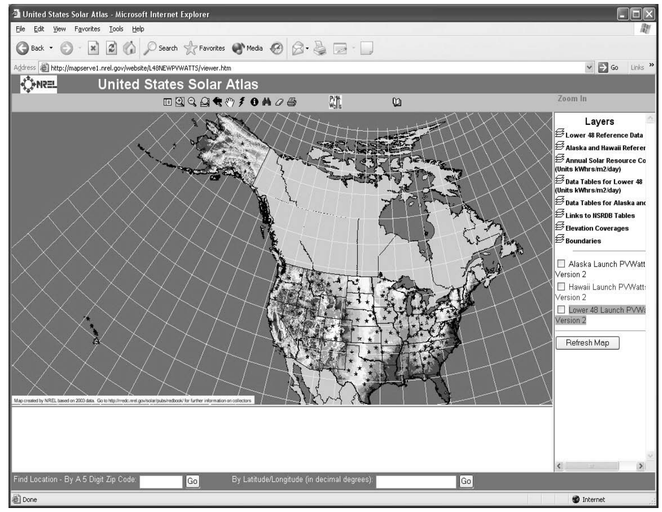


Fig. 2. Top-level "United States Solar Atlas" screen from which PVWATTS Version 2 is invoked.

In addition to elevation shading, a new feature was added permitting the user to display a map showing values of solar radiation for any of 14 different collector orientations or types. More options have also been added for selecting the location. Besides zooming on a region of the map to select a grid cell, the user may now select a location by entering either a zip code or the latitude and longitude coordinates.

PVWATTS Version 1 was updated with an option to provide hourly values of AC energy for each hour of a typical meteorological year (TMY). From the "AC Energy and Cost Savings" screen showing the results of the simulation, the "Output Hourly Performance Data" button may be clicked to display hourly performance. If desired, hourly performance results may be saved as a text file. This feature is not available for Version 2 because Version 2 results are determined with interpolations using monthly solar radiation values.

FY 2004 accomplishments included critical technical updates to the NEC, UL standard 1741, and IEEE standards. Certification efforts used a two-pronged approach to include both installer and hardware certification.

Drafts of the inverter performance test protocol were updated through numerous inputs from industry, academia, utilities, and standards committees. More than 500 inquiries and inputs were recorded in 2004. The draft document continues to be updated with industry guidance, and with a major consideration that value exceeds costs and that tests be conducted in a manner that eliminates bottlenecks in the certification process. Critical sections of the document are being considered by the California Energy Commission for inclusion into its Emerging Renewables Program and will include an option for rebates to be based on system performance.

Testing of applicants continued throughout 2004, with nearly 200 approved certificants now on the rolls. NABCEP committees, supported through SNL, updated the applicant study guide, candidate handbook, task analysis, applicant requirements, and application forms. This work will be supported only minimally in 2005 through SNL, but has earned a five-year grant for continued support through the DOE Golden Field Office. Publications in 2004 included the updated *Study Guide for Photovoltaic System Installers and Sample Examination Questions.*

The 2005 NEC cycle was completed in 2004. The proposed consensus inputs from the SNL-led industry forum were widely accepted by the Code-Making Panel for inclusion in the 2005 code. The most significant changes included an easing of requirements for grounding PV arrays and allowing a first disconnect to reside within a building, provided DC circuits are enclosed in metallic conduit to the point of disconnect. The 2005 NEC was published in September 2004 and will be effective as of January 2005.

Several IEEE standards, recommended practices, and guidelines were supported by SNL in FY 2004. The most significant was the IEEE1547.1 document entitled a "Draft Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems." The IEEE1547.1 is scheduled for balloting early in 2005. Other related documents included "IEEE 1547.2 Draft Application Guide for the IEEE 1547 Draft Standard for Interconnecting Distributed Resources with Electric Power Systems," and "IEEE 1547.3, the Draft Guide for Monitoring, Information Exchange and Control of DR Interconnected with Electric Power Systems."

The UL standard UL1741 is undergoing revisions and a title/purpose change. The new title, "The Standard for Inverters, Converters and Controllers for Use in Independent Power Production Systems," indicates that this standard has been expanded from just PV inverters and now includes inverters for all types of independent power systems. The changes and additions are extensive and will be correlated with the IEEE1547 standard in order to unify required testing for utility-interactive inverters. The next edition of the UL standard is scheduled for release in mid-2005.

The International Electrotechnical Committee (IEC) standards often become law in Europe. SNL and NREL support the United States participation in IEC standards writing through technical expertise and subcontracts to have industry lead several of the standards activities. Much of the work is focused on assuring domestic and international industry interests and component compatibilities in these important international standards.

In the area of solar radiometry, we:

- Calibrated more than 180 broadband, 10 spectral, and 8 solar simulator sensors and systems for NREL and industry research applications.
- Validated classification of the FSEC Flash Solar Simulator for module rating in Florida.
- Characterized and classified six solar flash simulators for NREL and industry.
- Supported the September 2004 ISO 17025 accreditation of the NREL Photovoltaic Testing Group PV Reference Cell Calibration by integrating the required optical metrology functions into the PV Testing Group's Quality System.

We also completed all project-level milestones to:

- Install four new PV system test beds at the NREL OTF (9/1/04).
- Generate quarterly system performance reports and analyses and deliver to manufacturers (9/30/04).

- Improve NREL-revised PVUSA method for PV system performance rating and initiate effort to develop a consensus recommended standard for rating PV systems (9/10/04).
- Conduct and report results of NREL cavity pyrheliometer intercomparisons (5/1/04).
- Report on NREL pyranometer and pyrheliometer offset research results (9/15/04).
- Conduct first round of inverter certification tests (10/17/03).

4. Planned FY 2005 Activities

- Quarterly engineering test reports of at least nine small PV systems at the NREL OTF will provide PV module manufacturers with independent validation and characterization of energy performance ratings and long-term performance degradation rates.
- An improved, on-line PVWATTS software program/model that provides decision-makers, the public, and the industry with credible estimates of PV system electric-generation and costs for specific geographical locations, and on an hourly basis, will be developed and implemented.
- Robust technical support of important national standards, codes, and certification activities, which are needed to ensure safe installations that perform as expected, will continue.
- World-class solar radiometry will be developed and applied to the PV program and used to support industry.

5. Major FY 2004 Publications

Major publications resulting from the standards, codes, and certification work are typically the property of other organizations, including Underwriters Laboratories, the National Fire Protection Association, the Institute of Electronic and Electrical Engineers, the International Electrotechnical Commission, and the North American Board of Certified Energy Practitioners. The draft of *Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems* continues to be a very dynamic document, but is scheduled to be submitted to the IEEE standards board and will be published as a Sandia National Laboratories (SAND) document.

Myers, D.R., C. Gueymard, "Description and Availability of the SMARTS Spectral Model for Photovoltaic Applications," *49th Annual Conference of Society of Photo-Optical Instrumentation Engineers,* Aug. 2–6, 2004, Denver, CO.

Myers, D.R., A. Andreas, I. Reda, S. Wilcox, "Optical Radiation Measurements for Photovoltaic Applications: Instrumentation Uncertainty and Performance," *49th Annual Conference of Society of Photo-Optical Instrumentation Engineer's,"* Aug. 2–6, 2004, Denver, CO.

Myers, D.R., I. Reda, S. Wilcox, T. Stoffel, "Uncertainty Analysis for Broadband Solar Radiometeric Instrumentation Calibrations and Measurements: An Update," *World Renewable Energy Congress*, Denver, CO, Aug. 28–Sept. 3, 2004.

IEEE Standard 1526, "Recommended Practice for Testing the Performance of Stand-Alone PV Systems," The Institute of Electrical and Electronics Engineers, Inc., New York, NY, 10016-5997, ISBN 0-7381-3828-2 SH95177.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
Endecon Engineering Chuck Whitaker	San Ramon, CA chuck.whitaker@bewengineering.com	Continuum of work on IEC, IEEE, NABCEP, and NEC codes, standards, certification.	69.6
NABCEP Pete Sheehan	Malta, NY psheehan@nabcep.org	Support for the establishment of a national practitioner certification program.	200
Institute for Sustainable Power Mark Fitzgerald	Highlands Ranch, CO markfitz@ispq.org	Provide "Marketing" addendum for *Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems.*	24.5
Endecon Engineering Chuck Whitaker	San Ramon, CA chuck.whitaker@bewengineering.com	PTC system rating standard development	30.0
SUNSET Technologies Howard Barikmo	Scottsdale, AZ hbarikmo@aol.com	IEC-TC Secretariat support	69.7
PowerMark Corporation Steve Chalmers	Phoenix, AZ chalmers@powermark.org	Certification of PV modules and systems and IEC participation	69.8

System Evaluation and Optimization

Performing Organization: Sandia National Laboratories

Key Technical Contacts: Michael Quintana (Primary Contact), 505-844-047, maquint@sandia.gov
David King, 505-299-9184, dlking@sandia.gov

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

FY 2004 Budget: $1,316K

Objectives

- Develop, validate, and apply new testing procedures, based on energy production, that are needed to completely understand and optimize the performance of multiple components in fully integrated PV systems. This work provides the basis for system-performance modeling and testing standards needed to design and monitor PV systems based on energy production.
- Collect and analyze performance, reliability, and installation information from selected systems and components in order to develop technology baselines, identify performance and reliability issues, identify techniques that extend component lifetime, identify opportunities for cost reduction, and improve system design procedures.
- Identify system manufacturing methods and deployment strategies that improve system performance and reliability, reduce cost, and minimize technical and financial barriers to large-scale deployment of photovoltaic power systems.
- Conduct detailed testing of commercial inverter performance as a function of all factors (e.g., power level, temperature, input voltage) influencing the annual energy production of PV systems. The resulting inverter performance model will be a significant contribution to PV Advisor and other system design models. This work also includes a coordinated effort with other organizations (e.g., FSEC, SWTDI, Endecon, CEC) to evaluate the long-term aging behavior of inverters.

Accomplishments

- SNL's PV module/array performance model was thoroughly documented (SAND 2004-3535) to directly aid design and performance evaluations by Maui Solar, manufacturers, integrators, NIST, CEC, DOE-2 model, and Energy-10 modeling.
- Substantial product improvements (e.g., reliability, utility interconnection, power quality) resulting from tests on 15 beta-version inverters from 9 manufacturers at Sandia's Distributed Energy Testing Lab.
- SNL, with support from the Regional Experiment Stations and partners (e.g., manufacturers, suppliers, utilities), delivered initial SDA benchmark data on PV grid-tied systems. Results are being published in *Progress in Photovoltaics.*
- New inverter testing (including long-term performance) and modeling efforts are quantifying effects of temperature, voltage, voltage, and power level on inverter performance for SDA input.
- SNL and FSEC provided the technical assistance needed by the USDA to issue the announcement in September of its intent to list accepted PV systems on the Rural Utilities Service List of Materials; USDA is the first federal agency to offer direct financing to the 1000+ rural coops that purchase PV from the list.
- Extensive module performance calibration and annual energy modeling by SNL supported PowerLight's installation of the largest (10 MW) PV system in the world.

Future Directions

- Detailed module, array, inverter, and system research aimed at understanding and improving the performance, reliability, and cost of fully integrated PV systems.
- Performance testing to improve the performance models used for system design, annual energy predictions, field performance validation, component integration and optimization, long-term performance monitoring, and renewable energy financial incentive programs.
- Collaborative investigations to define system integration, manufacturing, and installation opportunities that could dramatically improve the performance, reliability, and installed cost of PV systems.
- Provide systems engineering and modeling support to promote the deployment of PV by the general public, federal and other agencies, and the PV industry.

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1. Introduction

Systems Evaluation and Optimization activities at Sandia National Laboratories are closely linked to the needs of manufacturers and system integrators. They provide the laboratory and field-test information needed to benchmark the performance and reliability status of current PV systems and to identify opportunities for improved system and component design and integration in next-generation systems. These activities are key to meeting the *DOE Solar Program Multi-Year Technical Plan* (MYTP) targets, as well as the goals of the *U.S. PV Industry Roadmap*.

The Systems Evaluation and Optimization Project is the focal point within the DOE Solar Program where the technology concerns of photovoltaic manufacturers, system integrators, and users converge. Manufacturers and integrators produce the components and systems that produce the end product, electric power, for the user. PV market development and subsequent growth depends on quality integration of components applied in an acceptable infrastructure to deliver safe, cost-effective, reliable electric power.

2. Technical Approach

The work conducted by the Systems Evaluation and Optimization Project requires intimate understanding of component and system performance measurements, principles of systems engineering and reliability, and system requirements for specific market infrastructures.

Project activities at Sandia National Laboratories are closely linked to the needs voiced by manufacturers and system integrators. The technical approach is to gather the laboratory and field-test information needed to benchmark the performance and reliability of state-of-the-art PV components and systems. Analyses examine performance and reliability characteristics of specific system configurations and test conditions. The aggregate information is incorporated into models that allow manufacturers and integrators to predict system performance and reliability, as well as to calculate system levelized energy cost. In addition, the information is applied to R&D opportunities for next-generation systems with improved system and component design, cost reductions, and optimized integration. These activities use the Systems-Driven Approach (SDA) and are key to meeting the Solar Program's MYTP targets, as well as the goals of the *U.S. PV Industry Roadmap*.

The Systems Evaluation and Optimization Task is divided into five subtasks. *Module and Array Testing,* primarily as a lab-based activity, supports system integrator's needs for accurate array energy modeling. Comprehensive outdoor testing (performance benchmarking) is conducted on commercial PV modules with performance coefficients archived in a publicly available database. The long-term goal is to transition this testing responsibility to a qualified commercial testing laboratory.

Inverter Testing employs two different approaches. The first is to perform detailed tests under a tightly controlled environment at SNL's Distributed Energy Technologies Laboratory (DETL). Benchmark testing is performed on commercially available products, and proprietary development testing is performed on new designs. The second approach is to perform long-term testing in field environments that are monitored but not controlled. These sites include DETL and partner facilities at the Southeast and Southwest Regional Experiment Stations and at sites operated by the California Energy Commission's (CEC's) Public Interest Energy Research (PIER) program. Common test methodologies are being evolved, and test results will be compared for consistency so that they can be incorporated into predictive models.

Fielded System Testing uses outdoor test procedures and data-analysis techniques established for modules and applies them to system-performance testing and analysis performed in cooperation with system integrators or owners. This effort benchmarks array and system-level performance with all installation and environmental factors considered, and provides the information required to optimize system designs for performance, reliability, and safety.

PV System Optimization applies knowledge gained through the previous subtasks to improve performance and reliability through optimized integration, moving closer to standardized system configurations.

System Performance Modeling captures benchmarking data, information, and analyses and-applies the knowledge to develop a system performance model that predicts performance for specific design configurations in specific locations.

Budget allocations by task are given below.

Task Title	FY 2004 Budget ($K)
System Performance Modeling	164
Inverter Testing	372
Module and Array Testing	396
PV System Optimization	194
Fielded System Testing	190

3. Results and Accomplishments

- Conducted and documented detailed energy analysis and identified optimization opportunities for a commercial off-grid hybrid PV system by Sacred Power.
- Completed the installation of a fully instrumented test capability for optimizing small system performance based on energy production.
- Produced improved array performance models in collaboration with Maui Solar, PowerLight, and RWE Schott Solar through comparison of measured and modeled energy production.
- Provided system consultation and modeling for 30-kW Amonix concentrators at Arizona Public Service.
- Conducted and documented test and optimization of off-grid PV/wind hybrid for SunWize/NTUA.
- Tested, analyzed, and documented energy production by BP Solar c-Si arrays in PNM grid-tied system.
- Completed PV benchmarking plan, defining input to PV Systems Analysis Model (PVSAM).
- Established Long-term inverter test activity with SERES, SWRES, and CEC/PIER.
- Provided performance test results of 15 PV inverter products to manufacturers.
- Completed benchmark tests on three commercial inverters, including models provided by CEC/PIER.
- Developed a matrix of dependencies to be used as inputs to inverter-performance model development for PV SDA, Maui Software, and others.
- Completed testing for validation study with NIST for commercial modules in BIPV applications.

- Provided module calibration (round robin) test support and reports for NREL, FSEC, ASU, and the PV industry.
- Characterized eight new commercial modules and added performance parameters to SNL's database.

4. Planned FY 2005 Activities

This project will consist of the following tasks:

- System Performance Testing/Modeling
- Inverter Performance Characterization
- Module, Array, and System Optimization.

The major expected results for FY 2005 include:

- Complete comprehensive effort with NIST to compare and validate SNL modeling method for BIPV, special session at ISES 2005.
- Develop and document experimentally verified multi-factor performance model for inverter performance modeling.
- Coordinate inverter long-term aging investigations at multiple sites/labs.
- Initiate and document collaborative effort with industry to define manufacturing, certification, installation, and deployment strategies for next-generation PV systems.

5. Major FY 2004 Publications

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

Inverter and BOS Development

Performing Organization: Sandia National Laboratories

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

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

FY 2004 Budget: $1,655K

Objectives

- Improve inverter reliability and performance for PV applications to include:
    - Mean time before failure of >10 years
    - Efficiency >94%
    - Cost less than $.90/watt
    - Providing modularity and expandability to function with energy sources
    - Meeting UL 1741 safety and listing requirements
    - Meeting FCC Part 15, Class B for electromagnetic emanation requirements
    - Meeting National Electric Code (*NEC®)* requirements
    - Designing for high-volume production.
- Improve and establish future inverter and BOS designs that allow full system integration levels while maintaining operating window flexibility.
- Influence certifications, standards, and codes through technology development and verification and through technical guidance enabled by testing and benchmarking.

Accomplishments

- Phase II contract with General Electric Global Research resulted in a 3500-W utility-interactive, multiple-input inverter with a 12-year-minimum MTBF. The inverter addresses many lifetime-related issues and may be vertically integrated in GE's new PV ventures. Delivery of the prototype to SNL is scheduled for early December 2004.
- Phase II contract with Xantrex Technologies, Inc., resulted in a 5000-W utility-interactive or stand-alone inverter with optional inputs (including a matching maximum-power-point tracker) and a 10-year-minimum MTBF. The inverter addresses many lifetime-related issues and may be integrated into a system assembly. Delivery of the prototype to SNL is scheduled for early November 2004.
- Phase II contract with SatCon Applied Technologies resulted in a 2500-W utility-interactive inverter with flexibility for inputs and a 12-year-minimum MTBF. The inverter addresses many lifetime-related issues and may be integrated into a system assembly. Delivery of the prototype to SNL is scheduled for early December 2004.
- All manufacturers are working to assure UL listing, quality control programs, and highly accelerated lifetime testing.

Future Directions

- The number of high-reliability contractors will be reduced from three to two as Phase III of the high-reliability inverter initiative moves to the manufacturability and final product definition stages. The two "highest probability of success" winners will be determined via a Phase II review and with test results from the Phase II prototypes delivered to SNL.
- Benchmarking and hardware characterization will play an increasingly important role in finalizing the high-reliability inverter initiative with specialized environmental and stress testing

anticipated. Full collaboration with the manufacturers will likely require multiple developmental test periods.

- Initiate a High-Tech BOS/Inverter Strategies program with a published 5-year strategies document and a follow-on request for LOIs from the PV and BOS industries. The LOIs will be formally evaluated to determine the winners of the competitive feasibility contracts designed to leapfrog inverter and BOS technologies.

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1. Introduction

Improved inverter reliability, performance, and costs can positively, and with a very high level of probability, impact the levelized energy costs of installed PV systems. Further, given that today's 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, the failure of a component such as an inverter can mean the system will never work again (end of life). This project relates to barriers O, P, Q, R, S, T, and U under "Technology Development" in the *DOE Solar Program Multi-Year Technical Plan* (MYTP). The work is specifically identified under Task 12 (High-Reliability Inverter Initiative, barriers R and S) and Task 13 (Inverter R&D 5-year Strategies, barriers R and S), but overlaps with Tasks 7, 8, 9, 10, and 11 because it provides a key element in each. In FY 2004, the BOS project managed the continuation of the High-Reliability Inverter R&D Initiative, performed critical BOS and inverter evolutionary test and development work, helped remove technical barriers to the installation of PV in California and other states, resolved conflicts in the use of the IEEE 929, IEEE 1547 interconnect standards, and influenced national electrical codes while assisting 11 manufacturers in the development of new products or capabilities.

The objectives of the Inverter and Balance-of-Systems (BOS) Project are to focus on R&D of power electronics and BOS hardware, the characterization of newly developed power electronics and BOS hardware, and establishing the suitability for incorporation into complete systems. The work also indirectly aids the development of codes, certification, and standards for PV applications through verifications and sanity checks that examine the impact on manufacturability. Many of the inverter-related activities also relate to other renewable energy technologies and, in fact, began as a collaborative effort with energy storage and distributed energy resources. The Inverter and BOS Project involves every U.S. PV inverter manufacturer and key charge-controller manufacturers, and also examines key products to determine impacts on the BOS and PV communities.

The BOS Project seeks to improve system efficiency, lower life-cycle cost, and improve levelized energy costs through improved use of power electronics and storage and the development of selected BOS (sometimes non-power electronics) components. The 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

The technical approach to inverter and BOS development has taken on a multi-faceted character. There are parallel approaches to accomplishing the technical aspects, with the Systems-Driven Approach (SDA) at the center of setting priorities and assuring a market influence into the R&D activities.

2.1 Parallel Approaches

The technical approach to inverter R&D is based on parallel approaches, but both apply the SDA and make extensive use of industry and consumer inputs. A major contract activity, the High-Reliability Inverter Initiative, is in progress. It was initiated in 2002 under a competitive bidding process to conduct three phases of R&D. A second and upcoming approach is the proposed High-Tech Inverter Research and Development—A Five-Year Strategy. The 5-year strategy is being organized to incorporate new component technologies such as wide-bandgap semiconductor devices, high-temperature components, thorough thermal management, highly integrated controls and drivers, advanced surge protection, innovative packaging, full systems integration, intelligence, communications, and consumer-friendly products. A third and critical approach is to provide benchmarking and analytical testing and evaluation of emerging inverter and BOS hardware and technologies through SNL's Distributed Energy Technologies Laboratory (DETL).

2.2 Systems-Driven Approach Inverter Workshops

The R&D initiative, 5-year strategy, and laboratory work at the DETL are based on the results of well-attended DOE workshops where the inverter industry, the PV industry, systems designers, utilities, universities, and laboratory experts assembled to provide valuable inputs and prioritization for needed R&D. All competitive contract awards are based on proposals, statements of work, and end products that meet the priorities for the workshops. The contracts for the high-reliability inverter work are listed below.

Task Title	FY 2004 Budget ($K)
High Reliability Inverter Initiative	2,055*
Inverter and BOS Development	430

*Includes $830K of FY 2003 carryover funds.

3. Results and Accomplishments

3.1 The High-Reliability Inverter Initiative

The High-Reliability Inverter Initiative was initiated in 2001, with the first contracts issued in 2002. The initiative was begun as a response to reports of unacceptable high percentages of inverter malfunctions and outright failures in PV installations. The schedule included three phases. The initiative focused on developing designs that could be mass-produced while improving reliability to at least 10 years (mean time before failure [MTBF]). Costs were to be improved or at least held in line. The work was coupled to market analysis and prospects for systems integration resulting in high (>10,000 units per year) production rates.

One theme of the first workshop and the initiative was to examine inverter improvement issues with respect to cost and reliability and to provide perspectives from each. Figure 1 shows the results of a components and materials session of the first workshop and from a high-reliability perspective. It shows the passive components (capacitors, transformers, connectors) as a topic needing the most attention from a high-reliability perspective.

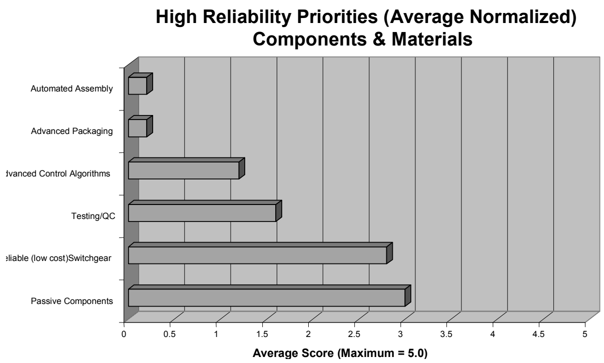

Fig. 1. Components and materials prioritization for high-reliability inverter development

Figure 2 shows another set of priorities based on low-cost considerations for inverters. Capacitors were identified as the highest priority. Thermal management that can be tied to components and packaging followed. All of the high-reliability initiative contractors carefully considered the results of the inverter workshop while designing their next-generation, high-reliability inverters.

The Phase I final reports were reviewed by inverter-cognizant personnel at ORNL, NREL, and SNL. This resulted in the three Phase II contracts. The three high-reliability inverter contractors are now in the final stages of Phase II. Deliverables consist of prototype development, follow-on market analysis, product layout, drawings and working prototypes. All contractors have initiated the testing for safety and UL listing. Some highly accelerated lifetime testing (HALT) has been conducted, but it is required of all. The three contractors will be submitting prototype inverter hardware to SNL for characterization and evaluation in December 2004. Phase II reports will be used in combination with hardware-evaluation results to determine which contractors can be funded for Phase III work. Phase III will take products to commercialization.

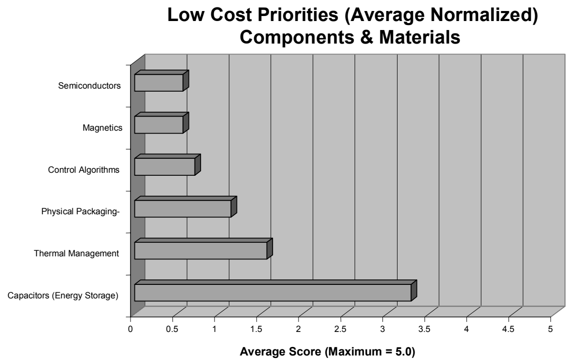

Fig. 2. Components and materials prioritization for low-cost inverter development.

Phase I activities were to:

1. Solicit inverter industry proposals requiring high-reliability goals and mass-production plans for 10,000 units/year. (Three proposals were selected from 12 submissions.)
2. Provide product configurations and architectures that maximize reliability while minimizing costs and manufacturing difficulty.
3. Provide a technical and market plan indicating how the new inverter will be developed.
4. Demonstrate adherence to UL, IEEE, and performance and safety requirements.
5. Report on the Phase 1 results (where the results were used to determine further development with original contractors).

Phase II is in progress. The activities are to:

1. Conduct Phase II with at least two contractors. It was determined that results of the Phase I work warranted Phase II prototype development with all three contractors (General Electric, SatCon, and Xantrex).
2. Finalize development of new inverter designs, with emphasis on efficient switching, manufacturing processes, packaging, thermal management, surge suppression, and overall enhanced performance.
3. Assess, test, and validate new designs, including full characterization, component-level tests, system performance analysis, packaging validation technology, and cooling effectiveness.
4. Validate compliance to utility-interconnection standards such as IEEE 1547 and UL 1741.

Phase III will:

- Be conducted with at least two contractors.
- Refine prototypes into commercial products, maintaining conformity to pertinent standards, performance, cost, and manufacturing objectives.
- Conduct testing of final products through laboratory evaluations, UL listing, HALT, environmental testing, and long-term evaluations.

Contract results are:

- Phase II contract with General Electric Global Research resulted in a 3500-W utility-interactive, multiple-input inverter, which has a minimum MTBF of 12 years, addresses many lifetime-related issues, and may be vertically integrated in GE's new PV ventures. Delivery of the prototype to SNL is scheduled for early December 2004.
- Phase II contract with Xantrex resulted in a 5000-W utility-interactive or stand-alone inverter with optional inputs that include a matching maximum-power-point tracker. The inverter has a minimum MTBF of 10 years, addresses many lifetime-related issues, and may be integrated into a system assembly. Delivery of the prototype to SNL is scheduled for early November 2004.
- Phase II contract with SatCon resulted in a 2500-W utility-interactive inverter with flexibility for input. It has a minimum MTBF of 12 years, addresses many lifetime-related issues, and may be integrated into a system assembly. Delivery of the prototype to SNL is scheduled for early December 2004.
- All manufacturers are working to assure UL listing, quality control programs, and highly accelerated lifetime testing.

3.2 High-Tech Inverter and BOS Research and Development—A 5-Year Strategy

This high-tech strategy for inverter and BOS R&D is currently in the planning stages, with a first draft of the strategy document nearly complete. The full description appears in the Planned FY 2005 Activities section of this report.

The completed milestones for this work are given below.

CPS Milestone ID#	Description of Milestone	Date Completed
15956	Conduct SDA workshop on energy storage for PV	11/30/2003
16207	Place High-reliability Contract with SatCon Applied Technology	10/30/2003
16208	Place Phase II High-Reliability Contract with GE Global Research	12/24/2003
16209	Place Phase II High-reliability Contract with Xantrex Technologies, Inc.	9/10/2003

4. Planned FY 2005 Activities

The planned FY 2005 activities will focus on power electronics, electrical components, and other BOS-related research and development.

The major activities are to:

- Complete Phase II of the High-Reliability Inverter Initiative (12/04).
- Conduct Phase III of the High-Reliability Inverter Initiative with the two contractors with the best likelihood of success (09/05).
- Provide evaluation and analysis of high-reliability developed inverters and other emerging technologies for BOS (09/05).
- Initiate High-Tech Inverter and BOS R&D—A 5-year Strategy, with a draft strategies document (01/05).
- Provide technical guidance to codes, standards, and certification using information obtained through evaluations and analysis of new high-reliability inverters and associated BOS hardware (09/05).
- Release request for LOIs to kick off the High-Tech Inverter and BOS R&D project (09/05).

A final draft of High-Tech Inverter and BOS Research and Development—A 5-year Strategy is scheduled to be completed in January 2005. The logistics of the strategy will be based on the outcome of DOE Solar Program inverter workshops and will strongly emphasize vertical integration of new inverters into complete PV systems and leapfrogging technology advances. It will be designed to partner with key stakeholders to prioritize needs before proceeding. The structure of the high-tech R&D strategy is proposed to conduct work in phases with interim sanity checks while allowing opportunities to introduce new contractors and ideas for evolving technologies.

5. Major FY 2004 Publications

Most of the development work associated with the High-Reliability Inverter Initiative contains proprietary information that restricts publications at this time. Each contractor provided a summary of its work at the DOE Solar Program Review Meeting in Denver, CO, on October 26, 2004. Each contractor is required to provide a final Phase II report; those will be published as SNL (SAND) documents early in 2005.

6. University and Industry Partners

The following organizations partnered in the project's research activities during FY 2004.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share
General Electric Global Research Joseph Smolenski	Niskayuna, NY smolenski@crd.ge.com	Competitive solicitation for Research on High-Reliability Inverters for PV Applications	{439} 884*	1,158*
Xantrex Technologies, Inc. Ray Hudson	Livermore, CA Ray.Hudson@xantrex.com	Competitive solicitation for Research on High-Reliability Inverters for PV Applications	{749} 998*	2,147*
SatCon Applied Technologies Leo Casey	Cambridge, MA Leo.Casey@satcon.com	Competitive solicitation for Research on High-Reliability Inverters for PV Applications	{805} 956*	1,015*

* Total contract costs. FY 2004 expenditures in brackets. Contracts carry over into FY 2005. FY 2005 funding is needed.

Domestic PV Applications

Performing Organizations:	National Renewable Energy Laboratory Sandia National Laboratories
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@hq.doe.gov
FY 2004 Budgets:	$926K (NREL), $96K (SNL)

Objectives

- Support development of DOE Systems-Driven Approach (NREL and SNL).
- Address the markets and applications issues raised in the *U.S. 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 USDA Farm Bill Solar Program (NREL and SNL).

Accomplishments

- Supported development of program criteria and evaluation of proposals for USDA Farm Bill (NREL and SNL).
- Conducted three consumer workshops at the Denver Western Stock Show with public attendance of about 450 (NREL).
- Conducted solar application workshops for farmers in Nebraska and Kansas (NREL).
- Performed rooftop surveys for the U.S. Department of State HQ building, Washington, DC, and the U.S. Federal Building, Raleigh, NC (NREL).
- Provided technical support to the City of Palo Alto, per DOE request.
- Developed partnership with DOE's Rocky Mountain Oilfields Testing Center to test use of PV in oilfields (NREL).
- Provided technical support to U.S. EPA 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 providing tech 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 three consumer workshops at the Denver Western Stock Show (NREL).
- Provide logistical support for Solar Decathlon 2005 (NREL).

1. Introduction

The Domestic PV Applications Project supports the analytical, applications, and market development activities of the DOE Photovoltaic program and the development and use of a Systems-Driven Approach (SDA). The objective is to provide a focal point for DOE activities through project development, dissemination of information and raising public awareness, subcontract management, and technical assistance, as defined in Section 4.1.1.5, Task 10 of the *DOE Solar Program Multi-Year Technical Plan* (MYTP). 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

The Project consists of two tasks:

2.1 Training, Education, and Technical Assistance (NREL)
We work to raise public awareness through training, education, and technical assistance for domestic applications. The client base includes other NREL R&D activities, DOE and other federal agencies and programs, the U.S. PV industry, and specific application sectors, such as the insurance industry and communities.

FY 2004 activities were structured to address the markets and applications issues raised in the report of the *U.S. PV Industry Roadmap*. Raising consumers' awareness and understanding of PV's benefits and availability was given the highest priority of all activities in the markets and applications area.

2.2 Domestic Technical Support (SNL)
SNL has active partnerships with several state and federal agencies, including the USDA and the USDA Forest Service, the National Park Service, and the Bureau of Land Management, as well as with several tribal utilities and other tribal organizations. These partnerships have focused on leveraging SNL's 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.

Budget allocations by task are provided below.

Task Title	FY 2004 Budget ($K)
Training, Education and Technical Assistance (NREL)	926
Domestic Technical Support (SNL)	96

3. Results and Accomplishments

Major results and accomplishments during FY 2004 include the following:

- Supported development of program criteria and evaluation of proposals for USDA Farm Bill (NREL and SNL).
- Conducted three consumer workshops at the Denver Western Stock Show with public attendance of about 450 (NREL).
- Conducted solar application workshops for farmers in Nebraska and Kansas (NREL).
- Performed rooftop surveys for the U.S. Department of State HQ building, Washington, DC, 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's Rocky Mountain Oilfields Testing Center to test use of PV in oilfields (NREL).
- Provided technical support to U.S. EPA Supplemental Environmental Projects, (SEPs) (NREL).
- Assisted 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).
- Provided technical assistance to priority Native American renewable energy programs (SNL).

4. Planned FY 2005 Activities

4.1 Training, Education, and Technical Assistance (NREL)
Activities during FY 2005 will address some 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 nontechnical audiences. An example of this are the three consumer workshops conducted each January at the Denver Western Stock Show, where 400 to 500 public attendees come to learn about PV. We also will provide technical support to federal, state, and local organizations, such as the Rocky Mountain Oilfields Testing Center in Casper, WY, U.S. Department of State HQ in Washington, DC, and the Maryland Science Center in Baltimore, MD, for the installation of PV systems. DOE HQ activities will be supported upon request.

4.2 Domestic Technical Support (SNL)
Activities in FY 2005 will focus on assisting 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, and technical assistance to priority Native American renewable energy programs.

5. Major FY 2004 Publications

Stafford, B., and Thornton, J.P., 2004, "Successful Design of PV Power Systems for Solid State Lighting Applications," *Proceedings of the Fourth International Conference on Solid State Lighting Conference*, August 2004.

Thornton, J.P., 2004, "Photovoltaic Applications in Energy Security," *Proceedings of WREC VIII (World Renewable Energy Conference)*, September 2004.

Larsen, W., 2004, "Outreach is Serious Fun," *Proceedings of the DOE Solar Program Review Meeting*, October 2004.

Campbell, S.B., Coots, J.J., and Mar, B., 2004, "Native American EmPowerment: Solar Electric Initiatives," *Proceedings of the DOE Solar Program Review Meeting*, October 2004.

Hanley, C.J., and Thornton, J., 2004, "The Role of Technology Adoption within the Department of Energy's Solar Energy Technologies Program," *Proceedings of the DOE Solar Program Review Meeting*, October 2004.

Thornton, J.P., 2004, "Renewable Energy Technologies—America's Well-Kept Secret," *EnergyBiz Magazine*, November/December 2004.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
Carolynne Harris Knox	Washington, D.C. carolynnehknox@mindspring.com	Definition of Solar Decathlon 2005 layout with respect to large public attendance (200,000+)	30*
En-Strat Associates Gerry Braun	Darnstown, MD Gbraun12@comcast.net	Development of guidelines and design criteria for PV on school emergency centers	50*
Sustainable Buildings Industry Council Mathew Nowakowski	Washington, D.C. mnowakowski@sbiccouncil.org	Determination of institutional barriers to adoption of BIPV in commercial buildings sectors	50*

*Awarded September 2004

Building-Integrated Photovoltaics

Performing Organization: National Renewable Energy Laboratory

Key Technical Contact: Cécile Warner, 303-384-6516, cecile_warner@nrel.gov

DOE HQ Team Leader: Richard King, 202-586-1693, richard.king@hq.doe.gov

FY 2004 Budget: $1,816K

Objectives

- Accelerate adoption of building-integrated PV in new residential and commercial construction through successful collaborative industry partnerships among PV manufacturers, installers, builders, designers, and the trades.
- Carry out the next Solar Decathlon university competition of 100% solar-powered homes that demonstrate building-integrated PV and solar technologies in marketable residential applications.

Accomplishments

- Completed an independent analysis, through partnership with NAHB, DOE HQ, and NREL experts of the potential and barriers to the Zero Energy Homes (ZEH) concept in order to determine the future direction for this element of the program.
- Continued the implementation of the 2005 Solar Decathlon university competition, releasing the final regulations, solidifying sponsors, and supporting teams.
- Awarded a subcontract for development of home energy monitor for building-integrated PV ZEH.

Future Directions

- Carry out the 2005 Solar Decathlon and release a solicitation for the 2007 event.
- Develop and implement the strategies outlined in the ZEH due diligence analysis.

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1. Introduction

The Building-Integrated PV 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 three distinct, interrelated activities within this overall effort.

2.1 Solar Decathlon

The Solar Decathlon is a biennial event designed to educate students, increase public awareness of the value of energy, and accelerate solar energy R&D. It demonstrates that the surface of a building can be used to generate enough energy to power all the heating, cooling, electrical, communications, and transportation needs of a home and a home-based business. It fosters collaborations among architects and engineers at the outset of their careers to achieve the goal of demonstrating building-integrated PV and solar technologies in marketable residential applications.

2.2 PV in Buildings R&D

When a PV system is integrated into the building envelope, the designer must consider not only the energy produced by the systems, but also the system's effect on the building's lighting and thermal loads, to maximize both PV output and building energy savings. The PV in Buildings R&D activity specifically focuses on building-integrated photovoltaics, seeking scientific advances, engineering improvements, new product development, feedback to the user, and well-established standards for this technology.

2.3 Analysis of ZEH Potential

A Zero Energy Home (ZEH) combines energy-efficient construction and components with commercially available renewable energy systems such as solar water heating and PV. This combination can result in net zero energy consumption. A ZEH, like most houses, is connected to the utility grid, but can be designed and constructed to produce as much energy as it consumes on an annual basis. With its reduced energy needs and renewable energy systems, a ZEH can, over the course of a year, give back as much energy to the utility as it takes. The Building-Integrated PV Project required an independent, expert analysis of the potential and barriers to the ZEH concept in order to determine the future direction for this element of the program. The study was directed and conducted by independent sources and its findings were endorsed by experts in the building industry, represented by the National Association of Home Builders (NAHB). The work at NAHB-RC was conducted through an NREL subcontract to McNeil Technologies.

Budget allocations by task are provided below.

Task Title	FY 2004 Budget ($K)
Solar Decathlon	929
PV in Buildings R&D	487
ZEH Potential	400

3. Results and Accomplishments

3.1 Solar Decathlon

Preparations for the 2005 Solar Decathlon have proceeded well during FY 2004. We developed and released a new, updated, electronic-based version of the competition Rules and Regulations to teams in February. The new document incorporates a few improvements to the event, but more importantly, it is much easier to use and to find information in than previous versions. The Yahoo! Web site for team members of the 19 Solar Decathlon teams and organizers, which we launched in October 2003, is working well as a streamlined, efficient mechanism for us to convey vital competition information to teams, and for them to ask questions of us and of each other.

We began holding frequent conference calls between organizers and the participating teams during this fiscal year. These cost-efficient interactions are vital to track progress of teams and to inform them of important upcoming deadlines. The Solar Decathlon Website redesign was completed and went live in May 2004 (http://www.solardecathlon.org). The focus of the site's content is now on the upcoming event rather than the 2002 event in review. And, there are pages dedicated to teams and to media. The site is now much easier to navigate and has an improved look and feel. Additional content will be added during the next reporting period. All Solar Decathlon teams now have a (required) live Website that conforms to DOE and NREL guidelines. We have linked our site to each team's site upon passing our requirements.

We have received a commitment from the first of several high-profile architectural jury members during this period. Sarah Susanka, bestselling author of *The Not So Big House*, has agreed to participate in the judging of the Solar Decathlon architecture competition.

A 129-page technical report of the 2002 event was completed. *Solar Decathlon 2002: The Event in Review* is a comprehensive summary of all aspects of the inaugural event. We also completed design and printing of a new brochure promoting the 2005 event.

In June, we received the required design reports from the 19 Solar Decathlon teams for our review. These reports describe each project in detail, including drawings and building simulations that were conducted to develop the designs. We reviewed the designs for compliance with contest regulations, and have provided feedback to teams to improve compliance with the regulations.

We have developed the organizers' team, convening a productive team-building offsite retreat in August with NREL, Solar Decathlon contractors, and DOE GO and HQ personnel, as well as holding frequent project meetings. Subcontracts for building energy modeling, code compliance evaluation, and architectural consulting were awarded.

Milestone: Complete and distribute Solar Decathlon Rules and Regulations revision and update Website. *(Completed 9/2004.)*

3.2 PV in Buildings R&D

A subcontract to develop a "user-friendly home energy monitor" for ZEHs to Steven Winter Associates was awarded and has progressed well. We formed an alliance with HAI, a home automation company, to move toward production of a commercial product.

The Energy-10 software program, an important building energy modeling tool for architects and building designers, will be improved, via subcontract to the developer, to model building-integrated PV systems and rooftop solar thermal systems, as well as building energy.

Milestone: Award subcontract for development of home energy monitor for building-integrated PV ZEH. *(Award placed with Steven Winter Associates 11/03.)*

3.3 ZEH Due Diligence

A new project element emerged in FY 2004 to lead the DOE-NAHB-NREL effort to conduct an independent evaluation of the potential of Zero Energy Homes in the United States, from the viewpoint of the building industry. This project involved a subcontract with McNeil/NAHBRC and close collaboration among NREL PV, Buildings, and Analysis participants, as well as DOE managers from the Office of Building Technologies and the Solar Program. The team has agreed to an approach and desired outcomes, toward a December 2004 report deliverable from NAHB.

Milestone: Initial draft report on findings. *(Completed 9/2004.)*

4. Planned FY 2005 Activities

- Publish and solicit stakeholder buy-in for the outcomes of the ZEH due diligence analysis.
- Continue the implementation of the strategic plan for PV/buildings R&D, in conjunction with industry stakeholders, coordinated with the ZEB program element.
- Continue the implementation of the 2005 Solar Decathlon university competition in support of DOE HQ, coordinating sponsors, holding a teams' workshop in January 2005, and preparing subcontractors and organizers to conduct a successful event in October 2005.
- Award a subcontract for building energy monitoring during the event.
- Convene a Solar Decathlon sponsor meeting in early FY 2005.
- Release a solicitation for the 2007 Solar Decathlon event.

5. Major FY 2004 Publications

M. Eastment et al. (2004), *Solar Decathlon 2002: The Event in Review*, 129 pp., NREL Report No. DOE/GO-102004-1845.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
Norman Weaver Interweaver	Steamboat Springs, CO Norm_weaver@interwvr.net	Evaluate and coordinate the judging of building energy simulations for the Solar Decathlon. Develop and release an improved version of Energy-10.	94
Robb Aldrich Steven Winter Associates	Norwalk, CT raldrich@swa.com	Development of a Home Energy Monitor	156
John Priebe ALCP Architecture	Denver, CO Denver@aclparchitecture.com	Solar Decathlon drawings and submittals review and on-site inspections	55
Susan Piedmont-Palladino Virginia Tech-Washington Alexandria Consortium	Alexandria, VA spalla@vtech.edu	Fundamental research on new semiconductor materials for cheap PV electricity	17
Kevin DeGroat McNeil Technologies	Springfield, VA kdegroat@mcneiltech.com	Analysis of ZEH potential in the U.S. by the National Association of Home Builders	167

Million Solar Roofs Initiative

Performing Organizations: DOE Headquarters and Regional Offices
National Renewable Energy Laboratory
Sandia National Laboratories
Interstate Renewable Energy Council
National Energy Technology Laboratory
DOE Golden Field Office

Key Technical Contacts: Heather Mulligan (Project Manager, Primary Contact), 206-553-7693, heather.mulligan@hq.doe.gov
Carol Tombari (NREL), 303-275-38231, carol_tombari@nrel.gov
Charles Hanley (SNL), 505-844-4435, cjhanle@sandia.gov
Glenn Doyle (DOE/GO), 303-275-4706, glenn.doyle@go.doe.gov

DOE HQ Technology Manager: Glenn Strahs, 202-586-2305, glenn.strahs@hq.doe.gov

FY 2004 Budgets: $390K (NREL), $135K (SNL), $445K (DOE/GO), $1,500K (NETL)

Objectives

The major objectives of the Million Solar Roofs (MSR) Initiative are to:

- Facilitate the reduction of institutional barriers to marketplace adoption of 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 15 new MSR State and Local Partnerships during FY 2004, bringing the total to 89. In addition, 125 businesses, electricity providers, organizations, and agencies joined Partnerships, bringing the national total of participants to 822.
- Awarded $1.6M in State and Local Partnership grants—combined with $767,600 in cost-share—to support localized efforts to remove barriers and develop local markets for solar energy technologies.
- Provided engineering and economic analysis, on request from DOE Regional Offices on behalf of their Partnerships. For instance, the MSR technical team researched and responded to a question regarding whether solar residential rebates and grants for homeowners and businesses are taxable by the Federal government as income. (They are not.)
- Initiated/funded a telecommunications study involving Bell South, Verizon, and Emerson to explore opportunities for solar on switching stations to support their operations.
- Initiated series of state-specific economic analysis briefs, targeted at solar industry distributors and retailers, for their use in marketing their product; and calculated the value proposition for states by incorporating incentives, varying tax structures, etc.
- Commenced development of economic data bank, a tool for state and local decision-makers to calculate job creation and other economic benefits of solar.
- Created a link between the on-the-ground experience of MSR Partnerships and the ongoing solar systems research at SNL and NREL. In FY 2004, encouraged Partnerships in Hawaii, New York, California, Florida, Arizona, and Washington to become active contributors of data on PV and solar hot water systems to SNL's reliability database.

- Collaborated with Austin, San Antonio, and Tucson in developing solar-based energy security/surety programs in their communities. The "how to" information will be made available.
- Worked closely with two cities (Albuquerque and Tucson) to develop guidance—including a third-party financing system—for large-scale implementation of solar hot water and pool systems in municipalities. The "how to" information will now be disseminated to other municipalities.
- Produced *Annual Report*, plus executive summary titled *Million Solar Roofs: Partners Make Markets*, which is also printed and distributed separately as a marketing piece.
- Held peer meetings of MSR partners in each DOE region, to exchange ideas and share valuable informational resources. Held an Annual Meeting of MSR participants in conjunction with the ASES Conference.

Future Directions

- Continue providing economic analysis and technical assistance to the 89 State and Local Partnerships committed to advancing markets for solar energy technologies in their communities.
- Direct market studies based on the needs and issues identified by multiple MSR participants.
- Share information on a regular, routine basis through various forums, including the peer exchanges, Website, and other communication media.
- Further develop the feedback link between the Solar Program's laboratory-based R&D and the real-world experiences of solar technology users, marketers, and installers.
- Conduct a strategic review of Million Solar Roofs.

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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 to the DOE Solar Program's 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 provides 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. This network of 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 2004 were: 1) providing Partnerships access to small grants to support market development in their communities; 2) providing individualized technical assistance to partners upon 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 technical assistance (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 our information-sharing approach, we post the written TA reports on the MSR Website for all participants to use.

2.2 Information Sharing

With support from the Interstate Renewable Energy Council (IREC), MSR provided opportunities for information sharing by: 1) hosting at least one peer exchange among partners, and selected MSR Team members and guest experts as requested by the partners, in each DOE region; 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) and managing a dynamic Website 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.

Most economic analysis is subcontracted to Segue Consulting, the principal of which developed an analytical approach that captures the value of solar technology (versus cost). Website maintenance, meetings and conference call seminars' development, and metrics are subcontracted to IREC, an organization comprising renewable energy program managers in State Energy Offices.

3.3 Providing Feedback to the R&D Efforts

MSR has made, and continues to make, concerted efforts to link with researchers at SNL and NREL in an effort to provide customer-level feedback on market drivers, issues, and real-world system performance. Over the past year, MSR has encouraged Partnerships in Hawaii, New York, California, Florida, Arizona, and Washington to become active contributors of data on PV and solar hot water systems to SNL's reliability database.

Budget allocations by task are provided below.

Task Title	FY 2004 Budget ($K)
State and Local Partnership Grants	1,500
Technical Assistance and Performance Coordination with Labs	525
Communication and Outreach Support	445

3. Results and Accomplishments

During 2004, the MSR network grew significantly: 15 new Partnerships joined the effort, bringing the total to 89. In addition, 125 businesses, electricity providers, organizations, and agencies joined Partnerships, bringing the national total of participants to 822.

3.1 Accomplishments Resulting from Technical Assistance

MSR uses its growing network of Partnerships and participants to identify key issues of common interest and opportunities where the limited funding can be most effectively focused and leveraged. The single greatest barrier to widespread marketplace adoption of solar technologies, as identified by MSR Partnerships, is cost. Consequently, much of MSR's analytical work and technical assistance addressed this issue over the past year.

To tackle the challenge of cost, MSR champions the "value proposition" as an alternative to straight cost analysis. Partnerships have been able to use MSR-developed value-proposition tools when meeting with: civic leaders looking to address important public policy goals; utilities working to meet renewables portfolio standard (RPS) goals, systems benefits charge plans, or consumer demand for green electricity; and businesses interested in exploring opportunities to use more renewable energy in their operations.

In FY 2004, MSR developed several analytical pieces based on value-proposition analyses.

- At the request of the Solar Energy Industries Association, MSR commenced development of economic analysis briefs specific to each state. The briefs examine the sample costs and benefits of residential solar energy systems, taking into account each state's unique energy costs, tax structures, and financial incentives.
- Responding to a TA request from a utility partner developing a solar rebate program, MSR analyzed the impact on break-even turnkey costs of a number of rebate scenarios.
- To help state policy makers assess policy options for accelerating marketplace adoption of solar technologies, MSR started development of an "Economic Development Databank."
- Responding to a question from MSR Partnerships, the MSR technical team researched and responded to a question regarding whether solar residential rebates and grants for homeowners and businesses are taxable by the Federal government as income. (The answer is "no"—rebates and grants are not taxable as income.)

3.2 Accomplishments Resulting from Grants and Outreach

In addition to providing technical assistance, MSR provides small, competitively awarded grants of up to $50,000 to its State and Local Partnerships. In FY 2003, we estimate that the $1.5 million in MSR-awarded grants leveraged almost $7 million in non-Federal monetary resources. This does not include the many and varied in-kind commitments of MSR's 822 participants. DOE's funding for activities also complemented more than $100 million of state and utility incentives. Following are a few examples of resources leveraged during the past year.

- Nevada leveraged "No Child Left Behind" funding and the its Green Power program to introduce solar education into professional development for middle school teachers.
- The Florida SunSmart Partnership leveraged almost $2 million from state government programs.
- New Jersey's MSR activities have complemented its RPS and state funds, which provided rebates totaling $5 million this past year.

State and Local Partnerships use their grant funding to undertake actions to address barriers that make if difficult for solar technologies to penetrate the established energy market. The following are a few examples of their accomplishments made with MSR grant funding in the past year.

- The Kentucky Partnership supported passage of a net metering bill this year.
- The Bay Area Solar Consortium addressed precertification of several solar system designs with the California State Architect, for ease of adoption by schools.
- The Oahu Partnership continued a successful relationship with the military, which resulted in the installation of solar on military housing units.
- The Washington State Partnership helped 10 Pacific Northwest Public Utility Districts to adopt solar green power incentive programs based on the successful Chelan County SNAP program.
- New York State Energy Research and Development Authority is developing accredited PV installer training programs and institutions, and is helping installers obtain certification from the North American Board of Certified Energy Practitioners.

As a major part of DOE's solar deployment activities, MSR actively seeks opportunities to move solar technologies into new market areas. In the recent past, MSR has worked with its Partnerships to make inroads into the residential housing market, as exemplified by MSR's San Diego Partnership and its work with Shea Homes. This past year, MSR funded NREL to conduct a study involving Bell South, Verizon, and Emerson to explore potential applications for solar in the telecommunications industry; the study is a first step in an effort that could result in solar on thousands of switching stations across the country.

3.3 Results of Linking Back to R&D Efforts

MSR has made, and continues to make, concerted efforts to link with researchers at SNL and NREL in an effort to provide customer-level feedback on market drivers, issues, and real-world system performance. Over the past year, MSR has encouraged Partnerships in Hawaii, New York, California, Florida, Arizona, and Washington to become active contributors of data on PV and solar hot water systems to SNL's reliability database. MSR will continue to seek and expand these mutually beneficial relationships in the coming year.

Finally, MSR took steps in FY 2004 to conduct an important exercise in programmatic self-assessment. In preparing for a strategic planning meeting that has been postponed until the new calendar year, the MSR Team laid the groundwork and intellectual underpinnings that will be used to reassess program goals and objectives; identify stakeholders and critical allies; improve program procedures; lower transaction costs; and change the program name. MSR is in a good position to take up this programmatic self-assessment again beginning in January.

4. Planned FY 2005 Activities

In FY 2005, MSR will:

- Complete a discussion paper on improving the scope and effectiveness of MSR by renaming, adding grantee metrics reporting, and other changes/enhancements (11/30/04).
- Conduct a strategic review of the MSR Initiative and report findings (5/1/05).
- Award State and Local Partnership grants to support localized efforts that will facilitate the removal of barriers and lead to increased penetration of solar energy technologies in local markets (7/1/05).
- Provide TA to Partnerships and their members, and make information widely available to other Partnerships through a variety of communication tools (ongoing).
- Create a link between the on-the-ground technology experience of MSR Partnerships and the ongoing solar systems research at SNL and NREL (ongoing).

5. Major FY 2004 Publications

Million Solar Roofs: Partners Make Markets. Executive Summary, Annual Partnership Update Report; July 2004. (2004). 4 pp.; NREL Report No. BR-710-36402; DOE/GO-102004-1954.

6. University and Industry Partners

The following organizations partnered in MSR's activities during FY 2004.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share
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)	175	0
Interstate Renewble Energy Council Jane Weissman	Latham, NY jane@irecusa.org	Communication and outreach activities aimed at the 89 MSR Partnerships and their participating members.	145	0
Florida Solar Energy Center Jennifer Szaro	Cocoa Beach, FL jszaro@fsec.ucf.edu	State and Local Partnership Grant	49.5	0
North Carolina Solar Center Katy Ansardi	Raleigh, NC kansardi@nc.rr.com	State and Local Partnerships Grant	48.6	0
Appalachia Science for the Public Interest Joshua Bills	Mt. Vernon, KY solar@a-spi.org	State and Local Partnership Grant	48.7	0
Southface Energy Institute Laura Uhde	Atlanta, GA laura@southface.org	State and Local Partnership Grant	49	0

New York State Energy Research and Development Authority (NYSERDA) Adele Ferranti	New York, NY af1@nyserda.org	State and Local Partnership Grant	40	60
Vermont Energy Investment Corporation David Hill	Montpelier, VT dhill@veic.org	State and Local Partnership Grant	40	0
Massachusetts Division of Energy Resources Mr. Jan Gudall	Boston, MA Jan.gudell@state.ma.us	State and Local Partnership Grant	49.5	0
Long Island Million Solar Roofs Initiative Gordian Raacke	Farmingdale, NY reli@optonline.net	State and Local Partnership Grant	50	0
Cape and Islands' Self-Reliance MSR Partnership Megan Amsler	Cape Cod, MA meganams@reliance.org	State and Local Partnership Grant	50	0
The Vineyard Energy Project Kate Warner	West Tisbury, MA kate@vineyard.net	State and Local Partnership Grant	40	0
State of New Hampshire Peter Adams	Concord, NH James.Taylor@NH.gov	State and Local Partnership Grant	35	59.3
State of Maine Shirley Bartlett	Augusta, ME Shirley.bartlett@maine.gov	State and Local Partnership Grant	15	0
Solar Connecticut South Mark Pizzi	Fairfield County, CT Mark.edward@earthlink.net	State and Local Partnership Grant	10	0
Solar Connecticut North Thomas Filburn	Hartford, CT filburn@hartford.edu	State and Local Partnership Grant	10	0
City of Chicago Steve Walter	Chicago, IL swalter@cityofchicago.org	State and Local Partnership Grant	50	18.2
State of Iowa Kelley Myers	Des Moines, IA kelley.myer@dnr.state.ia.us	State and Local Partnership Grant	46.5	22
Great Lakes Renewable Energy Association John Richter	Dimondale, MI John.richter@glrea.org	State and Local Partnership Grant	50	0
San Luis Valley Resource Conservation & Development, Colorado James Mietz	San Luis Valley, CO James.mietz@co.usda.gov	State and Local Partnership Grant	45	27
Colorado Renewable Energy Society Patrick Keegan	Golden, CO pkeegan@energyscience.org	State and Local Partnership Grant	45	28
Community Office of Resource Efficiency (CORE) James R. Udall	Aspen, CO core@aspencore.org	State and Local Partnership Grant	32	37
Trees, Water and People Alison A. Mason	Ft. Collins, CO Alison@greyrock.org	State and Local Partnership Grant	40	0
Center for ReSource Conservation Seth Porter	Boulder, CO sportner@conservationcenter.org	State and Local Partnership Grant	32	0
National Center for Appropriate Technology Dale Horton	Missoula, MT daleh@ncat.org	State and Local Partnership Grant	45	0
City of Albuquerque Richard Harding	Albuquerque, NM rharding@cabq.gov	State and Local Partnership Grant	40	30
Sunsense Scott Ely	Carbondale, CO sunsense@sopris.net	State and Local Partnership Grant	31	0
Delaware Million Solar Roofs Coalition Brian Gallagher	Dover, DE bgallagher@e3energy.com	Sate and Local Partnership Grant	50	6.1
Commonwealth of Pennsylvania, Commission on Economic Opportunity Eugene Brady	Wilkes-Barre, PA hebegebe@sunlink.net	State and Local Partnership Grant	50	30

Energy Coordinating Agency of Philadelphia Liz Robinson	Philadelphia, PA lizr@ecasavesenergy.org	State and Local Partnership Grant	50	50
West Virginia Development Office Debi Conrad	Charleston, WV dconrad@wvdo.org	State and Local Partnership Grant	11.6	0
Venture Catalyst (for Greater Tucson Coalition for Solar) Valerie Rauluk	Tucson, AZ vajra@vecat-inc.com	State and Local Partnership Grant	50	132.8
Idaho Department of Water Resources Ms. K.T. Hanna	Boise, ID kthanna@idwr.state.id.us	State and Local Partnership Grant	50	12.5
Marin County Community Development Agency Gwen Johnson	Marin, CA gjohnson@co.marin.ca.us	State and Local Partnership Grant	50	24.7
Oregon Office of Energy Christopher Dymond	Salem, OR Christopher.S.Dymond@state.or.us	State and Local Partnership Grant	50	36.9
San Diego Regional Energy Office Ashley Watkins	San Diego, CA awa@sdenergy.org	State and Local Partnership Grant	50	27.4
University of Nevada, Reno Ellen Jacobson	Reno, NV jacobsoe@unr.edu	State and Local Partnership Grant	45	9.5
Washington State University, Energy Extension Mike Nelson	Olympia, WA miknel@westernsun.org	State and Local Partnership Grant	50	25
Maui Electric Company Limited Stefanie Tome	Maui, HI stome@hei.com	State and Local Partnership Grant	50	15
Great Valley Center, Inc. Jean-Pierre Batmale	Modesto, CA jpb@greatvalley.org	State and Local Partnership Grant	50	56.7
County of Santa Barbara Community Environmental Council Karen Feeney	Santa Barbara, CA KFeeney@cecmail.org	State and Local Partnership Grant	49.4	59.4
Washington State University, Energy Extension Ellen Lamiman	Olympia, WA ellenlam@methow.com	Cooperative Agreement with the Western Regional Office to assist Northwest Public Utility Districts with the development of solar green power programs.	20	10

International Solar Technologies

Performing Organizations: National Renewable Energy Laboratory
Sandia National Laboratories

Key Technical Contacts: Debra Lew (NREL), 303) 384-7522, debra_lew@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 2004 Budgets: $525K (NREL), $414K (SNL)

Objectives

- Provide data and analysis on cost, performance, and reliability of fielded PV systems.
- Remove barriers to the widespread deployment of solar technologies.
- Execute DOE commitments in international agreements and activities.

Accomplishments

- Provided technical and program design assistance and training certification for installation of 20 MW of PV in China's Township Electrification Program (NREL).
- Developed with DOE OWIP cofunding rural energy training modules for Brazil's Luz Para Todos program, a UN Development Program training in Chile, training in the Maldives, and two regional Mexico training sessions on NREL's HOMER® software (NREL).
- Helped launch IEA Task 10, "Urban Scale PV Applications," which is the first IEA PVPS Task in which the United States is an operating agent (NREL).
- Helped open markets for U.S. renewable energy companies. A dozen U.S. companies and organizations, including Uni-Solar Ovonic, GE, Pro Vision Technologies, and Hanalei Solar, participated in a China trade mission, resulting in at least six business partnerships (NREL).
- Completed installation of the wind/PV hybrid test facility, which powers village applications such as water purification, lighting, and refrigeration (NREL).
- Tested and released HOMER software version 2.1.
- Completed and documented ten-year reliability assessment with our local partner (FIRCO) of 46 PV water-pumping systems installed in Mexico (SNL/SWRES).
- Completed and documented five-year reliability assessment of an innovative PV lighting system developed by SunWize, a New York company, and installed in Chihuahua, Mexico (SWRES/SNL).
- Tested new battery prototypes designed by U.S. companies that have the potential for 15–25 years of operational life (SNL/SWRES).
- Provided technical assistance to large-scale PV projects in Central America and consequently gained access to the PV systems for future input into the DOE/SNL SOLARDB reliability database (SWRES/SNL).

Future Directions

- Field analysis and retrieval of PV modules to measure performance degradation in 12-month hot and humid climates (SNL/SWRES).
- Testing of PV-powered water pumping and purification applications at the PV/wind hybrid test facility (NREL).

- Testing of new low-load technologies to reduce system cost (SNL/SWRES).
- Benchmarking of PV systems in rapid growth markets abroad such as Japan and Germany.

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1. Introduction

One of the primary goals of the DOE Solar Program is to facilitate acceptance and integration of distributed solar power for both on- and off-grid applications. The international activities at SNL, NREL, and the New Mexico State University (NMSU) Southwest Region Experiment Station (SWRES) contribute to this goal by developing PV systems and applications, facilitating markets and business partnerships, and overcoming PV technology adoption barriers through international collaborations. Collaborations and leveraging include DOE's Office of Weatherization and Intergovernmental Programs (OWIP) and the U.S. Agency for International Development (USAID). Strategic targets include Brazil, Central America, China, India, Mexico, and others. The international program also works through such multilateral forums as the International Energy Agency (IEA), the World Bank, and the United Nations (UN). U.S. and global off-grid markets are forecast to continue growing at 15%–18% per year, and German and Japanese markets represent a substantial portion of near- and long-term U.S. industry sales. This paper details how international activities at SNL, NREL, and NMSU contribute to the relevant PV tasks and R&D milestones laid out in the *DOE Solar Program Multi-Year Technical Plan* (MYTP).

2. Technical Approach

The international groups at SNL, NREL, and 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 USAID and DOE OWIP 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.

3. Results and Accomplishments

3.1 NREL International

NREL's International PV Project helped to stimulate and leverage major rural electrification initiatives using PV. NREL and the Institute for Sustainable Power (ISP) provide technical and program design assistance and training certification for the US$340 million Chinese Township Electrification Program, which has included installation of 20 MW of PV, and the Brazilian Luz Para Todos program (this US$2.4 billion program includes a renewable energy component). NREL supports training of women as solar power entrepreneurs in West Bengal, India, through the Energy Research Institute to support the growing solar home systems market and the DOE/NREL-supported Ramakrishna Mission project. In addition, DOE OWIP cofunded NREL to develop rural energy training modules for the Luz Para Todos program, a UN Development Program training in Chile, training in the Maldives, and two regional Mexico training sessions on NREL's HOMER software. All of this has led to a local capability by government and utility decision-makers to understand the benefits of, and facilitate the implementation of, PV for rural electrification.

The Project helped launch IEA Task 10, "Urban Scale PV Applications," which is the first IEA Photovoltaic Power Systems Programme (PVPS) Task in which the United States is an operating agent. It includes three U.S.-led activities: a building-integrated PV (BIPV) market roadmap, urban planning tools, and market-driven approaches to BIPV development. In FY 2004, support for IEA Task 9, "PV in Developing

Countries," included development of financing, program design, and certification of best practice guides.

The Project has also helped to open markets for U.S. renewable energy companies. A dozen U.S. companies and organizations, including Uni-Solar Ovonic, GE, Pro Vision Technologies, and Hanalei Solar, participated in a China trade mission, resulting in at least six business partnerships. OWIP cofunded an industry stakeholder meeting that resulted in a focus on policy assistance to strategic countries and on market and policy information dissemination.

NREL has expanded 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. Live data and system details will be available on the Web. Collaborations with the Solar Energy Center in India have yielded test results from 21 kW of U.S.-manufactured thin-film PV.

The HOMER software version 2.1 was tested, and the final version was released in November 2004 as a key milestone for the Project. In FY 2004, HOMER software users grew from 3000 to 4500. Interest from many organizations, such as GE, has resulted in HOMER software enhancements and training sessions around the world.

3.2 SNL/NMSU International

In FY 2004, the international groups at SNL and SWRES worked closely together to accomplish two main technical tasks for off-grid, PV applications: systems benchmarking (MYTP Table 4.1.1-6, Task 7, Milestones 35, 50) and battery testing for U.S. companies selling into the PV market (MYTP Table 4.1.1-6, Task 14, Milestone 65).

In late 2003 and early 2004, a reliability assessment was done with our local partner (FIRCO) of 46 PV water-pumping systems installed in the Mexican states of Baja California Sur, Chihuahua, Sonora, and Quintana Roo. The survey found that three-fifths of the systems were still functioning after up to ten years of operation. The failures that did occur were due mainly to breakdowns of the pump controllers and inverters. Of interest, even though a wide variety of U.S. PV module types and brands were used in the various water-pumping systems, none of the PV modules failed.

A five-year reliability assessment was also done of an innovative PV lighting system that was developed by SunWize, a New York company, and installed in Chihuahua, Mexico. Field assessments of 35 homes found 80.1% of the systems in good condition (no component failures) and 11.4% in fair condition (one failed lamp). PV modules were the most reliable component with no failures experienced. In the 5.7% of systems that were not operational, lamps, fuses, or controllers were the components that failed.

The international groups at SWRES and SNL started in FY 2004 to investigate and test new battery prototypes designed by U.S. companies that had the potential for 15–25 years of operational life. SNL conducted a test series on battery prototypes that were provided. and SWRES examined the field applications for the prototypes. The FY 2004 battery testing was done according to the IEEE Standard 1361 for testing and evaluating batteries used in stand-alone photovoltaic systems.

During FY 2004, SNL and SWRES provided technical assistance to large-scale PV projects in Central America and consequently gained access to the PV systems for future input into the DOE/SNL SOLARDB reliability database. In Nicaragua, SWRES helped the National Energy Commission train its staff and local industry on the PV NEC codes and then develop NEC-based technical specs for their US$23 million PV project (>500 kW_p) funded by the World Bank. Through our NEC training and technical assistance in Guatamala and Honduras, SNL and SWRES will also have access to 50–2000-W_p PV projects in 2005 that are sponsored by the UN, the Global Environment Facility, and the World Bank.

4. Planned FY 2005 Activities

- Retrieve and perform field analysis of U.S.-approved PV modules to determine degradation rates in 12-month hot, humid, and coastal climates (SNL/NMSU, 5/05).
- Document performance data from application of NiMH batteries for PV systems (SNL/NMSU, 4/05).
- Conduct lab and field tests of LED-lighting prototypes integrated with off-grid PV for indoor and outdoor lighting (SNL/NMSU, 6/05).
- Document performance data from water purification and pumping tests at hybrid test facility (NREL, 9/05).
- Hold IEA PVPS Task 9 on PV in Developing Countries Annual Meeting in Denver (NREL/SNL/NMSU, 3/05).
- Document progress in IEA PVPS Task 10 on Urban-Scale PV Applications (NREL/SNL/
- NMSU, 9/05).
- Develop international strategic plan and revise MYTP to address off-grid cost targets and international testing and deployment (NREL/SNL/NMSU, 1/05).

5. Major FY 2004 Publications

A. Cota, O. Montufar, R. Foster, M. Gomez, M. Ross, C. Hanley, V. Gupta, A. Romero, "Ten-Year Reliability Assessment of Photovoltaic Water Pumping Systems in Mexico," *Solar 2004*, American Solar Energy Society, July 9–14, 2004, pp. 1-6.

R. Foster, L. Estrada, A. Cota, "Five-Year Reliability Assessment of Solisto PV Home Lighting Systems in Chihuahua, Mexico," *Solar 2004*, American Solar Energy Society, July 9–14, 2004, pp. 1–6.

N. Argaw, *Renewable Energy Water Pumping Systems Handbook*, NREL/SR-500-30481, July 2004.

C. Hanley and R. Foster, "Renewable Energy Technologies for Rural Development in Latin America," *Third IERE General Meeting*, Nov. 26, 2003, pp. 1–11.

J. Ku, D. Lew, and S. Ma, "Sending Electricity to Townships," *Renewable Energy World*, pp. 56–67, September-October 2003.

L. Ojinaga, R. Foster, L. Estrada, J. Colmenero, M. Ross, "Uso de Sistemas Fotovoltaicos en Escuelas de Educación a Distancia: Telesecundarias en Chihuahua, Mexico (Use of PV Systems for Distance Education)," XXVII Semana Nacional de Energía Solar, ANES, Chihuahua, Chihuahua, Mexico, Oct. 6–10, 2003, pp. 489–493.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
New Mexico State University Robert Foster	Las Cruces, NM rfoster@nmsu.edu	Analysis of fielded systems in international applications	330
Inst. for Sustainable Power Mark Fitzgerald	Denver, CO markfitz@ispq.org	IEA PVPS Task 9 on PV in Developing Countries	60
Segue Consulting Christy Herig	Redington Shores, FL cherig@tampabay.rr.com	IEA PVPS Task 10 on Urban-Scale PV Applications	115
TERI Usha Balakrishnan	Centreville, VA usha@teri.res.in	Training for women as solar entrepreneurs in West Bengal	36
Mistaya Engineering Tom Lambert	Calgary, Canada Tom_lambert@nrel.gov	HOMER software enhancements	40
Rubem Souza	Manaus, Brazil Rubem_souza@yahoo.com.br	Hybrid system design	20
Beijing Jikedian Ma Shenghong	Beijing, China msh@mail.iee.ac.cn	Village Power Workshop	10

PV Systems Analysis

Performing Organizations: National Renewable Energy Laboratory
Sandia National Laboratories

Key Technical Contacts: David Mooney (NREL), 303-384-6782, david_mooney@nrel.gov
Robert Margolis (NREL), 202-646-5053, robert_margolis@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 2004 Budget: $831K (NREL), $336K (SNL)

Objectives

- Develop a solar energy systems model that will allow users to investigate the impact of variations in physical, cost, and financial parameters to better understand their impact on key figures of merit.
- Develop a model with a user-friendly, intuitive interface.
- Develop a model to be used by DOE and laboratory management and research staff as a tool in informing R&D investment decisions. 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.
- Improve the analytical basis for understanding the system and policy drivers of PV technologies in various markets.
- Conduct an analysis of the associated costs and performance of PV systems in a key market sector, namely, commercial and utility-scale systems.

Accomplishments

- A beta model was completed that offers the user the ability to conduct parametric studies on performance, costs, and financing for a 2.4-kW grid-tied residential PV system.
- Existing models were encoded into the PV model. The primary models included were PVWATTS and the SNL-developed module performance model.
- Provided analytical support to U.S. industry PV roadmapping process.
- Completed analysis examining the reliability, security, and time-of-use value of PV. Three papers based on this work were presented at the ASES Solar 2004 Conference (July 2004), two papers were presented at the WREC 2004 Conference (August 2004), and one article was published in Refocus Magazine (August 2004).
- Completed an analysis of the performance, cost, maintenance, installation, and design of PV systems installed by Arizona Public Service over a multi-year operational period. This work has been accepted for publication in 2005 in the journal *Progress in Photovoltaics*.

Future Directions

- Refine PV performance and cost models based on discussions with technology experts and user feedback.
- Update to include commercial and project finance models.
- Develop and incorporate more complete inverter models into PV system model.
- Continue work on technology-policy tradeoff studies, in particular, to support state-level activities.

- Continue analyses of parameters required for determination of levelized energy costs of installed PV systems as input to a revised *DOE Solar Program Multi-Year Technical Plan*.

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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 performance/cost 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 energy cost (LEC), and system capital and O&M costs. The benchmarking effort is structured to document the current status of these and other key figures of merit. The 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 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 systems 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.

The analysis team focused its initial efforts on three main tasks. The first task is to develop 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 is on models and modeling: using existing models—such as EIA's National Energy Modeling System, 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 that will help meet the needs of the broader Systems-Driven Approach modeling effort.

The analysis portion of this task also set out to evaluate policies, as well as other factors, that impact the value of PV technologies in a variety of markets. This task involves using existing models (such as the Clean Power Estimator), 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 actors.

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 2004 Budget ($K)
PV Advisor Modeling	427
PV Market, Value, and Policy Analysis	536
System Reliability and Cost Analysis	204

3. Results and Accomplishments

- Converted preliminary Excel-based model to MatLab code (4/04).
- Reviewed existing models for incorporation (5/04).
- Conducted preliminary model review with selected participants (7/04).
- Demonstrated beta version of PV performance, cost, and financing model (9/04).
- Established framework for, and provided preliminary results of, determining the O&M costs of utility-scale PV systems in several configurations (9/04).

3.1 PV Performance, Cost, and Financing Model

The system-performance simulation module calculates the transient, generally hour-by-hour, performance of a collection of components configured into an overall system design. These calculations are done in the background and are not visible to the user. To predict PV module performance, the model will initially use NREL's PVWATTS methodology (see http://rredc.nrel. gov/solar/codes_algs/PVWATTS).

Expanding on the current, simple cost model, future versions of the cost-input module will include detailed component- and systems-level capital costs, as well as a component- and systems-level O&M costs model as part of the default systems. These cost parameters will be accessible for modification by the user. Costs can be entered through the user interface or derived from a more detailed cost model implemented within a Microsoft Excel environment. As is the case with other portions of the model, the user will be able to not only modify default values, but to redefine the model itself. Such user-defined models will allow for sophisticated roll-up of materials and labor costs, with varying relationships to system size and capacity, to meet the user's specific needs.

The financial module calculates the system cost and revenue streams for a given configuration, its associated input data, energy production, and various project-specific financial input assumptions. Based on this information, the module will be used to calculate information of interest to the user, such as project earnings, detailed cash flows, debt payments, equity income, LEC, after-tax internal rate of return (IRR), and debt service coverage ratio.

An important feature of the finance module is that it will offer a variety of standard schemes for financing solar-related projects. The user will be allowed to select financing mechanisms related to the project at hand, e.g., mortgage, commercial loan financed systems, or standard power project debt/equity financing. Default financial parameters are provided. However, the user is allowed to vary the financial parameters to address project-specific requirements or to assess the sensitivity of output parameters to financing assumptions.

Preliminary results have been generated for the default 2.3-kW grid-tied residential PV system. To begin to assess the functionality of the PV performance, cost, and financial models, 5 of the more than 70 model parameters included in the model for this default system have been varied to allow the user to explore sensitivities. These variables include system lifetime, inverter efficiency, module efficiency, inverter cost, and inverter lifetime. While extensive validation must still be undertaken to gain further confidence in the model's input and output accuracies, these preliminary results are informative in demonstrating the types of analyses that the model will enable. Figure 1 shows one of these results.

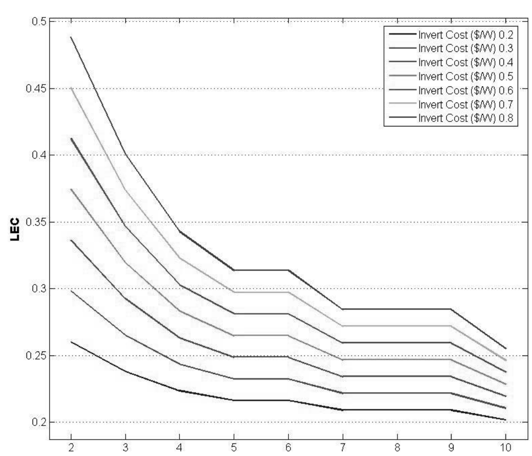

Fig. 1. A plot of the impact of inverter lifetime on levelized energy cost for a range of inverter prices.

In the example plot, the user can readily see that to achieve a given LEC, a variety of combinations of inverter lifetime and inverter costs are possible. The model will help reveal and quantify these and other combinations. This information, along with other relevant considerations, will help inform researchers and program managers in determining the R&D path to targets that represent the most cost-effective and lowest-risk combination to achieve the target LEC.

3.2 PV Market, Value, and Policy Analysis

With respect to value analysis, our emphasis has been on quantifying the reliability, security, and time-of-use value of PV. Two examples of the types of analysis that have come out of this effort include Perez et al. (2004) and Hoff and Margolis (2004). Perez et al. used satellite images to examine the availability of dispersed PV during the August 14, 2003, Northeast power outage. They concluded that had a local dispersed PV generation base amounting to at most a few hundred megawatts been on line, power transfers would have been reduced, point-of-use generation and voltage support would have been enhanced, and uncontrolled events would not have evolved into the massive blackout. This type of analysis helps build the foundation for understanding the potential for solar technologies to play a role in making the electricity grid more robust and secure.

Hoff and Margolis compared the value of PV systems to residential customers under time-of-use (TOU) and standard rates (i.e., non-TOU rates). They found that the value of switching from a standard to a TOU rate and then adding a PV system is highly dependent on the customer's original load profile and the size of the PV system installed. For example, for the case of a typical residential customer in PG&E's service territory in California, they found that bundling PV with a TOU rate switch would increase the value of the PV system by 20% to more than 100%. They also examined existing TOU rates across the United States and found that they would increase the value of PV for most locations in the United States, with the increase ranging from negligible to more than 50%.

3.3 System Reliability and Cost Analysis

Working with Arizona Public Service, an intensive study was conducted on 5 years of data collected from 49 grid-connected flat-plate PV systems that have been installed in its service territory over the last 5 years. These systems range in size from the smallest at 1.9 kW in several locations to multiple systems totaling 1.9 MW_{dc} at the Prescott Airport. There are four different configurations—fixed horizontal, fixed south facing at latitude tilt, one-axis tracking horizontal with north-south axis orientation, and one-axis tracking 30-degree tilt (very near latitude tilt) with north-south axis orientation. This analysis investigated aspects of performance, cost, maintenance, installation, and design.

Such an analysis is of high value to the benchmarking efforts of the Systems-Driven Approach, as well as to the partner organization. In this case, most of this installed PV capacity is in support of the Arizona Corporation Commission Environmental Portfolio Standard goal that encourages APS to generate 1.1% of its energy generation through renewable resources by 2007, with 60% of that amount from solar. For APS to continue to meet the requirements of this EPS, they must work to accurately assess all aspects of system cost and performance, so they can develop an accurate business model for the development and management of such projects. In this way, this activity serves as a model for utilities in other states that may need to conform to their own state-driven incentive programs.

Figure 2 shows an example output from the analysis, showing the final annual yield of systems under these various configurations in Phoenix over the 5-year period. Final annual yield is defined as kWh_{ac} output divided by nameplate kW_{dc} of the system.

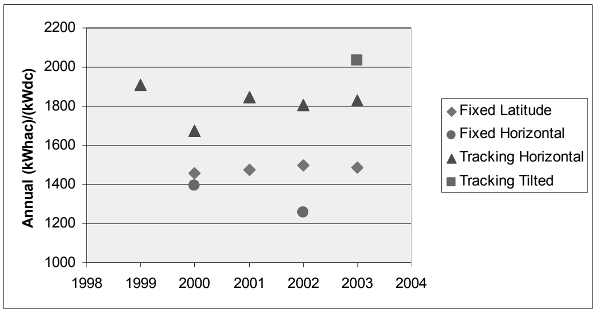

Fig. 2. Final annual yield for Phoenix

The analysis has also initiated an investigation into costs to operate and maintain these systems. At this point, it has been determined that the average annual cost of O&M for the tracking horizontal configurations is 0.35% of the initial system installed cost. The collection of adequate data for such an analysis on a statistically significant basis, however, will require further collection over an extended period.

This analysis has generated several conclusions, which have been documented in a paper that has been accepted for publication in an upcoming edition of the journal *Progress in Photovoltaics.* Among these conclusions:

- The tracking horizontal configuration provides the least energy cost of the configurations examined.
- For the systems examined, the energy production benefits of tracking were substantial—between 23% and 37% better than fixed configurations.
- For 2003, the average installed cost for tracking horizontal systems greater than 90 kW_{dc} is $5.96/$W_{dc}$, with the least expensive costing $5.18/$W_{dc}$.

Additional conclusions can be found in the paper.

4. Planned FY 2005 Activities

- Refine PV performance and cost models based on discussions with technology experts and user feedback (9/05).
- Develop and incorporate more complete inverter models into PV system model (3/05).
- Release version one of the PV model (6/30).
- Continue to work on improving our understanding of the long-term market potential for PV technologies
- Carry out detailed value analysis of PV technologies.
- Complete a PV cost model for inclusion in the PV system model.
- Conduct an historical study of trends in costs and prices of installed PV systems and the positive impacts of the DOE Solar Program on these costs.

5. Major FY 2004 Publications

R. Perez et al., "Availability of Dispersed Photovoltaic Resource During the August 14th 2003 Northeast Power Outage" Paper presented at the ASES 2004 Conference in Portland, Oregon, July 11–14, 2004.

T. Hoff and R. Margolis. "Are Photovoltaic Systems Worth More to Residential Consumers on Net Metered Time-of-Use Rates?" Paper presented at the ASES 2004 Conference in Portland, Oregon, July 11–14, 2004.

L. Moore, et al. "Photovoltaic Power Plant Experience at Arizona Public Service: A 5-Year Assessment," accepted for publication in FY 2005 by *Progress in Photovoltaics.*

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share
SENTECH, Inc** Jonathan Hurwitch	Bethesda, MD jwitch@sentech.org	Provide MatLab coding support for modeling effort	70	0
SUNY Albany Richard Perez	Albany, NY perez@asrc.cestm.albany.edu	PV capacity value analysis	50	0
Clean Power Research Thomas Hoff	Napa, CA tomhoff@clean-power.com	Distributed PV value analysis	50	10
SENTECH, Inc. Jonathan Hurwitch	Bethesda, MD jwitch@sentech.org	Value analysis of non-rooftop PV systems and support for joint solar-hydrogen workshop	68	0
McNeil Technologies Kevin Degroat	Springfield, VA Kdegroat@Mcneiltech.com	Support for Solar Program roadmapping and expansion of Systems-Driven Approach	110	0
University of California at Berkeley Daniel Kammen	Berkeley, CA kammen@berkeley.edu	Literature review of photovoltaic technology cost and performance projections	30	0

** Award pending

Regional Experiment Stations

Performing Organizations:	Sandia National Laboratories DOE Golden Field Office
Key Technical Contact:	Michael Quintana (SNL), 505-844-0474, maquint@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 2004 Budgets:	$200K (SNL), $2,000K (DOE/GO)

Objectives

- Team with the national laboratories to meet 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 Technical Plan* (MYTP).
- Structure work and set priorities to reflect a commitment to applying the Systems-Driven Approach (SDA).
- 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

- Dr. James Fenton was named the new director of the Florida Solar Energy Center (FSEC).
- FSEC Solar for Schools Program: 29 PV systems were installed and monitored with teachers trained in those schools to incorporate solar energy into their curriculum.
- Performed battery capacity discharge testing at National Park Service's largest off-grid PV system, 150-kW Dangling Rope Marina PV System, Glen Canyon National Recreation Area, UT.
- Million Solar Roofs Award for FSEC: Best progress in Southeast Region in 2004.
- Provided a system rating and current field evaluation of the SMUD PV-1, 1 MW array prior to its 20th anniversary re-commemoration by the state of California.
- Designed, installed, and commissioned the Inverter Long-Term Test Facility at the SWRES for study of long-term performance and reliability trends of residential-scale inverters.
- IEA: SERES and SWRES are working with eight countries to develop a comprehensive PV database including performance and economic data.
- FSEC module testing to A2LA and PowerMark requirements:
    - Atlantis Solar Sun Slate
    - Evergreen EC51, EC55, EC102, EC110
    - Kyocera KC125
    - Shell SM55.
- Considerable variability was measured in the solder bond strength of back ribbon in Kyocera multicrystalline PV module that had severe performance degradation.
- Found that initial performance in the hot and humid climate of high-voltage-biased Energy Photovoltaics minimodules fabricated using improved SnO_2/TCO is satisfactory.
- Performed 20 technical site evaluations for implementation of solar and wind energy in rural Brazil for Bahia Rural Secretariat of Infrastructure and U.S. Trade Development Agency.

Future Directions

- Support transition of RES cooperative agreements from DOE/ALO to DOE/GO
- Support DOE/GO administration of the RES cooperative agreements by monitoring technical activities, assuring that milestones align with program priorities and deliverables are met.
- Increase resources for and priority of benchmarking activities to assist the overall program goal of revising the MYTP in FY 2005.
- Conduct a continuous review of activities to improve alignment with the SDA.
- Prepare documentation necessary to renew the DOE-RES cooperative agreements.

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1. Introduction

The Regional Experiment Stations (RES) have contributed to DOE's National Photovoltaics program for two decades. The Southwest Regional Experiment Station (SWRES) is affiliated with New Mexico State University and the Southeast Regional Experiment Station (SERES) with the University of Central Florida. RES capabilities 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 areas of the DOE PV program.

RES goals are to provide value-added technical support to the DOE Solar Program to effectively and efficiently meet the R&D needs identified by the SDA in pursuit of targets specified by the MYTP. RES work is integrated into DOE's Annual Photovoltaic program plan and is highly collaborative. RES support is an integral part of the following program projects:

1. Module Reliability R&D
2. Inverter & BOS 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, and other groups comprising the NCPV, as well as their 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 RES builds on fielded system expertise that is unique to DOE's 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 Test and Analysis of Fielded PV Systems

Data gathered from fielded systems provide powerful opportunities 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 program participants. In addition, this activity recognizes the positive role the government can play by adopting PV and consequently provides agencies, such as the National Park Service, USDA Rural Utility Service (RUS), DOD, BLM, and various states, the technical assistance needed to successfully demonstrate the value of PV.

2.2 Infrastructure Development

This activity consists of training, design review and approval, and codes and standards development activities. Training occurs through multiple venues and in several subject areas. Poor installation has become a key issue with fielded PV systems; the RES have addressed this issue consistently. Activities began by providing training to interested parties and have evolved to the creation and establishment of a National Certification Program, an independent activity that the RES were instrumental in creating. Similarly, training of inspectors and installers is now evolving into a system of training 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 engenders consumer confidence. Certification is also the basis for assuring optimal awards from government incentive programs.

2.3 Long-Term Component Testing

The RES provide unique environments for environmentally stressing PV components. Initially, the RES 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 understand issues associated with controls and generator interactions. Both of these activities are complementary to SNL's baseline tests that establish initial component performance parameters.

3. Results and Accomplishments

- Training:
  - o Trained >100 code officials in one-day workshops in New York and Florida.
  - o Held four weeklong workshops that trained contractors to properly install PV systems (>50 trained).
  - o Held NABCEP preparatory course for >100 people from across the United States (voluntary certification for PV installers).
- FSEC/USDA/SNL Partnership: the USDA RUS has officially adopted FSEC's Design Review Process as a prerequisite for placing systems on its list of materials.
- Two inverters have been tested for industry: the Fronius IG3000 and one for beta testing.
- Performed complete assessment of utility-scale PV power plants in Michigan, Arizona, and California for performance, reliability, and cost system benchmarks.
- Performed PV system field tests of on-grid and off-grid PV systems: Tucson, AZ; Las Cruces, NM; Farmington, NM; Sacramento, CA; Yellowstone National Park, WY; Phoenix, AZ; Amarillo, TX; and Albuquerque, NM.
- Performed 10-year reliability assessment of PV water pumping systems in Chihuahua, Mexico.
- Prepared monthly I-V data analyses have for ASE Americas ribbon Si, two types of Shell Solar monocrystalline Si, and BP Solar a-Si:H and Uni-Solar Ovonic a-Si:H PV modules.
- John Wiles served as Secretary of the PV Industry Forum; drafted 30 recommended changes to the 2005 National Electrical Code, of which 26 were adopted.
- Technical Assistance: Monitoring and maintaining PV system in Dry Tortugas National Park.
- Continuing progress made in benchmarking the performance and costs of about 150 PV systems installed in Florida.

- Samples have been extracted and are being analyzed for baseline study of First Solar CdTe PV modules.

4. Planned FY 2005 Activities

This project will consist of the following tasks:

- Benchmarking
- PV systems analysis and engineering
- Codes and standards development
- Component testing
- IEA support.

Expected results for FY 2005 include the following:

- Completion of comprehensive benchmarking.
- Efforts to address codes and standards differences between the European Union and the United States.
- Gather inverter data and participate with SNL to create a well-defined and documented inverter model.

5. Major FY 2004 Publications

Gobind Atmaram, "Photovoltaic Modules and Systems Certification Program," *19th European Photovoltaic Solar Energy Conference,* Paris, France, June 7–11.

Bill Young, "Photovoltaics: Disaster and Energy Security Applications," *8th World Renewable Energy Conference*, August 28–September 3, 2004, Denver, CO.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
Florida Solar Energy Center Jim Dunlop	Cocoa, FL Dunlop@fsec.ucf.edu	PV systems research	1,000
Southwest Technology Development Institute Andrew Rosenthal	Las Cruces, NM arosenth@nmsu.edu	PV systems 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 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. SH&L is also developing solar hybrid lighting. 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 Sargent & Lundy Consulting Group projected that large CSP systems will be able to produce power in the 3.5¢ to 6.2¢/kWh range by 2020 with continued R&D and sufficient deployment. Our goal by 2010 is to reduce the cost of energy from CSP technology to 7¢/kWh. This will be done through R&D carried out by the national laboratories and industry combined with the establishment of 1000 MW of concentrating solar power plants deployed by the states and their industry partners.

Solar Heating & 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) in half to an equivalent of 4¢/kWh. The objective for FY 2005 is to build, install, and begin evaluating prototype units at locations throughout the southern part of the country that can achieve the 4¢/kWh goal. These systems, however, were designed only for mild climates. During FY 2004, conceptual designs were completed for low-cost systems applicable for freezing climates. The goal is for the cost to be cut from today's 12¢/kWh to 6¢/kWh by FY 2009.

Results and Accomplishments

Concentrating Solar Power

There were several technical accomplishments during FY 2004. Perhaps the most innovative was the work done on the 25-kW Stirling dish/engine system. Stirling Energy Systems (SES), the developer of the technology, enlisted assistance from SNL in developing a significantly improved version of the system. To effectively integrate SES and SNL staff, and to make the best use of the test facilities at SNL, SES moved much of its technical staff to Albuquerque and determined that the first six dish/engine systems (representing a new generation of hardware) would be built at the National Solar Thermal Test Facility in Albuquerque.

A new trough concentrator was completed and made ready for the 1-MW project in Arizona and the upcoming 65-MW project in Nevada. The concentrator has a lightweight design and builds on the experience with the concentrators that have been operating in the Solar Energy Generating

Systems (SEGS) in California for the last 14 years. Characterization of a prototype by NREL indicated that the concentrator performs as well as the more expensive SEGS concentrator. A cooperative agreement was initiated with the Western Governors' Association. This was done to facilitate the actions of Nevada, New Mexico, Arizona, and California to explore the potential of building 1000 MW of new solar capacity in their region.

Solar Heating & Lighting
The Cooperative Research and Development Agreement that led to the development of the roof-integrated thermosiphon solar water heating system was completed. Several manufacturing issues were resolved, and industry sent a unit to the Solar Rating and Certification Corp. for certification. As industry finishes work on the development of these systems, which are applicable only to warm climates, work has begun on systems applicable to freezing climates. NREL and SNL completed the conceptual designs of a system and began the analysis of it. ORNL completed development of its "beta" hybrid solar lighting system. This second-generation system shows marked improvement in design over the first generation.

Although the most recent reorganization of the Energy Efficiency and Renewable Energy Office moved the Zero Energy Homes (ZEH) activity from the Solar Program to the Building Technologies Program, the Solar Program sponsored a ZEH impact study during FY 2004. This study was headed by the National Association of Home Builders Research Center. The objective of the study was to estimate the energy and environmental impact that could result from the widespread adoption of ZEH. Preliminary results indicated that ZEH has the potential to reverse the upward trend in new home energy consumption and begin to decrease the energy consumption of the entire U.S. housing stock.

New Directions

The CSP Subprogram has developed a new strategy that emphasizes early 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. R&D activities have been established to support the trough and dish/engine industry as it readies for projects. Projects are already under way in Arizona and Nevada (the first significant CSP projects in more than 10 years), and it is expected that other projects will begin in FY 2005. Similarly, CSP projects are under way in Spain and Israel. This burst of activity after years of inactivity provides encouragement that CSP technology will soon become competitive in the intermediate power market and start generating large quantities of electrical power.

During FY 2004, for the first time in many years, a new-generation solar water heater was introduced. The RITH system, developed by the Salt River Project under a CRADA with SNL, provides an interim step to DOE's cost goal for solar water heaters. Analysis shows the polymer water heaters being evaluated will meet the 4¢/kWh goal. The next steps are to correct problems identified by the systems being field-tested and begin prototype development of the solar water heating systems that can operate in freezing climates. Evaluation of the beta hybrid solar lighting system has proven the technical feasibility of the concept. The next step is to transfer the technology to industry partner(s) that want to commercialize it. This will be the primary objective during FY 2005.

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. 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 program 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 2004 are:

Dish/Engine System R&D
- Designed, fabricated, and installed the first next-generation, 25-kW Stirling Energy Systems dish/Stirling system; began initial operation of the system and started monitoring performance.

Parabolic Trough R&D
- Modeled a new selective coating that appears to meet the long-term selective property goals for parabolic trough receivers.
- Completed a thermal-cycling test of filler material for a molten-salt thermocline storage system and verified that the filler material would survive a 30-year commercial lifetime.

Advanced Concepts
- Completed pilot plant production run of ReflecTech silvered polymer reflector with improved UV stability.
- Provided significant industry support related to reflectors to the concentrating photovoltaics industry.

CSP Systems Analysis
- Developed state-by-state maps for California, Arizona, New Mexico, and Nevada describing economically viable sites for large-scale CSP plants.
- Developed regional analysis of existing/planned transmission capacity plus a review of state-level major transmission constraints.

Dish/Engine System R&D

Performing Organization: Sandia National Laboratories

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

FY 2004 Budget: $900K

Objectives

- Perform R&D on dish/engine components and systems.
- Increase the reliability and reduce the cost of dish/engine components and systems.
- Support industry in its commercialization and deployment efforts.
- Support Stirling Energy Systems in its efforts to commercialize a 25-kW dish/Stirling system.
- Install and start testing of the first next-generation 25-kW dish/Stirling system.
- Develop a performance baseline for the next-generation system.

Accomplishments

- Co-location of 12 Stirling Energy Systems (SES) engineering and technical staff at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, NM.
- Design, fabrication and installation of the first next-generation, 25-kW SES dish/Stirling system.
- Initial operation of next-generation system and start of performance monitoring.

Future Directions

In FY 2005, the focus of the dish/engine activity is the continued support of SES at the NSTTF. Activities will include the following:

- Install a six-dish system, mini power plant.
- Establish field-operating parameters and develop systems control approaches.
- Measure and define baseline system performance.

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1. Introduction

Stirling Energy Systems (SES) of Phoenix, AZ, is pursuing an aggressive development and deployment schedule for its 25-kW dish/Stirling system, which is aimed at bulk power generation markets. The SES hardware is based on the well-established McDonnell Douglas (MDC) design, which dates from the 1980s, with refinements for reducing manufacturing costs. SES is working closely with SNL's engineering team to utilize their well-established design and operational experience and to maximize the possibility of success.

This year SES deployed a first prototype of the upgraded system design at SNL's National Solar Thermal Test Facility (NSTTF) in Albuquerque, NM. SES has a significant engineering presence at SNL in order to enhance technology transfer and facilitate support. SNL engineers provided critical development support to resolve structural and optical issues with the prototype dish, resulting in the successful operation of the system within SES's aggressive schedule. The successful operation of the first new dish led to the start of manufacture of five more units, which will also to be installed at SNL. These will form a "mini-power plant," scheduled for operation in 2005, for demonstration and exploration of field operating issues, and reliability improvement.

The DOE dish/Stirling program is working closely with SES to improve the system performance and reliability and to support SES' deployment in the near term, (both explicit goals of the *DOE Solar Program Multi-Year Technical 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 the SES 25-kW dish/Stirling system. The system, which came from the successful MDC system, has been redesigned to reduce cost and improve manufacturability. SES's objective is to put this system into production as early as 2007 with a target market of bulk power production in the southwestern United States. This corporate goal is enabled by 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 accelerate the system cost reduction by rapidly moving to high production rates in support of bulk power production. This has the advantage of lower cost through automation early in the product design cycle, and lower O&M cost through consolidation of O&M resources at a single site in comparison to smaller-scale installations distributed at many locations. It also allows for consolidation of O&M activities and knowledge bases for more rapid identification and implementation R&D needs.

The CSP Program proposed and implemented close cooperation between the SNL and SES teams; SES determined it best to co-locate its engineering team at the NSTTF in Albuquerque. This provides direct access and the direct transfer of technology and expertise and allows the engineers daily hands-on access to the dish systems. This is critical to accelerating the development and deployment path defined by SES and provides for rapidly training new solar engineers.

Early in the fall of 2003, the newly formed Dish Team installed an SES-owned MDC system as a development platform at SNL. The control system was upgraded to the ones developed by WG Associates (which is now a division of SES), SNL's 10-kW Advanced Dish Development Systems [1]. These controls allowed us to rapidly move to unattended automated operation of the system, greatly increasing the hours of system operation. We used this prototype to catalog issues, verify performance, and test new hardware approaches. This dish system was designated "serial number 00."

During the summer of 2004, SES installed a SES-built dish at SNL, implementing reduced-cost approaches for design and fabrication. This system serves as a prototype for the SES commercial system and, after significant cooperative re-work of the design to address structural issues identified during assembly, the low-cost system performance was improved to exceed that of the original MDC system. This system incorporated drive motor, mirror facet, and mechanical joint design improvements over the MDC system and is the very first system fabricated by SES. This system, which is designated as SN 0, is being used to explore potential reliability and further cost reduction issues.

Finally, SES is pursuing an aggressive schedule to install five more dishes at SNL by Christmas 2004, creating a six-dish "mini-power plant" to be used to address field control, operations, and maintenance of a dish power plant. All of the dish system hardware is funded through SES investor financing while, through the DOE CSP program, SNL provides access to technical expertise in the form of in-kind engineering support, technology transfer, training, and facilities.

3. Results and Accomplishments

The serial 00 system was operated at SNL for 1,045 hours during FY 2004, primarily in the unattended mode of operation. We developed effective closed-loop tracking algorithms to optimize system performance continually by balancing the cylinder temperatures of the operating Stirling engine. We cataloged the problem areas on this system and used this information to guide development changes on the system redesign where feasible. A major change involved eliminating the troublesome "fast slew system" of the old design by replacing the drive motors with faster DC drives and providing secondary fail-safe with azimuth slewing. We also explored possible field alignment tools and schemes for use with the production systems. SN 00 is no longer being operated, but it is available for testing engine modifications if needed. Once SN 00 was installed, daily operations have focused on this unit.

The serial 0 system was designed and fabricated using lower-cost fastening systems and employs Panaltec structural facets [1]. These facets have a typical RMS slope error of 0.6 to 0.8 mR, as measured with NREL's VSHOT system [2]. Combined with the low-iron-glass reflective surface, the optical performance of the new dish has exceeded expectations.

Driven by cost reduction, some of the changes implemented in the redesign of SN 0 led to a dish structure that was too flexible for safe operation, as the peak flux in the vicinity of the receiver varied exceeding the design limits by nearly a factor of 3. The design flux in the region of the receiver aperture is 90 W/cm². Through an aggressive measurement and remediation program, the design team identified and resolved all of the structural issues and reduced the flux levels to acceptable levels. We used flux mapping systems to verify that the flux patterns are now consistent with the system design specifications. All of the system improvements were designed to reduce manufacturing costs and were applied to the design of the five-unit build.

System operation of SN 0 started on August 3, and we accrued nearly 300 hours of operation through the end of FY 2004 on September 30. Operation of the system continues as we catalog faults and develop remediation plans to address each fault category. We have started to map the baseline performance of the system by installing traceable, calibrated instrumentation.

Finally, based on the upgrades to serial 0, the team completed a revised drawing package, and SES started fabricating the next five units. These units will be installed at SNL, with the goal of having an operational six-dish mini-power plant by December 23, 2004. The design team also started an extensive analytical modeling activity of the new dish structure, in order to provide feedback to the design process aimed at further reducing costs in the next-generation design. The output of the analytical model was compared and calibrated to measure structural deflections as dish mock-up was loaded at the steel fabricator in Phoenix, AZ. Most deflections were found to be in agreement with the predictions of the model within 10%. The model is also being used to validate the design changes that were empirically introduced on SN 0.

The team also started designing a major software upgrade to the dish controller to support the mini-power plant operation. The key change involves upgrading the communications so the controls can be integrated into a field-wide SCADA system with a multi-drop serial network.

SES is developing the in-house capability to fabricate the Kockums-designed engine. Five new engines are in fabrication at SNL and at subcontract component suppliers. These components and engines will be used in the mini power plant. The engine support structure and radiator assembly has been substantially redesigned to reduce cost, provide superior access to the engine, and use off-the-shelf components where possible.

The foundations and conduits have been installed for the additional five systems. System installation will begin with pedestal and electronics in October and dish assembly and alignment will follow in November and December. This rapid deployment of five dishes is aggressive and involves manpower being provided by Schuff Steel, the dish manufacturer.

SES is also actively pursuing opportunities for additional multi-unit prototype dish installations in the next year or two. In parallel, SES has a design team addressing issues and developing suppliers and customers for a large-scale deployment. SES is continuing to grow its workforce at SNL with about 12 engineers and technicians on-site permanently and others coming to the NSTTF for periodic testing and support. This combined team is dedicated to meeting the immediate mini-power plant deadlines while simultaneously preparing for commercial production. The daily access by engineers to prototype hardware is considered critical to the success of the rapid development cycle. Additional tools for laboratory testing are being developed and implemented, and will accelerate the development and qualification of new hardware solutions, especially on the engine package.

SNL has instituted record keeping and data acquisition approaches will become the “key” tools for determining the root causes of problems, characterizing performance, and improving the systems. We are starting to compile the key data to establish baseline performance of the system and the mini-power plant.

SES and SNL successfully formed a highly effective dish/Stirling team. This fiscal year, the team has transitioned from operating old MDC dish technology to deploying and operating the first SES-built system. This system incorporated modern manufacturing techniques, updated controls, and a lower-cost approach to fabrication. Key suppliers are involved in the design, fabrication, and deployment of the first new system. SES is on track to deliver, install, and operate a six-dish mini power plant by Christmas 2004. An aggressive program of identifying and cataloging problems, and developing and implementing solutions, has made operation of the new system a success. We have started to baseline the system performance in terms of power, availability, and reliability.

The SES approach to marketing, development, and deployment of many dish/Stirling systems in centralized power plants is unique and aggressive. The first dish deployed at SNL, as well as the upcoming mini-power plant, are key steps in developing the technology and expertise needed for this undertaking. 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 laboratories.

We acknowledge that an effort of this magnitude involves a dedicated team willing to immerse themselves in the development process.

4. Planned FY 2005 Activities

In FY 2005, the focus of the dish/engine activity is the continued support of SES at the NSTTF.

Activities will include the following:

- Install a six-dish system, mini power plant.
- Establish field-operating parameters and develop systems control approaches.
- Measure and define baseline system performance.

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Parabolic Trough R&D

Performing Organizations: National Renewable Energy Laboratory
Sandia National Laboratories

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FY 2004 Budgets: $2,207K (NREL), $972K (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 field, thermal energy storage, and power plant technologies to meet MYTP long-term goals.
- 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

- Solargenix completed the final design and fabrication of its first commercial parabolic trough concentrator prototype and began construction of its first full-scale systems for testing at a test facility in Nevada.
- NREL modeled a new selective coating that appears to meet the long-term selective property goals for parabolic trough receivers.
- SNL completed a thermal-cycling test of filler material for a molten-salt thermocline storage system and verified that the filler material would survive a 30-year commercial lifetime.
- Several new fluid classes have been identified for investigation that appear to have potential for application as higher temperature heat transfer fluids or as direct thermal energy storage fluids.
- SunLab is supporting Arizona Public Service and Solargenix in the design of a new 1-MWe parabolic trough ORC solar power plant currently under construction in Arizona. SunLab is also working with Nexant to develop a thermocline storage system design for future testing at the plant.
- The VSHOT instrument, used for measuring the slope error of a concentrator surface, was adapted for use with short focal length parabolic trough concentrators and used at the Solargenix factory to evaluate the slope error of their new concentrator.
- FY 2004 USA Trough Initiative request for LOI was completed to support near-term technology. Three proposals were selected for negotiation of statements of work.

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 lab capability to support trough testing and analysis.

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1. Introduction

Parabolic trough technology represents the lowest cost central station solar power option. 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 there are a number of technical approaches that 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. Additionally, 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*. These are solar field technology, thermal energy storage technology, solar power plant technology, and 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 DOE USA Trough Initiative. This effort focused on completing the design of the new Solargenix concentrator and field testing two full size collectors at a new test facility in Nevada.

Lab support focused on performance testing of the new Schott receiver at the SNL National Solar Thermal Testing Facility's (NSTTF) rotating collector platform. Lab R&D efforts also continued the development of receiver advanced selective coating technologies. The focus is on developing selective coating with improved thermal/optic properties and that are thermally stable in air up to 500°C.

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 needs (approximately \$30/kWht). The objective of the TES R&D effort is to develop the next generation of TES technology what will cost substantially less (\$10-15/kWht). The DOE R&D effort focuses on developing single tank (thermocline) TES systems, application of direct molten-salt TES systems where 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). During FY 2004 specific activities included the completion of a multi-year thermal-cycling test of the filler material for a single tank thermocline TES system, the development of the design for a thermocline TES system for the Arizona Public Service (APS) 1-MWe test that could be used to understand operational considerations of a thermocline storage system in a commercial solar plant, and identification of new fluid families that might be used as a HTF in parabolic trough plants.

2.3 Solar Power Plant Technology

During FY 2004 the primary activities focused on supporting the development of the 1-MWe parabolic trough/Organic Rankine cycle power plant underdevelopment by APS and Solargenix. SunLab participated in the design review process, acting as a technical consultant to APS. SunLab also supported the development of an O&M database for tracking O&M costs of the plant once it begins operation in 2005. The O&M database is an adaptation of a database that SNL developed for tracking O&M costs of PV systems that APS currently uses.

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 2004 activities include the adaptation of the VSHOT parabolic dish concentrator slope measurement tool for use with short focal length parabolic trough concentrators. This required modifications to the VSHOT hardware and the control and analysis software.

Budget allocations by task are provided below.

Task Title	FY 2004/CO* Budget ($K)
Solar Field Technology	1,704/177
Thermal Energy Storage	515/122
Solar Power Plant Technologies	235/8
Systems Integration	353/65

*Carryover from FY 2003

3. Results and Accomplishments

3.1 Solar Field Technology

During FY 2004, Solargenix continued the development of its new parabolic trough concentrator and has completed the full prototype design. The structure used for thermal performance testing at SNL in FY 2003 was structurally load tested to failure. Based on this test, Solargenix has optimized the structural design for both perimeter and interior solar field locations. Designs have been completed for drive and end pylons. A new hydraulic drive system has been developed and tested. A new collector local controller has been developed and field-tested at one of the existing trough plants. Two collector modules have been provided for testing at a new Solargenix test facility in Nevada. Thermal performance testing of these collector modules will be completed during FY 2005. The wind load testing to be conducted as part of this effort is also planned for completion during FY 2005.

The latest phase of the USA Trough Initiative LOI was issued in FY 2004 for near-term component manufacturing. Six companies responded with LOI. Three proposals were selected for award:

- Solargenix: optimization of concentrator and receiver sizes, alternative concentrator design, drive system cost optimization.
- Industrial Solar Technology: advanced concentrator design for power plant application.
- Solutia: improved heat transfer fluid for use with thermal energy storage.

These projects will be funded with both FY 2004 and FY 2005 funding. Two of the proposals include options for additional work in FY06 if funding allows.

Laboratory support of parabolic trough solar field technologies included the thermal performance testing of new receivers. During FY 2004, SNL completed a number of upgrades to the rotating platform at the NSTTF that is used to conduct trough receiver thermal performance testing. These included upgrades to the wiring, data acquisition system, and thermal loop. The LS-2 collector on loan from KJC Operating Company was reinstalled on the platform, and efforts were made to accurately align mirrors and receivers. Preliminary test runs were made with the Solel UVAC receivers. This allowed new test staff to come up to speed and fine-tune testing procedures.

NREL continued the development of advanced high temperature selective coatings. A new coating has been modeled that has potential to meet the long-term performance goals for receiver selective coating.

3.2 Thermal Energy Storage (TES) Technology

SNL completed the thermal cycling test of filler material for use in a molten-salt thermal energy storage system operating at 450°C. The test used a ternary molten-salt mixture of calcium, sodium, and potassium nitrate. The filler material was composed of quartzite rock and silica sand. A test apparatus was developed that would allow a volume of rock and sand to undergo temperature cycles as volumes of hot (450ºC) and cold (285ºC) salt passed through. The test which ran for approximately 15 months validated that the filler material should be able to survive 10,000 temperature cycles, the number of cycles a commercial plant would see in a 30-year life. A detailed report (Brosseau, 2004) provides a description of the tests, summarizes the results, and provides recommendations for further study.

A SunLab and industry team has developed a preliminary design for a thermocline storage system for the APS 1-MWe-trough plant currently under construction. The plant is being constructed without thermal energy storage, 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 to minimize 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 still provide cost effective TES.

NREL has been working to develop 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. The focus of this work has been on organic fluids. Earlier work on Imidizolium salts only identified fluids capable of operating at temperatures up to 200ºC -250ºC. Current work has shifted to look at variations of the current biphenyl/diphenyl oxide that will lower its vapor pressure or to consider using low-cost, high performance lubricants. A number of sample fluids have been synthesized and testing of thermal stability and other key properties are in progress.

3.3 Solar Power Plant Technology

During FY 2004 SunLab supported APS on the design and development of its 1-MWe trough/ORC solar power plant. SunLab participated in the design review process where the design of the plant was finalized. SunLab independent assessment of the design verified that the parabolic trough solar field and the organic Rankine cycle power plant should operate as expected and perform to the levels expected by APS. SNL completed a preliminary prototype of its PV O&M database program adapted for uses in a parabolic trough power plant.

3.4 Systems Integration

NREL completed the adaptation of the VSHOT for use with parabolic trough collectors and successfully field-tested the system at the Solargenix collector factory. The test enabled Solargenix to make modifications to the concentrator design to improve the optical accuracy of the collector. However, the test showed that further improvements to the trough VSHOT system would be helpful to speed up field use and improve the usefulness of the system in both factory and field test applications.

4. Planned FY 2005 Activities

Key highlights for FY 2005 include:

- Complete performance test of new Schott receiver on SNL rotating platform (12/04).
- Complete design of trough concentrator for next generation CSP trough system (03/05).
- Complete optical testing of trough concentrator for next generation CSP trough system (7/05).
- Complete prototype sample and property testing of new high-temperature selective coating (9/05).
- Prototyping and testing of new advanced heat transfer fluids for trough applications (9/05).
- Place contracts on USA Trough near-term component manufacturing LOI (3/05).
- Conduct assessment of dry cooling on parabolic trough power plants (9/05).
- Continue development of VSHOT and LFOCS optical characterization tools for trough applications (9/05).
- Complete NREL 2-axis tracker test bed to allow optical and thermal characterization of new trough concentrators and receivers (9/05).

5. Major FY 2004 Publications

Brosseau, D, P. Hlava, M. Kelly, 2004, “Testing Thermocline Filler Materials and Molten-Salt Heat Transfer Fluids for Thermal Energy Storage Systems Used in Parabolic Trough Solar Power Plants,” SAND2004-3207, July 2004.

NREL, 2004, “California Solar Power Detailed Technical Report for Southern California Edison,” NREL/MP-710-35284, November 2003.

Kearney, D., Price, H., 2004. "Advances in Parabolic Trough Solar Power Technology," In: Kreith, F., Goswami, D.Y. (Eds.), Advances in Solar Energy. Vol 16. ASES, Boulder, Colorado, in press.

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6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share
Solargenix Energy Randy Gee	Raleigh, NC randycgee@comcast.net	Developed and field testing of parabolic trough concentrator.	800	200
Nexant Bruce Kelly	San Francisco, CA bdkelly@nexant.com	Design of thermocline storage system for APS 1-MW plant.	50	0
K&A David Kearney	Vashon, WA dkearney10@comcast.net	Analysis of thermal energy storage technologies	50	0
TBD (3 awards)	TBD	USA Trough "Near-term components" LOI solicitation	200*	20%

* Award pending, will also use FY 2005 funding.

Advanced Concepts

Performing Organization: National Renewable Energy Laboratory

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

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

FY 2004 Budget: $110K

Objectives

- Develop advanced reflector materials that are low in cost (less that $\$1/ft^2$ or $\$10.76/m^2$) that maintains 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

- Performed and published new cost analysis that shows the SAIC advanced solar reflective mirror (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.
- Completed pilot plant production run of ReflecTech silvered polymer reflector with improved UV stability.
- 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 photovoltaics industry.

Future Directions

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

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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% to the solar concentrator. These goals should be achieved with the lightweight front-surface reflectors that include anti-soiling coatings through technology advances. 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.

Three subcontracts initiated in FY 2000 and FY 2002 and funded from prior year funds were completed in FY 2004. Durability testing was performed on the candidate materials supplied under the subcontracts. The first subcontract with Science Applications International Corporation (SAIC), which ended 9/30/04, was to produce a promising low-cost reflector material, a silvered specular substrate protected by an alumina coating several microns thick, developed under a previous subcontract on a laboratory scale roll-coater. The second subcontract with Swisher and Associates was to perform a new cost analysis of this material. The third subcontract with ReflecTech was to improve the UV stability of a polymeric solar reflector, developed under a previous subcontract, and to make a pilot run of the improved UV stable reflector.

Budget allocations by task are provided below.

Task Title	FY 2004 Budget ($K)
Durability Testing of Optical Materials	90
Advanced Reflector Materials	20

3. Results and Accomplishments

- Published results of durability testing of several mirror types (06/04).
- Performed secondary cost analysis, and published original and secondary cost analysis results of ASRM (11/03, 06/04).
- Completed pilot-scale run of ReflecTech material with improved UV stability (8/04).
- Provided status of test results of candidate solar mirror samples and identify promising candidates (09/04).
- Published Review Meeting proceedings (09/04).
- 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. Recently, two significant changes in mirror manufacturing have 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, use silvered, thick, slumped glass with a proprietary multilayer paint system designed for outdoor exposure and have been very durable. Flabeg recently converted their 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 middle of FY 2004.

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 30 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.

Thin-glass mirrors also use traditional wet-silvered processes on thin (<1 mm), relatively lightweight glass. Choice of adhesive affects the performance of weathered thin-glass mirrors, and corrosion has been observed in deployed mirrors. Initial analysis of a thin glass mirror matrix exposed in the WOM indicates commercial (non-mirror) back protective paint applied post mirror manufacturing is not beneficial. CPV manufacturers have expressed significant concern regarding the durability of thin-glass mirrors made with copper-free and lead-free paint systems.

Although glass mirrors with copper backlayers and heavily leaded paints have been historically considered robust outdoors, the new copper-free back layer and lead-free paint systems were designed for interior mirror applications and do not have the same durability. Development of a mirror-backing paint system suitable for outdoor applications, to be applied during mirror manufacturing, will be required to provide sufficient durability.

3.2 Aluminized Mirrors

Aluminized reflectors use a polished aluminum substrate, 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 NREL, and with accelerated exposure in the WOM. Recently, Alanod stopped selling this material for outdoor use because of problems associated with the delamination of the overcoat. The company is working to find a solution and to improve the abrasion resistance of the reflector.

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, CO. In addition, samples exposed in accelerated outdoor weathering tests (natural sunlight in Phoenix, AZ, 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.

3.4 Advanced Solar Reflective Mirror (ASRM)

The ASRM developed under a subcontract with SAIC that ended 9/04, 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 on a laboratory roll-coater. Many samples prepared have maintained 95% hemispherical reflectance after more than 3 years accelerated and outdoor exposure; testing is continuing. A new cost analysis shows 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.

While positive progress has been made to develop an advanced solar reflector, work has been severely limited due to a lack of funding during the last few years. NREL remains the world leader in the research on the durability development of advanced solar reflectors but research has been limited to durability testing of reflectors supplied by industry, which is ongoing. The glass mirrors, ReflecTech, and ASRM may meet the 10-year lifetime goals based on accelerated exposure testing. However, predicting an outdoor lifetime based on accelerated exposure testing is risky. At this time, because all solar reflectors have recently changed their production considerably, none of the solar reflectors available have been in test long enough to demonstrate the 10- to 30-year lifetime goal, outdoors in real time.

4. Planned FY 2005 Activities

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

- Provide status of test results of candidate solar mirror samples and identify promising candidates (09/05).
- Analyze and publish results of thin glass matrix (08/05).

5. Major FY 2004 Publications

Kennedy, C.E.; Swisher, R.; and Smilgys, R.V., 2003, "Cost Analysis of Solar Reflective Hard Coat Materials," *Proceedings 2003 AIMICAL Fall Technical Conference; 17th International Conference on Vacuum Web Coating*.

Kennedy, C.E.; and Terwilliger, K., 2004, "Dual 2004: Optical Durability of Candidate Solar Reflectors," In publication, ISEC2004-65111, *Proc. 2004 Solar Conf.* and *J Sol Energy Eng Trans ASME*, July 2005.

Kennedy, C.E.; and Swisher, R., 2004, "Dual 2004: Cost Analysis of Solar Reflective Hard-Coat Materials Deposited by Ion-Beam-Assisted Deposition," In publication, ISEC2004-65112, *Proc. 2004 Solar Conf.* and *J Sol Energy Eng Trans ASME,* July 2005.

Kennedy, C.E.; Terwilliger, K.; and Milbourne, M., "Summary of Status of Most Promising Candidate Advanced Solar Mirrors (Testing and Development Activities)," *CSP FY 2004 Milestone Report*, Sept. 2004.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share
Science Applications International Corporation Russell V. Smilgys	McLean, VA smilgys@apo.saic.com	Production of ultra-thin-glass solar reflective materials by ion beam assisted deposition using a laboratory-scale roll coater	422*	390.8 31.2**
Swisher and Associates Richard L. Swisher	Northfield, MN rswisher@deskmedia.com	Cost analysis of ultra-thin-glass solar reflective materials	13.2†	0
ReflecTech Randy Gee	Arvada, CO randycgee@attbi.com	Commercial laminate reflective film development	35.8†	0

* Funded with prior year (FY 2000, 2001, 2002) funds.
** Cost Plus Fixed Fee Subcontract
† Funded with prior year (FY 2002) funds. Firm Fixed Price Subcontract

CSP Systems Analysis

Performing Organizations: National Renewable Energy Laboratory
Sandia National Laboratories

Key Technical Contacts: Mark Mehos (NREL, Primary Contact), 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@hq.doe.gov

FY 2004 Budgets: $225K (NREL), $200K (SNL)

Objectives

- Provide support for CSP program analysis efforts related to implementation of 1000 MW of concentrating solar power in the southwestern United States.
- Support CSP-specific analysis related to implementation of the Systems-Driven Approach within the DOE Solar Program.
- Support DOE and EIA analysis requests on an as-needed basis.

Accomplishments

- Developed state-by-state maps for California, Arizona, New Mexico, and Nevada describing economically viable sites for large-scale CSP plants.
- Developed regional analysis of existing/planned transmission capacity plus a review of state-level major transmission constraints.
- Developed preliminary recommendations on the most promising locations for future CSP plants based on filtered resource, 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.
- Facilitated regional awareness and support of CSP 1000 MW Initiative through interaction with utilities, state energy offices, the CSP industry, and the Western Governors' Association (WGA), resulting in WGA decision to consider 1000 MW Initiative within Western 30 GW Clean Energy Initiative.

Future Directions

The primary activity for the systems analysis task in FY 2005 will be to continue support of the Southwest 1000 MW Initiative. Specific directions will include:

- Provide support to WGA with coordination of Task Force and stakeholder meetings.
- Provide support to CA Solar Task Force and explore ways to implement CSP within current RPS.
- Continue support of the New Mexico CSP Task Force to develop recommendations for 2005 legislature.
- Continue interactions with Nevada, Arizona, Texas, and Colorado in support of developing further CSP opportunities in those states.

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1. Introduction

The primary objective of this year's analysis effort was to identify economically viable locations for siting CSP plants in the U.S. Southwest and to communicate the results of this analysis to stakeholders for the states of California, New Mexico, Nevada, and Arizona. The viability of sites were determined in part by the level of direct normal solar radiation, area topography, access to unconstrained transmission, and proximity to load centers. The potential for economically viable power generation, combined with additional regional benefits such as job creation and pollution mitigation, were presented to state energy officials, utility stakeholders, and policymakers to support them with making more informed decisions regarding the development of their solar resource.

2. Technical Approach

2.1 1000 MW Siting Analysis

Solar resource data used for the state-by-state analysis were derived from high-resolution (nominally, 10 km) satellite-based cloud cover data. Direct normal incident (DNI) resource estimates were calculated using the Perez irradiance model [i]. To identify economically attractive sites, geographical information system (GIS) data filtering algorithms were applied to the resource data, along with land type (urban, agriculture, etc.); ownership (private, state, federal); and topography. The terrain available for CSP development was conservatively estimated with a progression of GIS filters as follows:

- Lands with less than 6.75 kWh/m^2/day of average annual direct-normal resource were eliminated to identify only those areas with the highest economic potential.
- Lands with land types and ownership that were incompatible with commercial development were eliminated. These included national parks, national preserves, wilderness areas, wildlife refuges, water, and urban areas.
- Lands with slope greater than 1% and with contiguous areas smaller than 10 km^2 were eliminated to identify lands with the greatest potential for low-cost development.

Because energy suppliers or buyers would need to consider how future CSP plants might fit into a transmission system, Platts Research and Consulting, under subcontract to NREL, provided an analysis of transmission constraints and proximity to load centers for lands which remained once the GIS filters were applied. The resource and land exclusions, together with the regional transmission constraints and proximity to urban load centers, led to preliminary recommendations of regional development centers for large-scale CSP installations.

2.2 Economic Impacts Analysis

In addition to the siting analysis, DOE funded the University of Nevada Center for Economic and Business Research[1] to conduct an analysis of the economic impact of deploying 100 MW to 1000 MW of CSP capacity in the state of Nevada. The purpose of the analysis was to estimate the economic impact, in terms of employment, personal income, and gross state product (GSP) of developing some portion of Nevada's solar energy generation resources. While the results of this analysis described in Section 3.2 are specific to Nevada, the data provide an estimate of benefits that could be realized if deployment took place in other states within the Southwest.

2.3 Southwest Stakeholder Interactions

A series of meetings were held with key stakeholders from the states of California, New Mexico, Nevada, and Arizona to present the results of the siting and economic impact analyses. A preliminary analysis of how the renewable portfolio standard (RPS) of each state pertained to a solar project and the resulting impact on residential ratepayers was also provided. In addition to these meetings, significant support was provided to the State of New Mexico as a result of Governor Richardson's implementation of a CSP Task Force for that state.

[1] The UNLV economic impact study was initiated in FY 2003.

3. Results and Accomplishments

3.1 1000 MW Siting Analysis

The results of the preliminary siting analysis are shown graphically in Fig. 1 below. The outlined areas for each state show the best locations for development of future CSP plants based on the application of GIS filters, and consideration of transmission constraints and access to load centers.

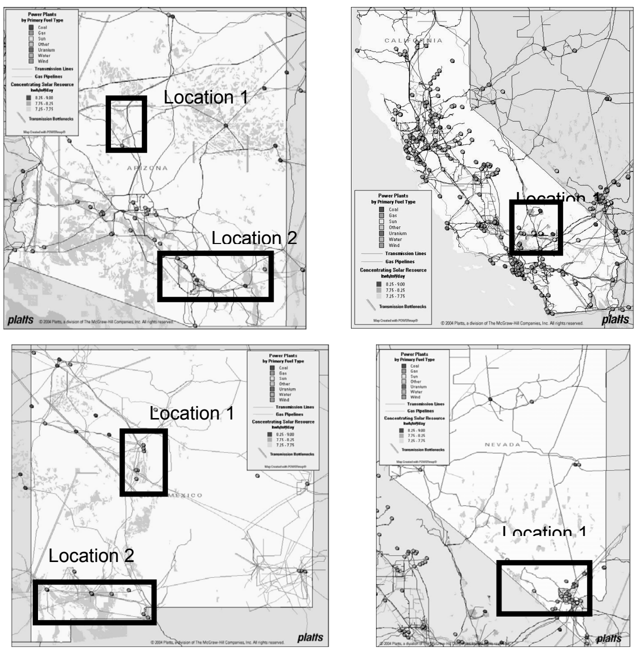

Fig. 1. Regional analysis of siting opportunities for large-scale CSP generation.

The resulting land area and associated CSP generation capacity are given in Table 1.

Table 1. Suitable Land for CSP Plants and Associated Generation Potential

	Available Area (mi^2)	Capacity (MW)
Arizona	25,527	3,267,456
California	6,421	821,888
Nevada	5,807	743,296
New Mexico	23,640	3,025,920
Total	**61,395**	**7,858,560**

The data in Table 1 show that, even if only the high-value resources are considered, there is potential for more than 7 million MW of solar generation capacity in the Southwest. Currently, there are about 100,000 MW of generation capacity in these four states. Each state has enough land illuminated by the highest solar radiation levels, such that only a small segment would be enough to generate its current electricity needs.

3.2 Economic Impact Analysis

Economic impacts were derived for three scenarios: a single 100-MW trough facility, three 100-MW trough facilities built over a 3-year timeframe, and ten 100-MW trough facilities built over a 10-year time frame. The results of the first and third scenarios are discussed here since the second scenario falls between these two extremes.

For the single-trough facility, the direct construction impact, including labor, capital, land, and contingencies, totals $485.6 million. Each year, 817 jobs are directly tied to constructing the facility. Indirect and induced job creation totals another 1,570 jobs during the construction phase, suggesting an employment multiplier of 2.9. Employment impacts average 140 jobs annually. Total personal income in Nevada attributable to the construction phase (2004 through 2006) and the O&M phase (2007 through 2035) is estimated to be $1.15 billion. GSP would be boosted by $1.14 billion.

As expected, the 10-plant scenario, 1000-MW total, offers the highest economic impact. Employment impacts are largest during the early years of the construction phase. Initial employment impact is 3,830 jobs in the first year of construction, rising quickly to a peak of over 6,940 jobs in 2005. The first post-construction year enjoys employment impacts of 1,090 jobs. Over the O&M phase, employment impacts average 1,800 jobs. Total personal income and GSP generated between 2004 and 2035 totals $9.37 and $9.85 billion, respectively.

The results revealed significant economic benefits, in terms of GSP, new employment, and personal income to the state of Nevada. As such, CSP generation is shown to be a potential source of significant economic development throughout the state. Tallying the economic and environmental benefits of solar-power generation, it is clear that it could be an important contributor to sustainable economic development in rural areas.

3.3 Southwest Stakeholder Interactions
Interactions with stakeholders in California, New Mexico, Arizona, and Nevada resulted in each state indicating its desire to participate in the 1,000 MW Initiative. In each case, the reasons were similar. They recognized the potential value of developing their solar resource to add diversity to their energy portfolio as well as provide an economic asset that could create jobs, particularly in rural areas. All expressed a willingness to work together to make this a regional activity.

Major outcomes of the discussions included the following:

- Creation of a New Mexico CSP Task Force with the intent to construct a 50 MW or larger CSP plant in the state.
- Announcement at WGA annual meeting to establish a stakeholder working group to develop options for consideration by the Governors in furtherance of the 1,000 MW Initiative.
- Announcement by the California governor's energy advisor that concentrating solar power should and must be able to play a valuable role in participating in RFP contracts.

5. Major FY 2004 Publications

Schwer, R. K.; Riddel, M., "Potential Economic Impact of Constructing and Operating Solar Power Generation Facilities in Nevada," 28 pp.; NREL Report No. SR-550-35037.

Mehos, M. S.; Owens, B. "Analysis of Siting Opportunities for Concentrating Solar Power Plants in the Southwestern United States." *Proceedings of the World Renewable Energy Congress VIII (WREC 2004)*, Denver, CO, NREL Report No. CP-550-36476.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
University of Nevada Center for Business and Economic Research Mary Riddel	Las Vegas, NV mriddel@unlv.edu	Analysis of economic impact of developing large-scale parabolic trough plants	18*
Morse Associates, Inc. Fred Morse	Washington, D.C. fredmorse@morseassociatesinc.com	Consulting for government and utilities on CSP applications and marketing policy	102
Platts Research and Consulting Brandon Owens	Boulder, CO Brandon_owens@platts.com	Competitive solicitation for "Research on Low-Cost, High-Efficiency Organic Solar Cells"	25

* Funded with prior year (FY 2003) funds.

References

[i] Perez, R.; Ineichen, R.; Moore, K.; Kmiecik, M.; Chain, C.; George, R.; Voignola, F. (2002); "A New Operational Satellite-to-Irradiance Model," Solar Energy 73, 5 pp. 307-317.

Solar Heating and Lighting

The Solar Heating & 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 universities 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. 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 goal is to reduce the cost of solar water heaters from the current equivalent level of around 8¢ to 10¢/kWh to around 5¢/kWh by 2005. These polymer collectors may also be integrated into roofs for further cost savings.

The Hybrid Solar Lighting program 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 2004.

Low-Cost Polymers
- Developed a new test protocol for integral collector-storage systems; validation of the new method is ongoing, comparing long-term performance with the calibrated model.

Materials Durability
- Subjected various candidate polymer glazing material constructions to accelerated exposure testing for an equivalent of up to 20 years' outdoor exposure in Miami, FL.

Industry Manufacturing Assistance
- Developed an energy monitoring strategy to support the sale of green tags for solar hot water (for USH_2O Consortium).
- Provided options for providing hot water to troops in Iraq (for U.S. Department of Defense).

Hybrid Solar Lighting
- Developed plastic primary mirror for 3rd-generation hybrid solar lighting system at one-tenth the cost of original glass mirror.

SH&L Systems Analysis
- Assembled simulation models were for three system types: glycol, drainback, and thermosiphon. Models were the basis for U.S. performance maps and cost-of-saved-energy analysis.

Low-Cost Polymers

Performing Organization: National Renewable Energy Laboratory

Key Technical Contact: Jay Burch, 303-384-7508, jay_burch@nrel.gov

DOE HQ Technology Manager: Glenn Strahs, 202-586-2305, Glenn.Strahs@hq.doe.gov

FY 2004 Budget: $1,107K

Objective

- Reduce the levelized cost of saved energy (COSE) for solar domestic hot water (SDHW) systems by ≥50%, from current COSE of 10–20 ¢/kWh to ≤5–10 ¢/kWh.

Accomplishments

- Two teams started field trials of their low-cost integral collector-storage (ICS) systems, with greater-than-expected savings for the Davis Energy Group/SunEarth (DEG/SE) ICS and lower-than-expected performance from the FAFCO ICS.
- DEG/SE has finalized product design and manufacturing equipment design. FAFCO has initiated a major redesign of its low-cost SDHW, focusing instead on a thermosiphon system based on use of pool collector technology.
- A new test protocol for ICS systems has been developed, and validation of the new method is ongoing, comparing long-term performance with the calibrated model.
- A report on cost-reduction potential for cold-climate SDHW systems was published.

Future Directions

- Field trials will continue on the DEG/SE ICS, and field trials will begin with the redesigned FAFCO mild-climate thermosiphon SDHW.
- DEG/SE will refine accessory components and plan for commercialization. FAFCO will continue refining the new thermosiphon design.
- Pipe freeze tolerance and prevention using polymer piping systems will be established for at least two available PEX piping systems.
- An RFP for development of cold-climate SDHW components, including tank and heat exchanger combination, will be issued.

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1. Introduction

As described in the *DOE Solar Program Multiyear Technical Plan*, Solar Heating and Lighting set the goal in FY 1998 to reduce the life-cycle cost of saved energy for solar domestic hot water (SDHW) systems by ≥50%. In FY 1999, focus was placed on reaching this objective for passive systems in mild climates. Assuming high volumes COSE for current mild-climate technology is ~10.2 ¢/kWh, giving a goal of ~5.1 ¢/kWh for the new technology.

Two industry teams (DEG/SE and FAFCO) have been developing unpressurized polymer ICS systems with load-side heat exchangers and began field-testing them in FY 2004. DEG/SE's ICS has a rotomolded tank and thermoformed glazing. Based on manufacturing issues, costs, and poor performance, the FAFCO team changed direction in late FY 2004 from an unpressurized ICS to a direct thermosiphon design based on the use of pool collectors. Both teams intend to commercialize products in FY 2005.

Support for the teams is being provided for materials testing, modeling, and system testing. New ICS system models have been produced to model the new systems. A new procedure for rating the ICS systems is undergoing testing and validation. Pipe freezing, freeze-protection valves, and overheating have been tested and analyzed. A new task in FY 2004 looks at cost-reduction opportunities for cold-climate SDHW.

2. Technical Approach

The cost of saved energy is the ratio of total costs to discounted total energy savings. Total cost is the sum of hardware, installation, and marketing costs (these three costs sum to 1^{st} cost) and present value of O&M costs. The approach here focuses on cost reductions rather than performance increases. Hardware, installation, and O&M costs are reduced through two related strategies: 1) use of polymer materials and manufacturing methods, and 2) product redesign aimed at parts' count reduction and simplified installation.

The development process has been structured in three stages: conceptual design, engineering design, and product development. Conceptual design (FYs 2000–2001) began with five teams, down-selected to two teams at the end of conceptual development. In FY 2004, teams were entering the product-development stage, with redesigns based on feedback from "torture tests" and field tests.

The key issue in using low-cost polymer materials and manufacturing is durability. Thus, accelerated testing of proposed materials is being done at NREL for both glazings and absorbers. Because the new system types have features not previously modeled, new ICS and thermosiphon models have been developed at NREL to accommodate them. The new models are integrated into a new rating procedure. Pipe freezing, freeze-protection valves, and overheating have been addressed through laboratory testing at NREL. Opportunities for cost reduction of cold-climate systems were identified by modeling costs in detail and projecting performance through simulation.

Budget allocations by task are provided below.

Task Number and Title	FY 2004 Budget ($K)
1. Polymer ICS Field Test	260
2. ICS Development	374
3. Technical Support	473

3. Results and Accomplishments

- Field installations were completed by both teams.
- Testing-based redesigns were done by 8/04 for DEG/SE, whereas a new system type is being proposed and developed by FAFCO.
- New ICS models and test procedures were developed, forming the basis for SRCC performance ratings for ICS systems.
- Specific improvements in cold-climate systems were identified that could lead to >50% reduction in the cost of saved energy.

3.1 Tasks 1,2 for DEG/SE

The DEG/SE system is shown in Fig. 1. The system has been performing somewhat above expectation in field trials. Expectation of saved energy is based on a standard draw volume and profile, and the high-draw volume and dispersed profile of the residences chosen yield increased performance relative to the standard case. The system was subjected to a variety of torture tests, including wind uplift, salt corrosion, water spray, hail impact, rough handling, panel creep, and wet/dry stagnation. The wind uplift test led to redesign of the glazing-tank clips. Unsatisfactory rate of leaks on rotomolding has led to a revised mold design that has apparently corrected the leaks. Projected COSE is 5.4 ¢/kWh, a 46% reduction vs. conventional ICS.

3.2 Tasks 1,2 for FAFCO

The new FAFCO thermosiphon system is shown by a CAD perspective in Fig. 2. The collector is a glazed pool collector. A direct, open-loop version with collector and storage at line pressure and with storage tubes alongside the collector is shown. This version suffers dramatically *for standard draw profiles* from reverse thermosiphoning at night. Performance loss compared to a version with storage above the collector (not shown) is estimated at 50%, because side storage provides no savings for morning and late-evening loads. The performance estimates will be grounded in simulation once the new thermosiphon models, which allow reverse thermosiphoning, are finished and validated. Once prototypes are completed, tests will be conducted to calibrate the model. If sense prevails and the top-mounted storage is used, projected COSE is 5.2 ¢/kWh, a 48% reduction vs. conventional ICS.

Fig. 1. The DEG/SE ICS unit on a roof in San Diego

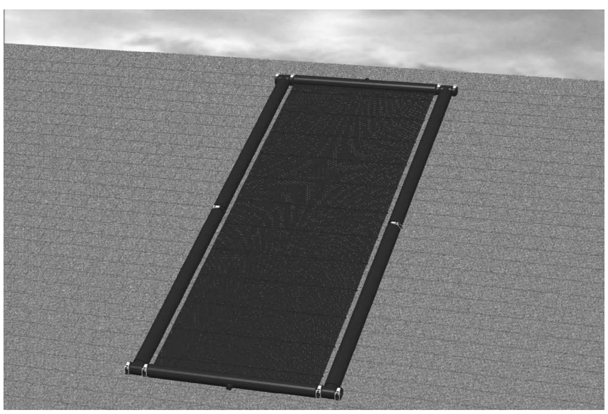

Fig. 2. The FAFCO thermosiphon design, shown in CAD perspective with storage tubes alongside the collector

3.3 Technical Support

It was shown that a polycarbonate glazing with a Korad© film coating will resist degradation from UV radiation upward of 20 years without yellowing or mechanical degradation. The absorber materials for both ICS systems experienced embrittlement under extended dry stagnation (a leak has occurred and the system is empty), but are expected to perform well under no-load, wet stagnation (no leaking, storage charged).

New models for conventional and unpressurized ICS were produced that feature immersed heat exchangers and variable loss coefficients based on first principles. The models can be calibrated with test results for rating projections. A new SRCC test protocol for model calibration has been developed and is being validated. Pipe freezing and market extension with freeze-protection valves (see Fig. 3) were characterized. Overheat protection by venting gaps above and/or below the absorber was shown to be ineffective as originally designed by one of the teams, but can provide some measure of materials protection when paths with high friction are avoided.

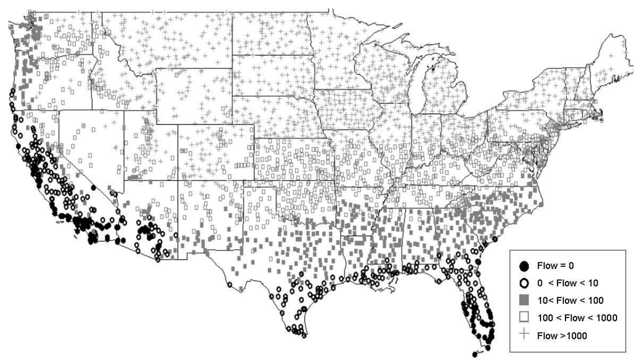

Fig. 3: Annual flow in gallons through an Eaton/Dole FP-35 freeze-prevention valve. Nominal set point is 35°F. Maximum acceptable water waste might be set somewhere between 100 (end of light grey square bin) and 1000 (end of open square bin) gallons/year.

3.4 Low-Cost Cold-climate SDHW

COSE curves were developed for a base case and potential improvements of three cold-climate SDHW system types: glycol, drainback, and indirect thermosiphon. Costs were computed in the context of new construction and high volume, implying conventional overhead cost factors and low marketing cost. First cost and COSE vs. potential improvement are shown in Fig. 4 for the glycol system. It was shown that >50% reduction in COSE is attainable for systems with low-cost BOS (polymer tanks, heat exchangers and piping, and valve package) and low-cost selective polymer collectors. COSE reduction slightly under 50% is attainable with BOS variations and either the base collector (selective metal-glass) or nonselective polymer collector.

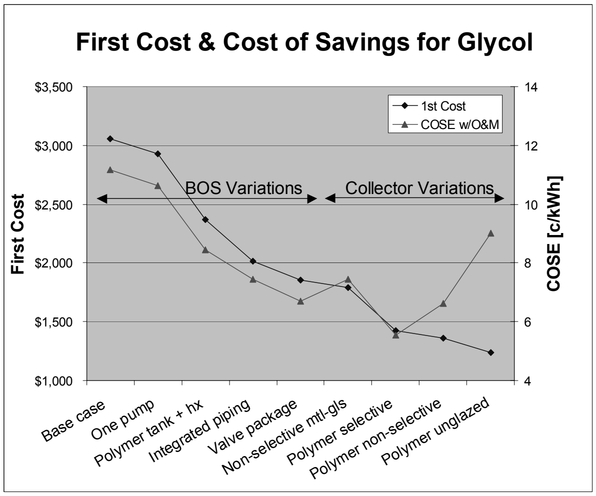

Fig. 4. First cost and cost of saved energy for the glycol cold-climate SDHW system. BOS variations are first, each remaining in place once done. The last four points on the curve are subsequent collector variations, from the glass-metal selective collector used in the base case.

4. Planned FY 2005 Activities

- Continue field monitoring, out to at least one year for each system installed.
- Implement manufacturing process design and begin commercialization of two low-cost SDHW systems for mild climates.
- Transfer Test Protocol for ICS to SRCC.
- Develop RFP for cold-climate SDHW cost reduction.

5. Major FY 2004 Publications

J. Burch, J. Salasovich, C. Christensen, and J. Thornton, "Geographical Variation in Performance of an Unglazed Solar System Meeting Water Heating and Space Conditioning Loads," *2004 ASES Conf. Proc.*, ASES, Boulder, CO.

J. Burch, T. Hillman, and J. Salasovich, "Cold Climate Solar Domestic Hot Water Systems: Cost/Benefit Analysis and Opportunities for Improvement," NREL TP-550-37012, September 2004.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share
Davis Energy Group/SunEarth Dick Bourne	Davis, CA dbourne@davisenergy.com	ICS Development and Manufacturing. Initiated field-testing of SDHW, addressed issues from testing, including excessive leaks.	250[a)]	50
FAFCO, Inc. Josh Eaton	Chico, CA jeaton@fafco.com	Warm Climate SDHW Development and Testing. Complete new SDHW design, build and test prototypes, and refine manufacturing processes.	200[a)]	50
University of Minnesota Jane Davidson	Minneapolis-St. Paul, MN jhd@me.umn.edu	Polymer Heat Exchangers (hx) and SDHW Systems. Research on promotion of stratification, hx materials durability, and hx scaling.	250	100

a) Contract awarded in FY2003, continuation on FY 2004 funds.

Materials Durability

Performing Organization: National Renewable Energy Laboratory

Key Technical Contact: Gary Jorgensen, 303-384-6113, gary_jorgensen@nrel.gov

DOE HQ Technology Manager: Glenn Strahs, 202-586-2305, glenn.strahs@hq.doe.gov

FY 2004 Budget: $300K

Objectives

- Identify alternative polymeric glazing and absorber materials/constructions that will allow design trade-offs and can help reduce the costs associated with SDHW systems.
- Perform materials testing to demonstrate that such candidate polymers will meet the durability requirements for real systems

Accomplishments

- Various candidate polymer glazing material constructions have been subjected to accelerated exposure testing for an equivalent of up to 20 years' outdoor exposure in Miami, FL.
- Several alternate/improved UV-screening films are being tested.
- The mechanical creep properties of candidate polymer absorber materials were measured.

Future Directions

- The reason(s) why thermally bonded UV screens provide less protection for polycarbonate glazings than adhesively bonded constructions will be investigated, and solutions will be proposed.
- UV screens with increased photopermanence will be evaluated.
- UV resistance of candidate absorber materials will be quantified.

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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 major objectives of this project are to 1) 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 (SDHW) systems, and 2) perform materials testing to demonstrate that such candidate polymers will meet the durability requirements for real systems.

2. Technical Approach

The primary property of interest for candidate polymeric glazings is their ability to avoid optical and mechanical degradation (yellowing and embrittlement) caused by 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 accelerated weathering chambers, and at NREL's unique UV-concentrator facility.

To assess the thermal stability of candidate polymeric absorber materials experiencing elevated temperatures associated with glazed collectors, mechanical properties (tensile modulus and strength, and strain at break) were measured as a function of time of thermal exposure to dry air and to heated deionized water. Creep measurements were also made at a variety of temperatures and stresses to address concerns about permanent deformations (large-scale bulging of the absorber materials) occurring during operation.

3. Results and Accomplishments

The major results and accomplishments of the project during FY 2004 included:

- Various candidate polymer glazing material constructions have been subjected to accelerated exposure testing for up to an equivalent of 20 years outdoor exposure in Miami, FL (09/04).
- The mechanical creep properties of candidate polymer absorber materials were measured (09/04).

3.1 Glazings

Various candidate polycarbonate (PC) glazing material constructions have been subjected to accelerated exposure testing at a light intensity level of 50 UV suns for up to an equivalent of 20 years outdoor exposure in Miami, FL (Fig. 1). The most promising construction uses a UV-screening film that is laminated to a PC sheet with an optically clear adhesive. Without the additional UV-screening layer, PC products (even those that incorporate an integral UV cap) exhibit 3%–5% loss in performance (solar-weighted hemispherical transmittance) after about 2–3 years equivalent exposure. In addition, severe visual yellowing occurs in the same time frame.

With the addition of a UV-screening film (Korad®), significant loss in hemispherical transmittance does not begin for samples exposed at 70°C until after ~15 years equivalent outdoor exposure. Samples exposed at 40°C exhibit greater durability. The loss in transmittance after prolonged weathering is not unexpected, because the UV-screening functionality of the Korad film degrades with UV exposure. However, a modified UV-screening film (having either increased thickness or increased loading with UV absorbers) could likely be expected to extend the useful life of PC glazings. We are presently testing several alternate UV-screening films. In addition, UV absorbers having greater photopermanence are being developed by the polymer additives industry and will be evaluated for use with PC glazings. Solar manufacturers have constructed prototype collectors using thermoformed glazings in which the Korad UV-screening film has been thermally laminated to as-extruded PC sheets. We have found that glazing samples produced this way do not exhibit adequate optical durability during accelerated exposure testing. Further research and testing are required and are being pursued to investigate this result.

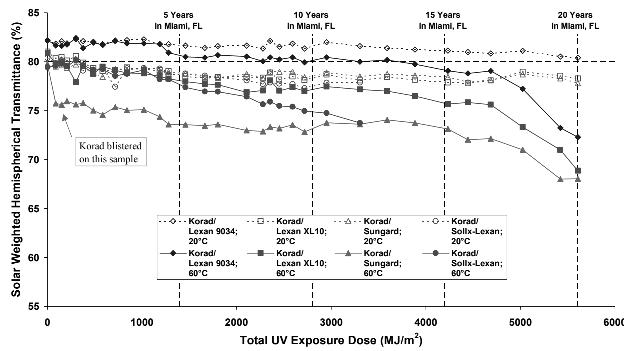

Fig. 1. Solar-weighted transmittance of various polycarbonate samples with Korad shield during UV-concentrator exposure

3.2 Absorbers

The mechanical creep of metallocene-based multi-density polyethylene (MBMDPE) was measured over a representative range of temperatures (30–90 ºC) and stresses (0.52–2.76 MPa). This allows creep compliance (D) to be calculated for a range of temperatures and stresses experienced during operation. The creep-compliance master curve at a particular reference temperature and stress can then be obtained by shifting measured values of D(t) to a new (extended) time. The resulting creep-compliance master curve (see Fig. 2) suggests that MBMDPE continues to creep with time. Approximately 2% strain will occur in about 10 years (~3x108s) at the reference stress and temperature condition.

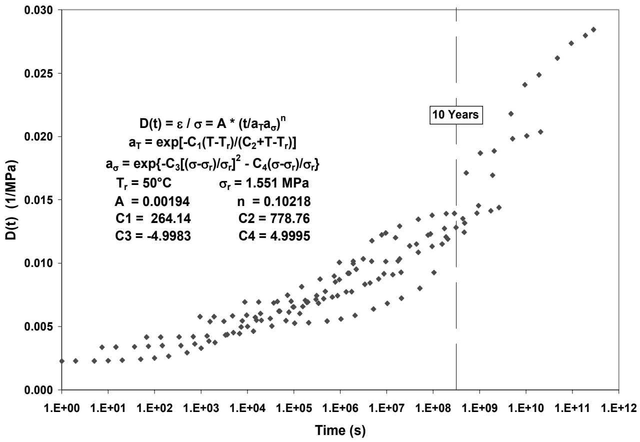

Fig. 2. Creep-compliance master curve for MBMDPE

4. Planned FY 2005 Activities

Based on very positive results using a UV screen adhesively bonded to polycarbonate sheet, industry has made a pilot version of a thermally bonded UV screen/polycarbonate construction. This material has degraded significantly faster than the adhesively bonded structure. During FY 2005, we will investigate this effect and propose and test solutions to the problem. We will also interact with industry to prepare and test samples of UV screens that incorporate newly developed UV absorbers that have increased photopermanence. Several industry partners are considering unglazed collectors that use polymer absorbers. The UV resistance of candidate absorber materials will be explored by performing dynamic mechanical analysis (DMA) as a function of UV exposure. A considerable advantage of DMA is that it is non-destructive, thereby greatly reducing the number of samples required. Samples will be exposed at NREL's UV-concentrator facility and in accelerated exposure chambers and outdoors. The most significant activities planned for FY 2005 include:

- The reason(s) why thermally bonded UV screens provide less protection for polycarbonate glazings than adhesively bonded constructions will be investigated and solutions will be proposed.
- UV screens with increased photopermanence will be evaluated.
- UV resistance of candidate absorber materials will be quantified.

5. Major FY 2004 Publications

Performance and Durability Assessment: Optical Materials for Solar Thermal Systems, M. Köhl, B. Carlsson, G. Jorgensen, and A. Czanderna, Eds., Elsevier Science & Technology Books, Oxford, England, 2004.

G. Jorgensen, "A Phenomenological Approach to Obtaining Correlations between Accelerated and Outdoor Exposure Test Results for Organic Materials," *Journal of Testing and Evaluation*, Nov. 2004, Vol. 32, No. 6.

G. Jorgensen, S. Brunold, B. Carlsson, M. Heck, M. Köhl, and K. Möller, 2004 "Durability of Polymeric Glazing Materials for Solar Applications," in *Proceedings of the 1st European Weathering Symposium EWS (XXIIIrd Colloquium of Danubian Countries on Natural and Artificial Ageing of Polymers)*, Gesellschaft für Umweltsimulation e.V., Prague, Czech Republic, September 25-26, 2003.

B. Carlsson, K. Möller, M. Köhl, M. Heck, S. Brunold, U. Frei, J.-C. Marechal, and G. Jorgensen, "The Applicability of Accelerated Life testing for Assessment of Service Life of Solar Thermal Components," *Solar Energy Materials & Solar Cells* 84 (2004) 255–274.

6. University and Industry Partners

There were no university or industry partner research activities that received subcontract funding during FY 2004.

Industry Manufacturing Assistance

Performing Organizations: Sandia National Laboratories

Key Technical Contact: Greg Kolb, 505-844-1887, gjkolb@sandia.gov

DOE HQ Technology Manager: Glenn Strahs, 202-586-2305, glenn.strahs@hq.doe.gov

FY 2004 Budget: $380K plus $115K (carryover)

Objectives

- Help solar thermal manufacturers improve their products.
- Help solar technology users design their systems to achieve maximum cost effectiveness.

Accomplishments

- Developed an energy monitoring strategy to support the sale of green tags for solar hot water (for USH_2O Consortium).
- Provided options for providing hot water to troops in Iraq (for DOD).
- Helped city officials integrate solar heating into new projects (for Tucson and Albuquerque).
- Developed a thermochromatic film to prevent overheat failure of the polymer collector (for Envirosafe Technologies, SunEarth, FAFCO, and NREL).
- Analyzed a design concept for a freeze-protected, passive collector system to meet near-term DOE cost goals (for SolarGenix, Energy Laboratory, Inc., Artistic Homes, DOE Building America, and NREL).

Future Directions

- Demonstrate a freeze-protected, passive collector system within a high-efficiency home (for U.S. thermosiphon manufacturer (TBD), Artistic Homes, and DOE Building America).
- Study combined solar heating and cooling systems (for Salt River Project).
- Complete development of thermochromatic film to prevent overheat failure of polymer collector (for Envirosafe Technologies).
- 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 provides technical assistance to the solar thermal industry. Through its Industry Assistance Program, SNL uses the 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 Website (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.

Task Title	FY 2004 Budget ($K)
Industry Manufacturing Assistance	380

3. Results and Accomplishments

During FY 2004, more than ten technical assistance projects were performed. The main results from the top five are summarized in this section.

3.1 Monitoring to Support Sale of Green Tags for Solar Hot Water Systems

The economics of solar-energy-system ownership can be improved through the sale of “green tags,” which represent the environmental benefits of the solar system. Green tags can be worth several cents/kWh, and the owner of the solar system can sell these tags to reduce the effective cost of system ownership. The PV industry is actively selling green tags, and the USH$_2$O consortium is trying to do the same for solar domestic hot water (SDHW) systems. Under the USH$_2$O concept, hundreds of homes within a particular utility district will all use the same type of SDHW system.

Before a green tag can be sold, the energy produced by the solar system must be measured. Monitoring hardware for SDHW systems can be costly. Thus, SNL suggested to USH$_2$O that a statistical approach be used: a subset of the total population should be monitored and statistical inference used to estimate the energy saved by the total population. SNL developed a statistical model for USH$_2$O that indicated only 10% of the homes within the utility district would need to be monitored to accurately predict the energy savings from a total population of several hundred homes. Thus, 90% of the metering hardware could be eliminated for an estimated savings of $100,000 or more on a large deployment.

3.2 Providing Hot Water to Troops in Iraq

The U.S. Army has a large number of temporary facilities in Iraq that are being powered by portable generators, mostly diesel. These generators produce electricity that is also used by electric water heaters in their facilities. Heating water with electricity is inherently inefficient; this is leading to logistical problems that are larger than necessary (i.e., more diesels and more fuel transport/consumption). In an attempt to reduce these problems, the Army asked SNL to identify and analyze alternative water-heating methods.

SNL compared the logistics and costs of using solar hot water systems vs. diesel heat recovery systems, and found that diesel heat recovery would be preferred, in most cases. Use of relatively inexpensive solar water-heating equipment from Middle Eastern or U.S. suppliers was identified to be a viable option for cases in which the diesel heat recovery system could not provide the entire hot water load at a particular site. Because of more pressing non-energy problems, the Army has not yet decided whether to implement the SNL recommendations.

3.3 Helping City Officials and Green Developers Integrate Solar into New Projects

SNL helped develop Sustainable Energy Standards for the City of Tucson. These standards included requirements for solar systems, preferably SDHW, on every new home. As the residing solar technology expert on the Standards Development Committee, SNL developed the draft standard for the minimum solar installation as a function of the type and size of the building. The standard applies to all residential, commercial, and industrial buildings. The proposed standard will be considered by the city council in the fall of 2004, and we will present expert witness testimony at the hearings. Also in Tucson, we are advising a developer regarding the development of a completely sustainable community in the downtown area. This development will have all on-site generation including combined heat and power, photovoltaics, and solar hot water.

SNL also worked with officials from the City of Albuquerque to develop a request for proposal for third-party-financed solar systems on all city pools. We served in the same capacity for the City of Tucson. The experiences of the City of Tucson will be captured on a future Website so that other communities can emulate the efforts.

3.4 Preventing Overheat Failure of Polymer Collectors

Polymer SDHW collectors are currently being developed by Envirosafe Technologies, Davis Energy Group, FAFCO, and 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. UV light degrades polymer materials. Fortunately, NREL has identified and tested a UV-protective film that is applied to the top of the collector glazing. Excessive operating temperatures can also 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 recently developed and tested a protective gel that should protect the collector from overheat failure. Applied to the underside of the collector glazing, the thermochromatic gel (a mix of polystyrene and poly-vinyl-methyl 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.) Results to date are encouraging, but lifetime tests and cost studies must be concluded before the gel could be considered a commercially viable product.

3.5 Freeze-Protected, Passive Collector

"Passive" solar hot water collectors are inherently simple and reliable because they do not require the "active" operation of pumps and valves. Two types of passive systems are widely used: the integrated collector storage and the thermosiphon. These collector systems have historically not been freeze-protected, thus limiting their use to southern climates. To expand the market, NREL and SNL studied design modifications that would freeze-protect these systems. SNL studied the roof-integrated thermosiphon (RITH) that was developed under a CRADA with Energy Laboratory, Inc., and the Salt River Project.

Two changes must occur to freeze-protect the RITH: 1) move the house insulation from the ceiling to the rafters, and 2) run glycol within the collector and transfer the heat to the tank inside the attic via a heat exchanger. Because the RITH is intended for the new home market, it is possible to specify rafter insulation prior to home construction. Rafter insulation prevents freezing temperatures in the attic, thus protecting the tank and supply/return water lines. Rafter insulation has additional energy-saving benefits and is becoming popular in high-efficiency homes.

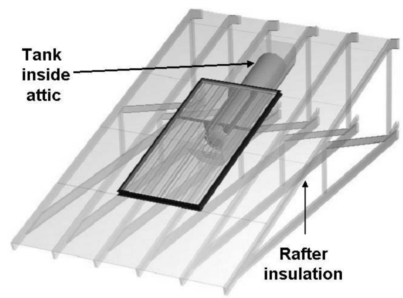

Fig. 1. Freeze-protected RITH

SNL's systems analysis suggests that a passive freeze-protected RITH could produce hot water for less than 9 ¢/kWh. This is significantly lower than the current active freeze-protected systems on the market (13 to 14 ¢/kWh.)

4. Planned FY 2005 Activities

- Issue RFP to demonstrate a freeze-protected, passive collector system within a high-efficiency home (for a U.S. thermosiphon manufacturer (TBD), Artistic Homes, and DOE Building America).
- Study combined solar heating and cooling systems (for Salt River Project).
- Complete development of thermochromatic film to prevent overheat failure of polymer collector (for Envirosafe Technologies).
- Help solar industry and city officials integrate solar heating into new projects (TBD).
- Help solar industry resolve manufacturing issues (TBD).

5. Major FY 2004 Publications

"Solar Heating Industry Assistance Program," http://www.sandia.gov/Renewable_Energy/solarthermal/Center/index2.htm

USH_2O—Utility Solar Water Heating Initiative, "Sample sizing for estimating energy savings from use of solar hot water systems," SNL (www.millionsolarroofs.com/articles/static/1/binaries/SandiaSHWMonitoring.pdf).

G.J. Kolb and Dave Menicucci, "Overview of Solar Heating Industry Assistance Program," *DOE Solar Program Review Meeting*, October 2004, Denver, CO.

6. University and Industry Partners

SNL performed R&D for the following organizations in FY 2004. These are not subcontract funds, but rather an estimate of the SNL R&D with these partners.

Organization/Contact	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
USH_2O Consortium Dell Jones (Sterling Planet)	Jacksonville, FL djones@sterlingplanet.com	Develop monitoring strategy for SDHW green tag sales	50
Polymer Collector Industry Bill Bostic (EnviroSafe Technologies)	Asheboro, NC envirosafe@triad.rr.com	Develop thermochromatic film to prevent overheat failure	50
U.S. Department of Defense Warren Neiden	Mobile, AL Warren.E.Neiden@sam.usace.army.mil	Hot water options for U.S. troops in Iraq	15
Thermosiphon Industry Mike Neuman (ELI, Inc.)	Jacksonville, FL mnewman@solarenergy.com	Passive, freeze-protected collector	50
Greater Tucson Coalition Valerie Rauluk	Tucson, AZ vajra@vecat-inc.com	Develop solar standard	50
SoCool Energy G.W. Keller	Phoenix, AZ gw@ussolid.com	Review of solar HVAC designs	15
Private Individual Carmine Cifaldi	Sarasota, FL ccifaldi@tampabay.rr.com	Review of solar storage design patent	2
Suwannee American Cement Rick Shields	Branford, FL ricks@suwanneecement.com	Review of ore heating design	5
ELI, Inc. Mike Neuman	Jacksonville, FL mnewman@solarenergy.com	Aid setting up RITH manufacturing facility	30
Private Individual Arthur Dreshfield	Walnut Creek, CA aadreshfield@aol.com	Advise on solar swimming pool for retirement community	2

Hybrid Solar Lighting

Performing Organization: Oak Ridge National Laboratory

Key Technical Contacts: Melissa Lapsa (FY 2005 Primary Contact), 865-576-8620, lapsamv@ornl.gov
Jeff Muhs, Duncan Earl

DOE HQ Technology Manager: Glenn Strahs, 202-586-2305, glenn.strahs@hq.doe.gov

FY 2004 Budget: $263K

Objectives

- Evaluate performance of 2nd-generation HSL system.

Accomplishments

- Completed performance evaluation of 2nd-generation HSL system and redesigned system.
- Developed plastic primary mirror for 3rd-generation HSL system at one-tenth the cost of original glass mirror.
- Redesigned solar tracker mechanism to reduce system costs.

Future Directions

- Testing and deployment of plastic primary mirror
- Fabrication and testing of 3rd-generation solar-tracking mechanism
- Development of hybrid solar-tracking controller.

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1. Introduction

Electric lamps revolutionized the way buildings were designed during the first half of the 20th century, virtually eliminating the need for natural light. Paradoxically, much of the second half of the century was spent developing ways to convert sunlight into electricity, in large part to power electric lamps. Use of natural light in buildings is coming full circle as concerns over the sustainability of electric lighting systems grow, especially in commercial buildings where a third of the electricity is consumed by lights. However, future lighting systems incorporating sunlight must offer the features of flexibility, convenience, reliability, and control that are lacking in daylighting systems of today. Hybrid solar sighting (HSL) systems have the unique potential to meet these requirements while providing value propositions beyond simple energy savings. This paper summarizes multidisciplinary R&D conducted in FY 2004 by several research organizations to advance the development of commercially viable HSL systems in the near future.

In coordination with its partners, Oak Ridge National Laboratory (ORNL) is leading the development of an HSL system that collects and couples visible sunlight into large-core plastic optical fibers for use in internal lighting [1,2] (see Fig. 1).

A major step toward the realization of this energy-saving technology is the development of an efficient solar collector constructed from low-cost optical components. In FY 2004, reducing the cost of the HSL solar collector was a prime objective. The high cost of the collector's glass primary mirror and the complex nature and high cost of the collector's tracking mechanism were specifically identified as areas with the greatest potential for cost reduction. The objectives in FY 2004 were to develop a low-cost option to the glass primary mirror and redesign the tracking mechanism in such a way as to establish a path forward toward a lower-cost tracking unit.

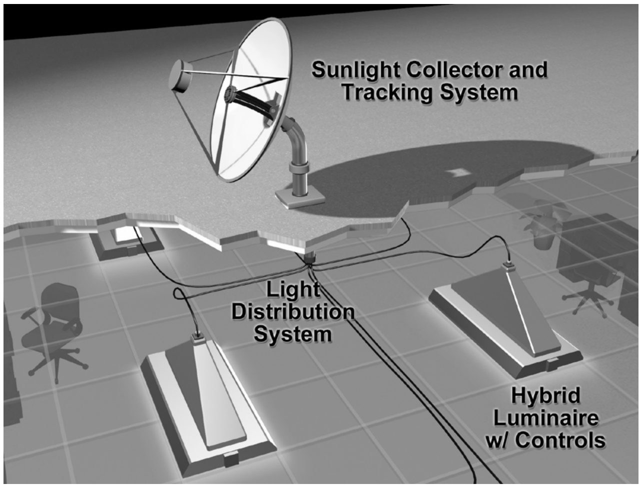

Fig. 1. The hybrid solar lighting concept

2. Technical Approach

Back-surfaced acrylic mirrors have proven to be a viable option for mirrors that must be deployed outside and exposed to harsh weather condition for a number of years. For the past 50 years, acrylic has been used routinely in applications such as traffic mirrors, aircraft windshields, and vehicle lighting and much data exists on its environmental durability to UV exposure and harsh weather conditions. As such, the development of a back-surfaced acrylic mirror to replace the 46”-diameter glass parabolic mirror currently used with the HSL solar collector was of great interest. Several manufacturers of acrylic mirrors were contacted regarding the requirements for the new mirror, and various fabrication and coating techniques were considered. Finally, a New Zealand company, Bennett Mirrors, was selected to pursue the fabrication of a 48”-diameter acrylic mirror with a second-surface silver coating.

In tandem with this effort, redesign of the HSL solar collector was performed to support and incorporate the new plastic mirror while also significantly reducing the complexity of the tracker assembly. The previous tracker, called the 2nd-generation unit, was designed around the size, weight, and structural properties of the glass primary mirror. In addition, this 2nd-generation unit was over-engineered to meet the extremely high tracking accuracies originally thought to be necessary. Design evaluations and field experience in FYs 2003 and 2004 provided a better understanding of the tolerances and requirements of the solar collector and, consequently, these modifications were incorporated into a 3rd-generation system. To ensure that the fabrication cost for the 3rd-generation system was significantly reduced versus previous units, a mechanical design house (Protomet Corp.) was used that specialized in design-for-manufacturer evaluations of prototype instruments. The results of their analysis and redesign are discussed in the following section.

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”-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 2005.

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 $4,000. Detailed modeling and final drawings have been completed and fabrication and testing of the new solar tracking unit is expected in mid FY 2005.

A broad-based public-private alliance continues to work together for the purpose of commercializing HSL. In addition to ORNL, the Hybrid Lighting partnership includes members such as the Tennessee Valley Authority (TVA), Wal-Mart, the Sacramento Municipal Utility District (SMUD), JX Crystals, SAIC, 3M, Honeywell, ROC Glassworks, Array technologies, Edison Electric Institute, several prominent universities, and other national laboratories. In FY 2004, the partnership continued to carry out the multi-disciplinary research and development needed to make HSL a viable commercial technology.

Under a contract awarded by the California Energy Commission, ORNL and SMUD in 2005 will install and begin operating an HSL system at SMUD's Headquarters in Sacramento, CA. ORNL is also scheduled to install an HSL system in a Wal-Mart store in Kauai, HI, in an effort to evaluate energy savings and sales trends associated with HSL daylighting. TVA is also helping to fund new research and development of the HSL lighting fixtures, or luminaries, that combine electrical lamps and optical fibers. The latest luminaries will be available in 2005 as part of an HSL display at the American Museum of Science and Energy in Oak Ridge, TN.

4. Planned FY 2005 Activities

Evidence suggests that using sunlight in its natural form in commercial buildings—in which nearly a third of the electricity is consumed by electric lights—is a more practical near-term solution for reducing nonrenewable energy use than using sunlight to generate electricity. However, this statement holds true only if future lighting systems incorporating sunlight offer the features of flexibility, convenience, reliability, and control that are generally lacking in daylighting systems of today. New hybrid solar lighting systems have the unique potential to meet these requirements, assuming the cost of this advanced technology can be made affordable. Research in FY 2005 aims to demonstrate significant cost reductions in the HSL technology while still maintaining the high performance demonstrated in past years. The successful fabrication and deployment of an acrylic primary mirror and testing of a redesigned, simplified, solar collector tracking mechanism and controller are planned for FY 2005.

5. Major FY 2004 Publications

D. D. Earl and L. C. Maxey, "Alignment of an Inexpensive Paraboloidal Concentrator for Hybrid Solar Lighting Applications," *Proceeding of the SPIE Annual Meeting 2003,* Nonimaging Optics: Maximum Efficiency Light Transfer VII, (2003).

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[1] J.D. Muhs, "Hybrid Solar Lighting Doubles the Efficiency and Affordability of Solar Energy in Commercial Buildings," *CADDET Energy Efficiency Newsletter* December 2000, pp. 6.

[2] J.D. Muhs, "Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy Systems," *Solar 2000, July 16–21, 2000,* American Solar Energy Society.

SH&L Systems Analysis

Performing Organization: National Renewable Energy Laboratory

Key Technical Contact: Jay Burch, 303-384-7508, jay_burch@nrel.gov

DOE HQ Technology Manager: Glenn Strahs, 202-586-2305, Glenn.Strahs@hq.doe.gov

FY 2004 Budget: $250K

Objective

- Determine cost reductions needed to achieve at least 50% reduction in the cost of saved energy (COSE) for cold-climate solar domestic water heaters.

Accomplishments

- Simulation models were assembled for three system types: glycol, drainback, and thermosiphon. The models were the basis for U.S. performance maps and later cost of saved energy (COSE) analysis.
- Cost models were assembled for three aforementioned system types with a series of hypothetical balance-of-system (BOS) and collector variations from a base case using today's technology.
- It was shown that COSE could be reduced by more than 50% if the new BOS components and selective glazed collector could be built for the hypothesized cost.

Future Directions

- Meetings with U.S. solar industry manufacturers and installers will be held to present analysis results and seek their input on reasonableness and desirability of the suggested R&D.
- An RFP for development of low-cost, cold-climate systems will be issued when funds are available. The RFP will be focused on BOS improvements if there is consensus in the solar industry on that direction.

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1. Introduction

As described in the *DOE Solar Program Multiyear Technical Plan* [1], the Solar Heating and Lighting (SH&L) program set the goal in FY 1998 to reduce the life-cycle cost of saved energy (COSE) for solar domestic water heater (SDWH) systems by ≥50%. In FY 1999, focus was placed on reaching this objective for passive systems in mild climates, with two teams currently wrapping up work on polymer integral collector-storage (ICS) systems. The SH&L program plan begins to focus on cold-climate SDWH in FY 2005, looking to achieve the 50%-reduction goal by FY 2009. The objective of this work is to determine if the goal of 50% in COSE is realistic for cold-climate SDHW systems.

2. Technical Approach

Three system types are considered: glycol, drainback, and indirect thermosiphon. For cold climates, glycol and drainback are common, whereas the thermosiphon is relatively novel. COSE is estimated by simulating performance (at TMY2 sites) and estimating costs under a new-construction market scenario. With new construction, the installation is more efficient and marketing costs (at 25% of hardware+installation cost) are smaller, compared to the more-common "retrofit scenario" assumed in [2]. Costs are taken either as the "best available" costs provided by manufacturers or as estimated from similar products, rather than as costs from detailed analysis of specific designs. Costs include direct materials (collector and BOS hardware), installation (labor, materials, overhead/profit), marketing, and O&M. Cost-modeling framework and algorithms are detailed in [2]. When a component is varied, installation costs and O&M costs are varied accordingly, as in [3].

We define a series of hypothetical cost-reduction measures for each system type. As in Table 1, BOS variations include unpressurized polymer storage with immersed polymer heat exchangers, integrated polymer piping, and an integrated valve package. A variation specific to glycol systems is to eliminate the storage-side pump with a thermosiphon loop between heat exchanger and solar storage tank. Collector variations and assumed costs are given in Table 2.

Table 1. BOS Components and Assumed Cost

Component	Description	Cost[1]
Metal tank/ ht exchanger	Conventional tank with external side-arm hx	$460
Polym. tank/ ht exchanger	Unpressurized polymer tank with immersed polymer hx	$180
Integrated piping	Supply/return piping with integral insulation	$25/100[2]
Valve package	Factory-assembled unit of valves and sensors	$200

[1] Direct cost; no related installation costs or O&M.
[2] $1/ft for glycol and drainback; $4/ft for thermosiphon.

3. Results and Accomplishments

The BOS enhancements do not per se affect system performance; their impact is on first cost only. Simulations were done for the four unique sets of collector parameters (selective polymer = selective metal-glass) for all three system types, except that the unglazed collector has not been done with the thermosiphon system because of convergence problems. Efficiency of the glycol system with the four collector parameter sets is shown in Fig. 1. The efficiency is about constant for each collector, decreasing slightly with increasing site temperature. U.S. maps of savings, efficiency, and solar fraction for all systems/collectors can be found in [3], similar to Fig. 2.

Table 2. Assumed Collectors, Properties, and Costs

Collector	$F_r(\tau\alpha)_n$[1]	F_rU_l[1]	Cost
Metal-glass-selective	0.779	4.77	$500
Metal-glass-non-selective	0.768	7.245	$450
Polymer-selective[2]	0.779	4.77	$250
Polymer- non-selective	0.739	8.216	$200
Polymer-unglazed	0.88-0.029*v	10.24+ 4.69*v	$100

[1] Taken from [4], except for unglazed data from [5].
[2] Properties assumed as identical to the metal-glass selective collector.

Results for COSE for the base case and the best two variations for the three system types are shown in Table 3. With all cost-reducing BOS variations in place, the maximum reduction in COSE is obtained with the hypothetical selective polymer collector, and is over 50% for all system types. In all three system types, the result with the nonselective polymer collector is about the same as with the base-case metal-glass selective collector.

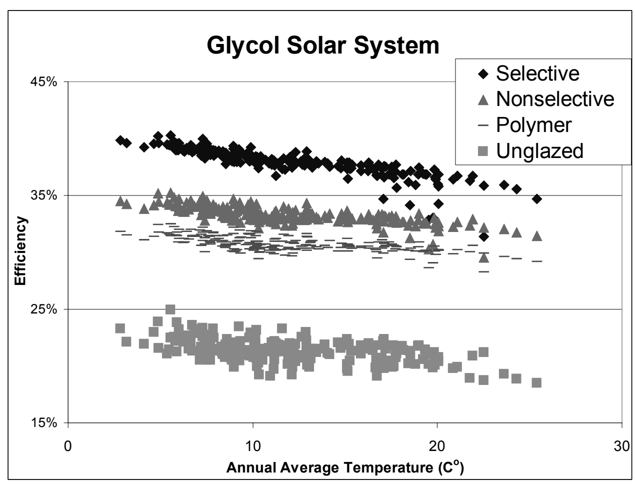

Fig. 1. Efficiency (Savings/Incidence) for the glycol system with the four different sets of collector parameters.

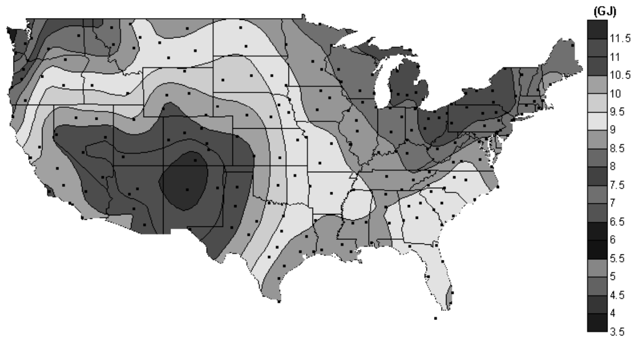

Fig. 2. U.S. map of glycol-selective annual savings of domestic water heating energy.

Results for all the variations on the glycol system are shown in Fig. 3. BOS variations are done first, followed by collector variations. Once a BOS measure is introduced, it remains for succeeding cases. BOS measures account for most of the COSE reduction. The nonselective metal-glass collector and the unglazed polymer collector are not effective measures because they increase COSE. Even though first costs are lowered, performance is lowered proportionally more. For all cases, only the use of the polymer collectors results in first cost under $1,500. For all three SDHW types, use of the nonselective polymer collector results in approximately the same COSE as the base-case selective metal-glass collector, but with lower first cost. For similar measures, the thermosiphon system always has the lowest COSE value by ~10%, because of elimination of the pump and controller needed in the two active systems.

Table 3. COSE for Three System Types

System	Glycol		Drainback		Thermosiphon	
	Base	Best2*	Base	Best2*	Base	Best2*
COSE (¢/kWh)	11.2	5.5/6.3	11.8	5.2/6.3	9.3	4.8/6.6
%Reduction2*	50.5/40.7		53.5/43.8		57.0/46.4	

Best2 and %Reduction2 cells give results for the two best cases: polymer-selective/polymer-nonselective. The COSE with today's selective metal collector is about equal to the COSE with the hypothesized polymer non-selective collector.

4. Planned FY 2005 Activities

Meetings with U.S. solar industry manufacturers and installers will be held to present analysis results and seek their input on reasonableness and desirability of the suggested R&D. The ASES 2005 Annual Conference provides a good venue.

It was originally intended to issue an RFP for development of low-cost, cold-climate systems in FY 2005. However, the FY 2005 budget for low-cost systems is reduced significantly from expectation, and the RFP will be postponed until FY 2006. The RFP will be prepared in FY 2005, but issued in FY 2006. The RFP will likely be focused on BOS improvements, assuming that there is consensus in the solar industry on that direction.

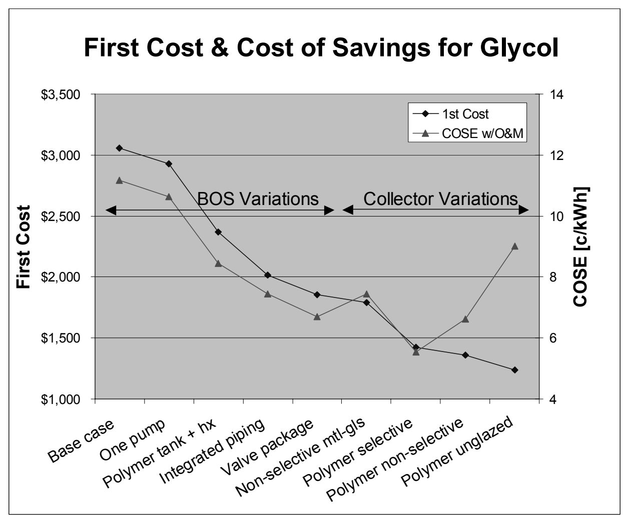

Fig. 3. First cost and COSE for the glycol system. COSE data are shown with/without O&M cost included.

5. Major FY 2004 Publications

J. Burch, J. Salasovich, C. Christensen, and J. Thornton, "Geographical Variation in Performance of an Unglazed Solar System Meeting Water Heating and Space Conditioning Loads," *2004 ASES Conference Proceedings*, ASES, Boulder, CO.

T. Hilman, *Cost and Benefit Analysis of Cold Climate Solar Water Heating Systems*. M.S. Thesis, CAEE Department, University of Colorado, Boulder, CO, 2005.

6. University and Industry Partners

Partners in the low-cost systems task are detailed elsewhere, in the report entitled "Low-Cost Polymers." That report focuses on ICS SDHW, which is where the partners mainly contributed. In regard to this subtask, there were no university or industry partners, this work being entirely in-house to prepare for the work with industry partners, to be funded under the FY 2006 RFP.

REFERENCES

[1] *Solar Energy Technology Program Multi-Year Technical Plan*. U.S. DOE/EERE, DOE/GO-102003-1775.

[2] J. Burch, J. Salasovich, C. Christensen, B. Lorand, and B. Scholten, "Cost-Benefit Modeling of Solar Domestic Hot Water Systems," *Proceedings of the ASES 99 Solar Conference*; ASES, Boulder, CO; June 1999.

[3] J. Burch, T. Hillman, and J. Salasovich, "Cold Climate Solar Domestic Hot Water Systems: Cost/Benefit Analysis and Opportunities for Improvement," NREL TP-550-37012, October 2004.

[4] Directory of SRCC Certified Solar Collector Ratings. Available at http://solar-rating.org

[5] S.J. Harrison, D. McClenahan, V.H. Nielsen, "The Performance of Unglazed Solar Collectors," *Proceedings of the 15th Annual Conference of the Solar Energy Society of Canada,* Penticton, B.C., June 1989, pgs. 235–239.

Systems Integration and Coordination

The National Center for Photovoltaics (NCPV), headquartered at the National Renewable Energy Laboratory (NREL) in Golden, CO, provides overall coordination of the PV Subprogram at the request of DOE. NREL and Sandia National Laboratories (SNL) in Albuquerque, NM, 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, TN, jointly participate in managing the Solar Heating & Lighting Subprogram.

Management activities include analysis, administration, budget control, reporting, and integration of programs, including oversight of staff, equipment, and facilities at the 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 Multi-Year Technical Plan (MYTP) and the Systems-Driven Approach to program management.

Some significant accomplishments in FY 2004 are listed below:

Systems-Driven Approach

- Completed a detailed analysis of the potential role of central and distributed solar energy technologies in the United States over the long-term, i.e., through 2050.
- Developed a user-tested, graphical user interface for the integration of PV, CSP, and solar hot water modeling into one platform and encoded existing PV performance and financial models into the integrated model.

Communications and Outreach

- Completed the first main phase of a comprehensive Solar Program Communications Plan.
- Went live with the new Solar Program Website (www.eere.energy.gov/solar).

Capital Equipment

- Prepared and submitted to DOE a multiyear (2005–2010) capital equipment plan for the NCPV, including national laboratories and university partners.
- Developed a “prototype” process-integration tool interface design that will serve as the basis of future tools used in the new Science and Technology Facility (S&TF).

Small Business Innovative Research

- Awarded seven Phase 1 “New Energy Sources” grants of $100K each.

Program Management

- Met two EERE JOULE milestones: 12.7%-efficient crystalline silicon and 10.1%-efficient thin-film module, made by U.S. manufacturers in commercial production.
- Published first-ever MYTP for the Solar Energy Technologies Program.

Systems-Driven Approach

Performing Organizations:	National Renewable Energy Laboratory Sandia National Laboratories
Key Technical Contacts:	Christopher Cameron (SNL on detail to DOE, Primary Contact), 202-586-1495, chris.cameron@ee.doe.gov Charles Hanley (SNL), Robert Margolis (NREL) Mark Mehos (NREL), David Mooney (NREL)
DOE HQ Technology Managers:	Thomas Rueckert (Primary Contact), 202-586-0942, Thomas.Rueckert@hq.doe.gov Robert Hassett, 202-586-8163, Robert.Hassett@hq.doe.gov
FY 2004 Budgets:	$922K (NREL), $461K (SNL)

Objectives

- To develop 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 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 Solar Program.
  - Initiated review of PV module cost and performance targets.
  - Completed a detailed analysis of the potential role of central and distributed solar energy technologies in the United States over the long-term, i.e., through 2050.
- **Benchmarking –** Began collecting performance and life-cycle cost data at the system and component level for residential, commercial, and utility-scale PV systems.
- **Modeling –** Developed a user-tested, graphical user interface for the integration of PV, CSP, and SHW modeling into one platform and encoded existing PV performance and financial models into the integrated model.

Future Directions

- **Analysis**
  - Continue work on analysis of long-term benefits of solar.
  - Complete review of out-year cost and performance targets.
- **Benchmarking –** Benchmark all solar technologies, with an initial emphasis on residential, commercial, and utility-scale PV systems.
- **Modeling –** Complete integration of other solar technologies, beginning with parabolic trough power systems and solar water heating, into the SDA model.

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1. Introduction

The DOE Solar Program began formulating the Systems-Driven Approach (SDA) to R&D portfolio management and prioritization with a workshop held in December 2002. The *Solar Program Multi-Year Technical Plan* (MYTP) states "All technical targets for R&D on the components and systems funded through the Solar Energy Technologies 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 SDA provides a framework for program planning that supports this objective. Under the tasks described below, data and tools are being developed to support application of the SDA to decision making by program management. The SDA team works closely with other projects, especially the PV Systems Analysis Project.

2. Technical Approach

Before the SDA can be rigorously applied to the task of prioritizing research activities, the tools supporting it must be developed for each of the supporting tasks. SDA activities will ultimately support the full portfolio of technologies currently funded by the Solar Program. However, because detailed systems analysis models have already been developed for concentrating solar power and solar domestic hot water systems, the initial focus of the development effort is on flat-plate photovoltaic systems.

Budget allocations by task are provided below.

Task Title	FY 2004 Budget ($K)
Analysis	557
Benchmarking	402
Modeling	424

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 the system and policy drivers of those technologies in various markets in both the short and long term. We are also improving the analytical basis for projecting the Program's economic and environmental benefits. Existing models, such as MARKAL and the Energy Information Administration's (EIA) National Energy Modeling System, are used to carry out analysis, and feedback is provided on how to improve the representation of solar technologies in these models. New models are also being developed.

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 carrying out these tasks, we use 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.

We are currently focused on three types of data related to fielded PV systems. These are: installed cost, including labor and materials components; system performance information over time, including energy production, cause of failure, and down time; and post-installation costs, usually brought on by scheduled and unscheduled maintenance and operation of systems.

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 subcontract funds. However, the SE and SW Regional Experiment Stations are supported, as documented as a separate project.

Table 1. Partnerships for the Collection and Analysis of PV Benchmarking Data

Application/Partner	Data Set
Utility (100 kW and up)	
Tucson Electric Power	~4 MW installed
Arizona Public Service	~4 MW installed
Commercial (10–100 kW)	
Spire Corp.	~20 Chicago systems
PowerLight Corp.*	Multiple technologies
First Solar Electric Corp.*	~8 MW Germany; U.S.
Residential (<10 kW)	>250 PV systems
Florida Solar Energy Cntr.	90 sys. in MA, TX
Conservation Svcs. Group*	~100 homes in S. CA
Borrego Solar*	100's homes in N. CA
Sacramento Mun Util Dist*	

*Indicates new collaborations

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 Systems Driven Approach 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 section 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

With respect to long-term market-penetration projections, we carried out a detailed analysis of the potential role of central and distributed solar energy technologies in the United States over the long term, i.e., through 2050. In carrying out this analysis, we developed and used a modified version of EIA's National Energy Modeling System and produced a range of solar energy technology and policy focused scenarios. Our main conclusion is that solar energy is well suited to become a major contributor to the U.S. national energy portfolio over the next 25–50 years; however, achieving this vision will require setting aggressive but realistic R&D goals, as well as implementing policies aimed at increasing the penetration of solar energy technologies into the marketplace. Further details about this analysis can be found in Margolis and Wood (2004)[i].

We have also begun to examine how MARKAL (another model used in the DOE/EERE GPRA benefits assessment) represents solar and to develop our own PV market penetration model. The goal of this effort is to improve the representation of solar technologies in existing models and to develop an alternative model that will inform the work of other analysts, as well as meet the internal needs of the Program.

With respect to reviewing the Program's technical and economic targets, our initial focus has been on PV technology and the goal to reduce the levelized energy costs (LECs) of PV systems to \$0.06/kWh by 2020. Although our work in evaluating the feasibility of achieving this target is still in a relatively early phase, we have laid out a logical approach: begin with a review of PV module cost and efficiency projections, then carry out a review of inverter costs and performance projections, and finally, assemble a complete review of PV system cost and performance projections. At this point, we are working with researchers at the University of California–Berkeley to conduct a literature review of PV module cost and performance projections.

3.2 Benchmarking

Benchmarking is a long-term process, and the results to date are preliminary. The main source of data and analysis for the residential sector has been through the activities of the Florida Solar Energy Center (FSEC), through their support of state incentive programs. The FSEC database includes more than 250 installations, with expected cost information on about 100 such systems and continued performance monitoring of more than 40 systems.

We are also assessing downstream costs related to operation and maintenance of installed systems. Table 2 shows some of this type of data as it is being assimilated into the FSEC database. This information is being collected from installers as they honor system warrantees. Although not all O&M events for these systems are exclusively related to inverters, the information in Table 2 relates only to inverter actions and serves as an indication of the types of information that will be useful over time as program databases are populated.

Table 2. Sample Log of Inverter O&M Actions from the FSEC Database

Action – Mode	Count	Parts Cost ($) min – avg – max			Labor Cost ($) min – avg - max			Avg. Down Time (days)
Replaced Component – Inverter-Internal	5	0	340	1700	25	70	100	38.20
Repaired – Inverter-Fuse Failure-Unknown Cause	6	0	6.67	10	120	120	120	4
Repaired – Inverter-Internal	5	0	26.6	80	50	50	50	60.40
Repaired – Inverter-Fuse Failure-Known Current Surge	2	10	10	10	0	0	0	55
Repaired – Inverter-GFI	1	0	0	0				11

The benchmarking results to date are summarized in Table 3, which shows summarized parameters for the three sectors under study. Note that Table 3 covers several module technologies, as well as mounting configurations.

Table 3. Preliminary Benchmarking Results for PV Systems

Parameter	Units	Utility	Commercial	Residential
General:				
System Size	KWdc @STC	135kW	24 - 100kW	3 - 10kW
Module Technology:		mono, poly c-Si; a-Si, CdTe	mono, poly c-Si; CdTe	mono, poly crystalline
System Orientation		One axis tracking; fixed	Fixed - horizontal;	fixed
Inverter Size	kW	125 - 150	10 to 30	
Performance:				
Normalized monthly energy production	kWh/kWdc/POA,	0.78 - 0.86	0.6 - 0.8	0.66-0.78
Inverter efficiency	%	93 - 96	90	88 - 94
Installed Cost:				
Module price	$/Wp,dc	3.70 - 4.00	$2.25 - 7.74	4.13 - 4.95
Inverter price	$/Wac	1	$0.50	0.95 - 1.25
All-other BOS	$/Wac	0.02	$0.71	0.55 - 1.18
All BOS (if no breakdown)	$/Wac	1.5	$2.44 - 3.59	
Design labor	$/Wac	1	$0.20 - 1.15	
Install labor	$/Wac	0.43	$0.22 - 2.17	1.40 - 2.09
System Installed Price	$/Wac	6.00 - 7.5	$4.30 - $16.13	7.31 - 9.07
Total O&M Cost	$/kWhac	0.005 - 0.013	$0.02 - 0.15	Prelim.
System Unavailability		1% - 2%	1% - 2%	

3.3 Modeling

As discussed under technical approach, the modeling effort includes four distinct modules.

3.3.1 User-interface module. The user-interface module allows the user to access various default configurations of solar energy systems. Default system configurations, performance, and cost parameters are provided, but can be changed to evaluate the impact of these parameters on key results. Drop-down menus provide in-depth access to component-level inputs. Standard graphical and tabular results are available, or data can be exported to other software packages, such as Excel or PowerPoint.

In FY 2004, particular emphasis was placed up front 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 motivations for using the modeling tool. A mockup of the user interface was developed, and a series of usability sessions were conducted to provide feedback on the initial interface design. This feedback was used to refine the interface used for the working version of the model.

3*.3.2 System-performance module.* The system-performance simulation module calculates the transient, generally hour-by-hour, performance of a collection of components configured into an overall system design. These calculations are done in the background and are not visible to the user. To predict PV module performance, we have implemented the option to model performance based on SNL's "King" methodology[ii]. The King model is accessible from within TRNSYS[iii], which will be the transient simulation solver for the model that fully integrates all the solar technologies. TRNSYS was chosen in part to make available to the user the extensive, existing library of system components relevant to the Solar Program.

Because the model will ultimately be used for analysis of thermal, as well as photovoltaic systems, a generalized description of component and configuration input options are provided in the user interface. Options include the collector (PV module), converter (PV inverter), array/field (module configuration), storage (battery), and balance of system.

3.3.3. Cost-input module. A simple cost model has been incorporated into the current version of the SDA model. Future versions of the cost-input module will include detailed component and systems-level capital costs, as well as a component and systems-level O&M costs model as part of the default systems. The user-interface permits access to these cost parameters for modification by the user. Costs can be entered through the user interface or derived from a more detailed cost model implemented within a Microsoft Excel environment. As is the case with other portions of the model, the user will be able to not only modify default values, but to redefine the model itself. Such user-defined models will allow for sophisticated rollup of materials and labor costs, with varying relationships to system size and capacity, to meet the user's specific needs.

3.3.4 Financial-analysis module. The financial module calculates the system cost and revenue streams for a given configuration, its associated input data, energy production, and various project-specific financial input assumptions. Based on this information, the module will be used to calculate information of interest to the user, such as project earnings, detailed cash flows, debt payments, equity income, levelized cost of electricity, after-tax internal rate of return (IRR), and debt-service coverage ratio.

An important feature of the finance module is that it will offer a variety of standard schemes for financing solar-related projects. The user will be allowed to select financing mechanisms related to the project at hand, e.g., mortgage, commercial-loan-financed systems, or standard power project debt/equity financing. Default financial parameters are provided. However, the user is allowed to vary the financial parameters to address project-specific requirements or to assess the sensitivity of output parameters to financing assumptions.

4. Planned FY 2005 Activities

4.1 Analysis

During FY 2005, 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:

- Complete report on the economics of solar hydrogen (07/05).
- Complete review of the technical and economic targets for PV systems (module, inverter, and complete systems) (09/05).

4.2 Benchmarking

Benchmarking in FY 2005 will continue its focus on PV technologies, including concentrating PV, and the dataset will be expanded to include all major market sectors, covering both grid-connected and off-grid applications, as follows:

- Complete set of benchmarked tables for MYTP (06/05).
- Benchmarking report detailing status of the cost and performance of PV system installations, as input for models, MYTP, and external review (08/05).

4.3 Modeling

The capability of the SDA model will be expanded, as follows:

- Include capability to conduct sensitivity studies into beta version of solar analysis model (01/05).
- Complete integration of parabolic trough and solar water heating performance and cost models into next version of solar analysis model (9/05).

5. Major FY 2004 Publications

R. Margolis and F. Wood. "The Role for Solar in the Long-Term Outlook of Electric Power Generation in the U.S." Paper presented at the IAEE North American Conference in Washington, DC, July 8–10, 2004.

S. Grover and R. Margolis. "Commercial Customers and Market Drivers to Early Solar Adoptions" Paper presented at the ASES 2004 Conference in Portland, Oregon, July 11–14, 2004.

6. University and Industry Partners

The following organizations partnered in the Project's research activities in FY 2004 (no cost share).

Organization/ Principal Investigator	Location, e-mail	Description/Title of Research Activity	FY 2004 ($K)
OnLocation, Inc. Frances Wood	Vienna, VA fwood@onlocationinc.com	Modeling long-term projections of solar energy markets.	10
Segue Energy Consulting Christy Herig	Redington Shores, FL cherig@tampabay.rr.com	Solar energy value analysis	58
Renewable Energy Leadership Group Budd Annan	Phoenix, AZ annan@cox.net	Analytical support to Arizona EPS process	59
Janzou Consulting Steve Janzou	Evergreen, CO steve@janzouconsulting.com	Provide coding support for graphical user interface	57
University of Wisconsin, Madison Sandy Klein	Madison, WI klein@engr.wisc.edu	Provide support as needed for CSP, thermal model development and distributed processing enhancements	90
Software Design Works Kate Freed	Denver, CO kate@softwaredesignworks.com	Support graphical user interface design and usability testing	10

REFERENCES

[i] R. Margolis and F. Wood. "The Role for Solar in the Long-Term Outlook of Electric Power Generation in the U.S." Paper presented at the IAEE North American Conference in Washington, DC, July 8–10, 2004.

[ii] King et al., "Photovoltaic Array Performance Model," SAND2004-3535.

[iii] Klein et al., 2000. TRNSYS 15, A Transient Simulation Program. Solar Energy Laboratory, University of Wisconsin, Madison, WI.

Communications and Outreach

Performing Organizations:	National Renewable Energy Laboratory Sandia National Laboratories DOE Golden Field Office
Key Technical Contacts:	Don Gwinner (NREL), 303-384-6570, don_gwinner@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@hq.doe.gov Thomas Rueckert, 202-586-0942, Thomas.Rueckert@hq.doe.gov
FY 2004 Budgets:	$550K (NREL), $235K (SNL), $1,160K (DOE/GO)

Objectives

- Support the communications needs of the DOE Solar Program.
- Get the right information to the right people at the right time in the right form.
- Develop or assist in developing various print and electronic communications products.
- Measure changes in attitudes and behaviors about solar energy technologies over time.

Accomplishments

- Completed the first main phase of a comprehensive Solar Program Communications Plan.
- Developed exhibits, determined key messaging, and staffed booths at various solar-related conferences: e.g., ASES, International Builders' Show, SEPA, PVSC, SPIE, U.S. Green Building Council, WREC.
- Went live with the new Solar Program Website (www.eere.energy.gov/solar).
- Completed the final version of the *DOE Solar Program Multi-Year Technical Plan* (MYTP).
- Helped to develop and produce *Our Solar Power Future*, the U.S. PV industry roadmap.
- Published the *Solar Program Overview—FYs 2002 & 2003.*
- Went live with the 2005 Solar Decathlon Website and produced a new Decathlon brochure.
- Issued three new awards for: 1) The National Solar Tour, 2) the 2004 and 2005 Solar Power Conferences/Expos, and 3) the development of a National Solar Directory in support of the Solar Decathlon of 2005.

Future Directions

- Continue to "work" the new Communications Plan, including a focus on metrics.
- Redesign the NCPV Website.
- 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 MYTP to target audiences.
- Implement a metrics process to measure ROI of certain communications products and measure directional changes in attitudes and behaviors towards solar energy technologies.

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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. In FY 2004, the Program's communications team developed a comprehensive and strategic plan 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 included profiling eight key audiences, including their perceptions of solar technologies; formulating audience-specific messages and communication objectives and strategies; and proposing communications tactics to reinforce the objectives.

Specifically, this project supports the many communications needs of the Solar Program and helps 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, Websites, and CDs, as well as programmatic pieces such as the Solar Program Overview, Annual Report, and MYTP. As a result of our strategic planning process, the team is also enhancing distribution efforts of these products to key audiences of the Solar Program.

2. Technical Approach

The Solar Program helps to direct and support advances being made in the solar technologies of photovoltaics, concentrating solar power, and solar heating and lighting. But word of such advances must be communicated clearly and strongly to appropriate audiences. If not, the impact these advances could have on further technical progress may be stifled. And the continued growth of solar markets may be stunted. Therefore, we see the need for carefully tailored communications and outreach products and activities related to key targeted audiences. Within the Solar Program, managers are developing a systems-driven approach to assess the potential of various solar 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 can key into this approach by focusing on these same markets and determining how communications can be used to overcome barriers and address key issues.

To better accomplish the Program's communications goals, we developed a robust communications plan that:

- Provides a comprehensive guide to integrate the communications work across the three solar technology areas within our Solar Program.
- Coordinates communications efforts and reduces redundancy across several offices, namely DOE, NREL, and SNL.
- Strategically targets our efforts regarding audiences and key messages.
- Strengthens the effectiveness of our work by putting greater emphasis on targeted messages to those audiences and on distributing and evaluating our products for effectiveness or audience penetration.
- Improves our response to changes in markets, audiences, funding, and opportunities, allowing us to be flexible and able to prioritize our projects.
- Guides development of projects within the larger context of national, DOE, EERE, and Program plans, including the Solar Program's Systems-Driven Approach.
- Best leverages our limited resources of people, time, and funds.
- Cultivates a multi-year mentality involving a concerted focus on ongoing Program and communications goals.

Our final document represents the first comprehensive strategic plan that covers communications and outreach activities within the Solar Program. As an initial step in our planning, we took an introspective look at our own performance. We then focused on eight audiences that we consider critical at this time. An external audit of these target audiences involved evaluating their needs, values, and attitudes toward solar energy.

This information served as a starting point in establishing our communication objectives and strategies for each audience. Specifically, for each audience, we developed "positioning objectives," consisting of messages (what we want to say); the rationale for each message (why we want to say it); associated strategies (how, when, and where we are going to convey the messages); and the intended goals (what we expect our efforts to accomplish). These objectives were used to develop broad strategies and tactics that ultimately led to proposed communications projects within the implementation portion of the plan.

We focused on the following target audiences: 1) building industry, 2) consumers, 3) federal government, 4) solar industry and industry research partners, 5) state and local governments, 6) students—kindergarten through university—and educators, 7) university research partners, and 8) utilities and energy service providers.

Through our analysis, we tabulated preliminary answers for each audience to questions in six categories: audience make-up, decision-making process and influence, audience values, audience needs, audience attitudes, and internal audit.

Based on each audience's values, needs, and attitudes, we crafted communications objectives and identified tactics, which are specific activities and projects that support the objectives and strategies we outlined for each audience. The tactics reinforce at least one of the objectives listed. We will further develop these tactics with our clients' input and support, to ensure that the proposed projects align with their needs. Metrics will be sought to gain some measure of return on investment, as well as directional changes in attitudes and behaviors toward solar technologies.

3. Results and Accomplishments

- Received awards from the Society for Technical Communication, National Association of Government Communicators, and International Association of Business Communicators (for Bell Cell Anniversary suite of products, Homeland Security sheets, and other pieces).
- Completed first main phase of comprehensive Solar Program Communications Plan (03/04).
- Evaluated existing communication products through a gap analysis and needs assessment process; results of this analysis will be used on an ongoing basis to develop new solar communications products (09/04).
- Developed exhibits, key messaging, and staffed booths at various solar-related conferences: ASES, SEPA, PVSC, International Builders' Show, SPIE, U.S. Green Building Council, WREC.
- Went live with new Solar Program Website, www.eere.energy.gov/solar (02/04).
- Completed final version of Solar Program's first MYTP (01/04).
- Helped develop and produce *Our Solar Power Future*, the PV industry roadmap (09/04).
- Published *Solar Program Overview—FYs 2002 & 2003* (06/04).
- Developed (in collaboration with IEEE) and exhibited the "50th Anniversary of the Bell Lab's Solar Battery" exhibit and historic artifacts in Japan, France, and various U.S. locations (FY 2004).
- Coordinated the kickoff of the 2nd Solar Decathlon and team selection.
- Went live with 2005 Solar Decathlon Website and produced new Decathlon brochure (05/04).

4. Planned FY 2005 Activities

- Complete *Proceedings CD-ROM for the 2004 Solar Program Review Meeting*, which will include PDFs of 2-page papers for all subtask activities (01/05).
- Complete the *Solar Program Annual Report, FY 2004*, which will include extended papers for all subtask activities, plus summaries on major task areas (01/05).

- Plan and facilitate communications strategies around development of the "Home by Design" house for 2005 International Builders' Show (01/05).
- Increase building audience awareness of solar technologies through participation in builder events, article placement in building publications, coordination with NABCEP and other builder NGOs, and Solar Decathlon 2005 promotions (2005).
- Produce updated and redesigned displays and summary posters for the PV Manufacturing R&D display cases in the SERF (01/05).
- Publish the *Solar Program Overview, FY 2004*, which will cover R&D highlights from the Photovoltaics and Solar Thermal programs (4/05).
- Design and produce a 50-year anniversary exhibit and timelines for the ISES 2005 conference in Orlando, FL, Aug 2005 (08/05).
- Go live with a redesigned NREL PV program Website, which will update information currently on the NCPV Website and provide a portal to other stand-alone NREL solar R&D-related sites (09/05).
- Develop methods to improve our measurement of selected communications and outreach projects in the Solar Communications Plan and capture audience data to measure changes in attitudes and behaviors with regard to solar energy technologies (09/05).
- Assist in the update the MYTP to reflect changes in programmatic and industry priorities (9/05).
- Publish an updated PV program 5-Year Technology Plan, if managers determine it is needed (09/05).
- Execute Solar Decathlon 2005 event on the Washington Mall and target event activities to as many of the Solar Program's key audiences as possible; multiple workshops and presentations are planned (09/05).
- Identify and develop rapport with key members of each target audience, e.g., NGOs, to improve distribution channels and encourage collaboration (FY 2005).
- Conduct a competitive solicitation for the 2006–2007 American Solar Challenge car race.
- Support the Solar Decathlon by providing 20 electric vehicles for team use and public display.

5. Major FY 2004 Publications

U.S. Department of Energy, *Solar Energy Technologies Program—Multi-Year Technical Plan, 2003-2007 and Beyond*, 168 pp., DOE/GO-102004-1775 (January 2004).

S. Pedigo et al., *Solar Energy Technologies Program—Strategic Communications Plan, 2004 and Beyond*, 44 pp., internal NREL report (2004).

U.S. Department of Energy, *Solar Program Overview, Fiscal Years 2002 & 2003*, 36 pp., DOE/GO-102004-1938 (June 2004).

Solar Energy Industries Association et al., *Our Solar Power Future: The U.S. Photovoltaics Industry Roadmap Through 2030 and Beyond*, 16 pp. (September 2004).

R. Nahan et al., *2005 Solar Decathlon: Energy We Can Live With* (revision), 4 pp.; NREL Report No. BR-520-34686; DOE/GO-102003-1777 (2004).

R. Nahan et al., *2005 Solar Decathlon*. 4 pp.; NREL Report No. BR-520-36211; DOE/GO-102004-1942 (2004).

2005 Solar Decathlon Website, www.eere.energy.gov/solar_decathlon.

DOE Solar Energy Technologies Program Website. www.eere.energy.gov/solar.

October 2004 Solar Program Review Meeting registration and manuscript submission Website. www.eere.energy.gov/solar/review_meeting.

S. Moon and S. Pedigo, "The Silicon Cell Turns 50," *DOE This Month*, Oct. 2003.

S. Renfrow, "Will we have enough materials for significant PV production?," Solar FAQ, NREL Report No. FS-520-35098; DOE/GO-102004-1834 (2004).

S. Renfrow, "How much land will PV need to supply our electricity?," Solar FAQ, NREL

Report No. FS-520-35097; DOE/GO-102003-1835 (2004).

S. Moon et al., *Get Your Power from the Sun*, 20 pp., NREL Report No. BR-520-35297; DOE/GO-102003-1844 (2003).

S. Renfrow et al., *Heat Your Water with the Sun*, 20 pp., NREL Report No. BR-840-34279; DOE/GO-102003-1824 (2003).

M. Symko-Davies et al., *High-Performance PV Project—Exploring and Accelerating Ultimate Pathways: Phase 1B Review Meeting, October 20-21, 2003*. NREL Report No. CD-520-35267 (2004).

R. McConnell, L. Kazmerski, and S. Moon, "Tomorrow's Solar Cells," *Solar Today*, July/August 2004.

6. University and Industry Partners

The following organizations partnered in some of the Project's activities during FY 2004.

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)	Cost Share
Science Communications Mark Fitzgerald	Highlands Ranch, CO markfitz@ispq.org	Analysis of training needs for solar installers	5	0
PWT Communications Pat Weis-Taylor	Boulder, CO pwt_communications@comcast.net	Research and write draft of Solar Program Overview, FYs 2002 & 2003	22	0
Interstate Renewable Energy Council (IREC) Jane Weissman	Latham, NY jane@irecusa.org	PV4You and Million Solar Roofs outreach	642	0
New Resources Group Dan Eberle	Freeman, MO daneberle@mac.com	American Solar Challenge and Solar Decathlon	290	1,400*
Solar Electric Power Association Julia Judd	Washington, D.C. jjudd@solarelectricpower.org	National Solar Directory	103	0
Solar Electric Power Association Julia Judd	Washington, D.C jjudd@solarelectricpower.org	Solar Power Conferences and Expos	200	563**
American Solar Energy Society Brad Collins	Boulder, CO bcollins@ases.org	2005-2009 National Solar Energy Tour	250	12,800***

*Spread over 3 years; **over 2 years; *** over 5 years.

Capital Equipment

Performing Organizations: National Renewable Energy Laboratory
Sandia National Laboratories

Key Technical Contacts: Larry Kazmerski (NREL, Primary Contact), 303-384-6600, larry_kazmerski@nrel.gov
Tom Surek (NREL-PV), Pete Sheldon (NREL-S&TF)
Joe Tillerson (SNL, Primary Contact), 505-844-1806, jrtille@sandia.gov

DOE HQ Program Manager: Raymond Sutula, 202-586-8064, Raymond.Sutula@hq.doe.gov

FY 2004 Budgets: $600K (NREL), $300K (SNL)

Objectives

- Maintain state-of-the-art research and measurements capabilities for PV cells, modules, and systems at the National Center for Photovoltaics (NCPV) laboratories and at leading universities participating in the PV Subprogram.
- Conduct leading-edge research and provide measurements and characterization support for the U.S. PV community, including industry and university partners, consistent with the industry guidance as expressed in the *U.S. Photovoltaic Industry Roadmap*.

Accomplishments

- Prepared and submitted to DOE a multiyear (2005–2010) capital equipment plan for the NCPV, including national laboratories and university partners.
- Developed a “prototype” process-integration tool interface design that will serve as the basis of future tools used in the new Science and Technology Facility (S&TF).
- Completed design and initiated acquisition of a 10-chamber cluster tool for deposition of thin-film silicon, including chambers to permit combinatorial deposition of films. In this phase, only the transfer mechanism and load lock are to be acquired. This system will be completed with FY 2005 S&TF capital equipment funding.
- Procured, installed, and commissioned a two-axis UHV sample manipulator with heating and cooling capability to facilitate reaction kinetic studies performed on the surface analysis process-integration tool.
- Procured, installed, and commissioned an ion-beam miller required to prepare contamination-free cross-sectional samples for high-resolution transmission electron microscopy (TEM).
- Procured an ARES rheometer to perform dynamic mechanical analysis and rheological measurements; this instrument is capable of measuring the viscoelastic response of a fluid or the dynamic mechanical properties of solid materials.
- Purchased and installed new IV curve tracer system and two IR imaging systems to replace seriously deficient and aging equipment in both the Distributed Energy Test Laboratory and Photovoltaic Systems Evaluation Laboratory at SNL.

Future Directions

- Seek funding support for the multiyear capital equipment plan.
- Develop prioritized list of capital equipment items for the new S&TF.
- Install process-integration prototype tool at NREL and complete evaluation. Based on findings, finalize interface design and complete internal report summarizing findings.

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1. Introduction

The National Center for Photovoltaics (NCPV) supports and carries out the mission of the U.S. DOE National PV Subprogram. This work includes partnering with industry, university, and other federal research laboratories to aid and complement their efforts for developing and deploying economically competitive and reliable PV products (cells, modules, and systems). Inherent to these key support activities are: (1) state-of-the-art measurement and characterization laboratories that directly assist the program partners in the critical evaluation of their products; and (2) materials and device research facilities that provide both fundamental and applied research support for the PV Subprogram. Both aspects maintain the critical core research programs that are key to improving current technologies and are leading to next-generation technologies. Maintaining these core capabilities is identified as a high priority in the *U.S. PV Industry Roadmap*. In the current world context, these centralized activities are also key to maintaining the strategic and competitive edge over growing foreign competition, including laboratories in Europe and Asia that have established facilities analogous to the NCPV operations to assist their own industries and economies. To ensure the U.S. advantage in PV technology, it is critical to maintain support facilities, providing state-of-the-art equipment that can meet the growing needs of the U.S. Program toward meeting the performance and reliability goals of the *DOE Solar Energy Technologies Program Multi-Year Technical Plan* (MYTP–see http://www.nrel.gov/docs/FY04osti/33875.pdf).

2. Technical Approach

The U.S. PV program is in danger of losing its key leadership position and a critical technical resource that has been more than 25 years in the making. The capital equipment investments in the PV program have declined to insignificant levels since 1994, allowing for the replacement of only a few critical components annually (see Fig. 1). There have been almost no investments in our university resources. Maintenance and service costs have also escalated on existing major equipment due to age (see Fig. 2). In fact, several major systems are in jeopardy of becoming decommissioned because critical components are no longer available.

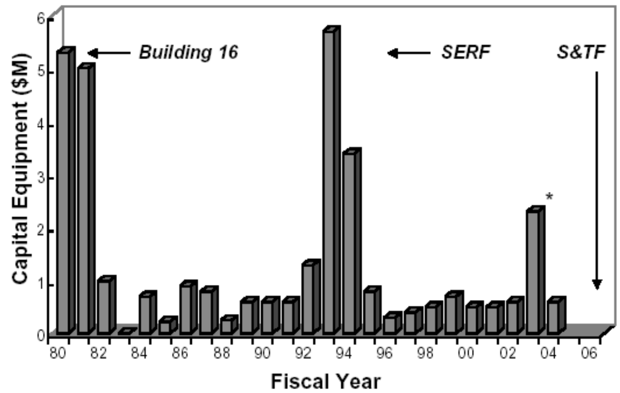

Fig. 1. NREL PV program capital equipment funding (FY 1980–2004)

The NCPV laboratories at NREL and SNL are the PV program leads for standards, measurements, and tests within the world PV community. But it is difficult to maintain technological and scientific leadership as investments in required capital equipment have steadily eroded. It has not been possible to invest in many newly available techniques and processes that have been developed since the last major capital equipment infusion in 1994. Much of the equipment in the NREL, SNL, and NCPV-partner university laboratories is generations removed from the state of the art.

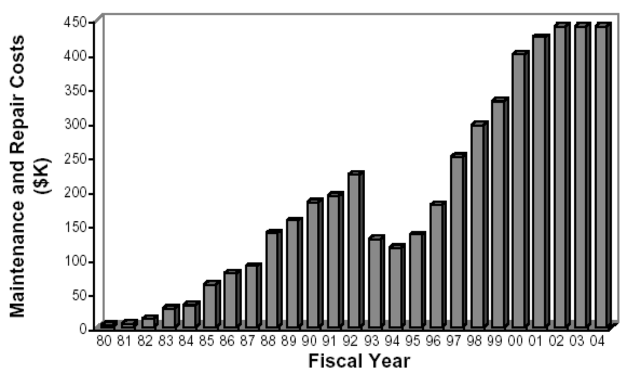

Fig. 2. NREL PV program measurements and characterization equipment maintenance costs

During FY 2004, the DOE Solar Energy Technologies Program requested a multiyear capital equipment plan. NCPV managers prepared such a plan with inputs from leading university research partners in the program. The multiyear 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) provide new equipment that provides capabilities introduced in the past 10 years that are essential to the competitiveness of the U.S. PV Program; and (3) provide the capital equipment necessary to fully outfit the new Science and Technology Facility (S&TF) so that we can meet our goal of reducing the time it takes to move a technology from the lab to the marketplace.

The FY 2004 funding for capital equipment was prioritized by the respective laboratories. The table below shows the available funding.

Task Title	FY 2004 Budget ($K)
NREL PV capital equipment	600
SNL PV capital equipment	300

3. Results and Accomplishments

The NCPV prepared and submitted a multiyear (FY 2005–2010) capital equipment plan to DOE (see Fig. 3). The plan details, by year, the equipment needs and priorities at NREL, SNL, and universities, as well as the S&TF.

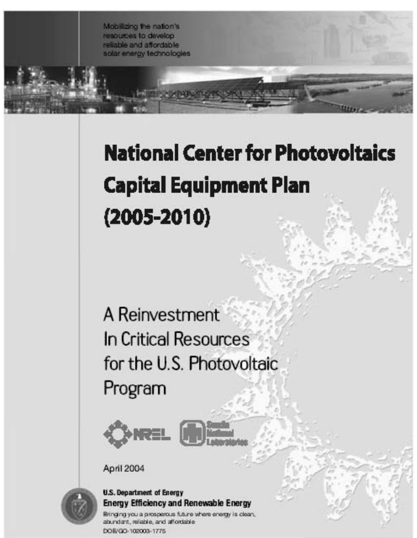

Fig. 3. NCPV multiyear capital equipment plan

Table I summarizes the capital equipment plan. The proposed investment supports the DOE critical core competencies in research at its national laboratories and university partners—critical to remaining competitive with growing foreign investments in these areas and supporting U.S. industry and technical leadership.

Table 1. NCPV Multiyear Capital Equipment Plan

	NREL Science & Technology Facility (S&TF) Replacement/Upgrade/ New Capabilities	SNL Replacement/Upgrade / New Capabilities	University University Solicitation plus GIT/ IEC Replacement/Upgrade / New Capabilities	*Total*
2005	$3,700K	$613K	-	*$4,313K*
2006	$9,700K	$1,970K	$740K	*$12,410K*
2007	$7,200K	$1,030K	$2,380K	*$10,610K*
2008	$6,800K	$360K	$1,479K	*$8,639K*
2009	$5,400K	$230K	$1,725K	*$7,355K*
2010	$3,700K	$395K	$214K	*$4,309K*
Total	*$36,500K*	*$4,598K*	*$6,538K*	*$47,636K*

There are several benefits expected from the new plan: (1) the DOE program will have *world-class laboratories* to support and advance its activities; (2) maintenance and downtime costs will be *minimized*, to more effectively and efficiently serve Program needs. In addition, scientific and technical staff can be *better directed and utilized* toward meeting the goals of the program—including any new PV program initiatives; and (3) the S&TF will have the capabilities necessary to meet the needs outlined in the *U.S. PV Industry Roadmap* in the areas of *Process Integration*, *Diagnostic Development,* and *Process Simulation.*

The prioritized list of FY 2004 equipment was prepared by the laboratories. The equipment was procured from the vendors and installed at the laboratories. Section 6 shows the list of capital equipment along with the new capabilities they provide for the program.

4. Planned FY 2005 Activities

Activities in FY 2005 will be determined by the funding available for capital equipment. The major focus will be on developing the initial equipment for the S&TF. The highest priority will be the process-integration equipment for crystalline silicon research. Key milestones in FY 2005 include:

- Develop prioritized list of FY 2005 capital equipment items (04/05).
- Complete final acceptance testing of the process-integration prototype tool at vendor's facility (09/05).
- Install process-integration prototype tool at NREL and complete evaluation. Based on findings, finalize interface design and complete internal report summarizing findings (09/05).
- SNL carryover funding will be used for emergency equipment replacement purchases in FY 2005, because no new funding was provided.

5. Major FY 2004 Publications

Our Solar Power Future: *The U.S. Photovoltaics Industry Roadmap Through 2030 and Beyond,* published by the Solar Energy Industry Association (SEIA), September 2004 (available on the SEIA website, http://www.seia.org). The roadmap requests a substantial commitment in the laboratory support facilities to support the U.S. PV industry.

6. Capital Equipment List for FY 2004

The following capital equipment items were purchased and installed at the NCPV laboratories during FY 2004. 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 2004 ($K) [NREL/SNL]
MV Systems, Inc. Golden, CO	Combinatorial Silicon Deposition	Complete design and initial chambers for a 10-chamber cluster tool. System to be completed in 2005.	192 [NREL]
Unifilm Technologies Boulder, CO	Load Lock for Sputter deposition Tool	This upgrade has increased the throughput of the Unifilm sputtering system fourfold, permitting samples to undergo preheating or post-growth cooling simultaneously during deposition on another sample.	30 [NREL]
Thermionics Port Townsend, WA	XPS Stage for Process Integration	Two-axis UHV sample manipulator with heating and cooling capability to facilitate reaction kinetic studies performed on the surface analysis process-integration tool.	60 [NREL]
Fischione Instruments Export, PA	Ion Beam Miller	Ion beam miller required to prepare contamination-free cross-sectional samples for high-resolution TEM.	62 [NREL]
Transfer Engineering Fremont, CA	Process Integration Sample Transfer Interface Prototype	Engineering design services and fabrication of S&TF prototype process-integration sample transfer interface.	170 [NREL]
TA Instruments New Castle, DE	ARES Rheometer	Perform dynamic mechanical analysis and rheological measurements.	113 [NREL]
FLIR Systems, Inc. Boston, MA	DETL – IR Imaging System	Thermal management is a critical issue to inverter reliability; this equipment provides the detailed temperature profiles to allow manufacturers to improve heat-dissipation design.	45 [SNL]*
FLIR Systems Inc. Boston, MA	PSEL – IR Imaging System	Replacement of 15+ year-old system used daily for diagnostic testing of PV modules. Thermal imaging data are critical for assessing failure mechanisms in modules.	50 [SNL]*
Keithley Instruments, Inc. Cleveland, OH	Programmable IV Curve Tester	Programmable IV curve tester allows precise characterization of PV cells and modules	56 [SNL]*

* Note: ~$150K carryover for SNL capital equipment will be used for emergency replacement purchases in FY 2005, because no new capital equipment funding has been provided to SNL.

Small Business Innovative 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@hq.doe.gov
FY 2004 Budget:	$1,685K

Objectives

- Support and augment programmatic core research.
- Support "solely U.S." small businesses involved in energy R&D.
- Help mitigate competition from off-shore entities in advanced energy R&D.
- Provide competitive, original, innovative, and advanced technology.

Accomplishments

- Awards that matured in FY 2003/2004:
    - 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.
- Seven Phase 1 "New Energy Sources" grants of $100K were bestowed, including awards for:
    - Amonix to develop a large (200-KW) PV concentrator electrolysis system for generating solar hydrogen.
    - GTi and Crystal Systems to generate a PV-oriented crystalline silicon supply.
    - UQM Technologies to produce a versatile, efficient, and reliable power conditioner for PV/utility applications.

Future Directions

- Focus on material and process cost-saving techniques for manufacturing solar/PV.
- Seek new solar concentrator designs for ease of manufacturing and cost reduction.
- Incorporate innovative ways to incorporate thermal energy into PV concentrators' electric output.
- Intensify the pursuit of the newest breakthrough in inexpensive organic PV solar cells.
- Achieve significant cost reduction in production of crystalline silicon PV products.

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1. Introduction

Each year, ten federal departments and agencies (including DOE) are required by the Small Business Innovative Research (SBIR) program to reserve a portion of their R&D funds for award to small, U.S.-owned businesses. The very high popularity of the SBIR program at DOE has necessitated cross-cutting 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 New Energy Sources SBIR category (Topic 28). Other solar subtopics, power electronics for PV, for example, are solicited in other major topics (such as 29). 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

Prior to the 2004 award, there was a 3-year hiatus in the Solar Program's participation in SBIR. The FY 2003/2004 solicitation in the renewable energy area included the following topics: New Technologies for General Illumination Applications, Energy Efficient Membranes, New Energy Sources, Sensors and Controls, and Innovative Waste Heat Recovery. The New Energy Sources subtopics were: Materials and Components for Solar Energy Systems, Low Head Hydropower Systems, Power Converters for Diverse Applications, Hydrogen Production via Electrolysis in Photovoltaics, and Wind Systems. One hundred and forty proposals were received in New Energy Sources and 80 of them went into the review cycle. Of these, seven were awarded the Phase 1 award of $100K per project for a 2-year time period. In April 2005, these seven will compete for the $750K Phase 2 award for 2.5 years. Photovoltaics received the lion's share of the solar awards (about a 4:1 ratio). The four solar/PV awardees in this solicitation were: Amonix (Torrance, CA) to develop a large (200-KW) PV concentrator electrolysis system for generating solar hydrogen; GTi (Nashua, NH) and Crystal Systems (Salem, MA) to generate a PV-oriented crystalline silicon supply (targeted at non-semiconductors); and UQM Technologies (Golden, CO) to produce a versatile, efficient, and reliable power conditioner for PV/utility application.

3. Results and Accomplishments

There are many successful outcomes of SBIR awards that matured in FY 2003/2004. Amonix (Torrance, CA) produced a novel concept to achieve high-packing density of solar cells with high reliability. AstroPower (Newark, DE) produced thin (less than 30 micron) silicon-film solar cells on glass-ceramic substrates. First Solar (Toledo, OH) automated an assembly-line production of materials for high-performance CdTe PV modules, as well as an environmentally responsible method to recycle thin-film CdTe modules. GTi (Nashua, NH) and Crystal Systems (Salem, MA) have developed advanced machinery for slicing crystalline silicon ingots (with a much reduced kerf loss) and are actively selling these worldwide. The large majority of Solar Program SBIR accomplishments, however, matured in the 1990s and are not in the scope of this publication. Now, with the new cross-cutting approach having been implemented as of FY 2003/2004, there will be much more activity.

4. Planned FY 2005 Activities

Further development of solar/PV systems is needed through creative and innovative approaches in engineering and design, new materials and processes, and cross-cutting activities with other fields. The following areas would complement and enhance the existing research activities:

- Fabricate ultra-thin layers of CIS and CdTe for PV modules (manufacture in 3 years).
- Develop new solar concentrator designs that could lower first costs, potentially lower operating costs, be easy to manufacture and install, and be replicable for large fields of troughs, heliostats, and/or dishes.
- Develop easily manufactured PV systems that can capture waste solar thermal energy (that heats the PV cell, especially concentrators) at high efficiency for cogeneration.
- Develop and manufacture solar cells (greater than 10% efficient) based on polymers, small molecules, dyes, chromophores, or other materials (e.g., quantum structures of inorganic materials) with good reliability, low cost, and easy manufacturability.
- Develop low-cost rapid processes for the production of crystalline silicon (with significant improvements of current technologies).

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. Reports on the FY 2004 Phase 1 awards are due in the March/April time frame of 2005. No reports from the 2004 time frame are on record as yet.

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location/e-mail	Description/Title of Research Activity	FY 2004 ($K)
Amonix Vahan Gharboushian	Torrance, CA drvahan@earthlink.net	Develop a large (200-kW) PV concentrator electrolysis system for generating hydrogen.	100
GTi Kedar Gupta	Nashua, NH gupta@gtequipment.com	Generate a PV-oriented crystalline silicon supply.	100
Crystal Systems Fred Schmid	Salem, MA fschmid@crystalsystems.com	Generate a PV-oriented crystalline silicon supply.	100
UQM Technologies Jon Lutz	Golden, CO jlutz@uqm.com	Produce a versatile, efficient, and reliable power conditioner for PV/utility application.	100

Program Management

Performing Organizations: National Renewable Energy Laboratory
Sandia National Laboratories

Key Technical Contacts: Larry Kazmerski (NREL, Primary Contact), 303-384-6600, larry_kazmerski@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 Sutula, 202-586-8064, Raymond.Sutula@hq.doe.gov

FY 2004 Budgets: $1,919K (NREL), $1,202K (SNL)

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 control and reporting in the research programs, including oversight of staff, equipment, and facilities at NREL and SNL.
- Provide leadership and support for various Solar Program activities, such as EERE Strategic Reviews, revisions of the *DOE Solar Program Multi-Year Technical Plan* (MYTP), and the Systems-Driven Approach to program management.

Accomplishments

- Met two EERE JOULE milestones in FY 2004: 12.7%-efficient crystalline silicon and 10.1%-efficient thin-film module, made by U.S. manufacturers in commercial production.
- Published first-ever MYTP for the Solar Energy Technologies Program.
- Facilitated the development of a 2006–2010 Transition Plan for Concentrating Solar Power.
- Organized largest-ever Solar Program Review Meeting (held in October 2004).
- Held groundbreaking for the new NREL Science and Technology Facility.
- Facilitated revision and publication of the *U.S. PV Industry Roadmap*.
- Facilitated development of an integrated water-heating industry technology roadmap—sponsored jointly by the Solar Energy Technologies Program and the Building Technologies Program.
- Aggressively supported Western Governor's Association 1000-MW Initiative through economic and site analyses, leadership in planning groups, and providing extensive technical input.
- Developed a long-term R&D plan for the Solar Energy Technologies Program as part of the Solar 2050 study.

Future Directions

- Organize annual Solar Program Review Meeting and support DOE Peer Review of Solar Program.
- Support revision of the Solar Program's MYTP.
- Implement Stage-Gate Process and Systems-Driven Approach to Solar Program management.
- Develop the FY 2006 Annual Operating Plan using the DOE Corporate Planning System database.

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1. Introduction

The DOE Solar Energy Technologies Program maintains a goal-oriented R&D portfolio, which 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 *Solar Energy Technologies Program Multi-Year Technical Plan* (MYTP – see http://www.nrel.gov/docs/FY04osti/33875.pdf). The objectives of this project are to provide the overall Program leadership, management, planning, coordination, and integration of research activities to conduct an efficient and effective program leading to the achievement of the Solar Program goals.

2. Technical Approach

The management of the research activities at NREL and SNL is coordinated under the various subprograms, as well as integrated at the laboratories by the respective Technology Managers for the Solar Program. 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 as a 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 respective 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., Systems-Driven Approach and MYTP) are supported by subcontractors, as detailed in Section 6.0 of this report. In CSP, operations and maintenance efforts related to the National Solar Thermal Test Facility are included here.

Task Title	FY 2004 Budget ($K)
PV Program Management – NREL	1,394
CSP Program Management and Communications – NREL	225
SH&L Program Management and Communications – NREL	300
PV Program Management – SNL	547
CSP Program Management, Facilities O&M, and Communications – SNL	655

3. Results and Accomplishments

The overall effectiveness of the Solar Program's management activities at the laboratories is measured by the many technical accomplishments by 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, Global Solar (Tucson, AZ), and ITN Energy Systems (Wheatridge, CO) received a *2004 R&D 100 Award*, the 19th such award for the NREL PV program since 1982.
- Timothy J. Coutts, Research Fellow in the NCPV, received the prestigious *IEEE William Cherry Award.*
- Cecile Warner (NREL) received the *2004 ASES Women in Solar Energy Award* at the ASES Annual Meeting.
- Bhushan Sopori (NREL) received a *2004 DOE Federal Consortium Technology Transfer Award*.
- Professor Ajeet Rohatgi, Director of the DOE Center of Excellence in Silicon Photovoltaics at the Georgia Institute of Technology, received the *NREL Paul Rappaport Award for 2003.*
- Robert (Bud) Annan, previously head of the DOE PV Program, received the *NREL Paul Rappaport Award for2004.*

- Ward Bower (SNL) was named *Distinguished Member of Technical Staff* based on his 40-year career at the laboratory.
- Bhushan Sopori (NREL) received the *NCPV Paul Rappaport Award* at the Solar Program Review Meeting.

The Solar Program's management team supported a number of key planning and review activities in FY 2004. The team supported the Strategic Review of the Solar Program, conducted by the Deputy Assistant Secretary of EERE, and developing and publishing the first-ever *Multi-Year Technical Plan* for the Solar Program (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 FY 2005. 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 are included as an appendix to this Annual Report.

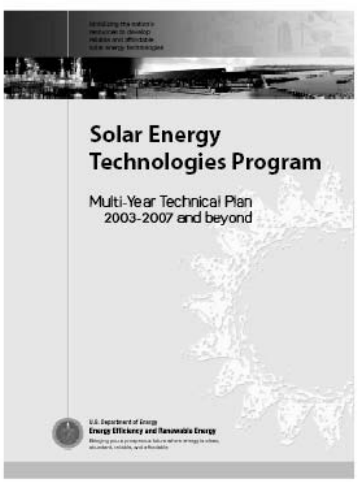

Fig. 1. The Solar Program's first-ever *Multi-Year Technical Plan* was issued in January 2004.

3.1 Photovoltaics Subprogram

The PV Subprogram achieved two EERE JOULE milestones for the Solar Energy Technologies Program in FY 2004: a 12.7%-efficient crystalline silicon module and a 10.1%-efficient thin-film module made by U.S. manufacturers in commercial production (the goals were 12.5% and 10%, respectively).

The NCPV Advisory Board continued to provide guidance and recommendations to the Program for research priorities. As a result, plans for FY 2005 involve considering the formation of a crystalline silicon project to strengthen the research program in this market-leading technology. Based on requests by the Advisory Board and the Solar Energy Industries Association (SEIA), the NCPV played a key role in facilitating the revision of the *U.S. PV Industry Roadmap.* The full title is *Our Solar Power Future: the U.S. Photovoltaics Industry Roadmap through 2030 and Beyond*. It was published by SEIA and released in October 2004. The roadmap (see Fig. 2) is meant to serve as a long-range guide for the U.S. PV program, and identifies the key market-support and R&D strategies to achieve U.S. industry leadership in technology and the marketplace.

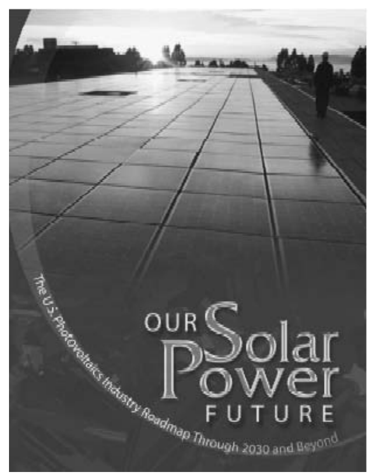

Fig. 2. The new *U.S. PV Industry Roadmap* was published and issued by the Solar Energy Industries Association in October 2004.

The NCPV led the development of an exhibit celebrating the 50th anniversary of the discovery of silicon solar cells at Bell Laboratories. The exhibit was jointly sponsored by the IEEE, DOE, and NREL, and was exhibited at some 11 venues including Japan, Europe, and the DOE Forrestal Building. The exhibit highlights the history and development of the first solar cells, and has received several awards from technical communications societies.

The NCPV submitted a multiyear Capital Equipment Plan (2005–2010) for the PV Subprogram to DOE/HQ program managers. The plan covers the reinvestment in critical resources for U.S. PV technology, and summarizes the critical capital equipment requirements for the national laboratories (NREL and SNL) and the NCPV's university research partners. The ability of the PV Subprogram to conduct leading-edge research requires a substantial investment in capital equipment on an ongoing basis.

Finally, there was significant progress on the Science and Technology Facility (S&TF) at NREL, the first major capital improvement project in the last 10 years. 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. The initial effort in FY 2005 will focus on crystalline silicon technology. A formal groundbreaking for the S&TF was held on July 27, 2004. The event included remarks and participation by R. Truly (NREL), J. Spigarelli (MRI), D. Garman (DOE), R. Sutula (DOE), Colorado Senator W. Allard, and Congressman B. Beauprez. Construction of the S&TF (see Fig. 3) was scheduled to begin in early CY 2005, with completion scheduled for late FY 2006.

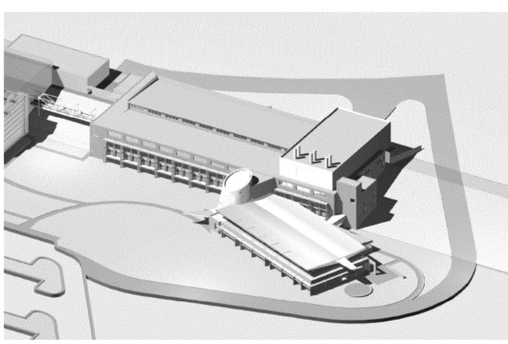

Fig. 3. Artist's concept of the new Science and Technology Facility at NREL

3.2 Concentrating Solar Power Subprogram

DOE has reexamined its CSP Subprogram to determine current prospects for reducing the cost of CSP to levels competitive with those of traditional energy sources. Continued advances in CSP technologies and new market opportunities nationally and internationally have led to the conclusion that the technology now has the potential to be competitive and to provide significant benefits to the Southwestern United States and beyond.

Given projected technology improvements and deployment opportunities, DOE developed a technology R&D and deployment strategy to promote the transition of CSP from proven technical system to initial market competitive status. NREL and SNL provided significant analytical support in the development of this strategy, identified as the CSP Technology Transition Plan. These efforts also directly supported the Western Governors' Association 1000 MW activity as it moves toward reality; these included economic and site-location analyses, as well as extensive discussions with energy planners in California, New Mexico, Nevada, and Arizona. R&D upgrades of dish and trough concentrators have directly supported important industry partnerships. A unique and effective partnership arrangement was developed to best leverage DOE funding of activities that support the development of the next generation of dish systems.

3.3 Solar Heating and Lighting Subprogram

The SH&L Subprogram facilitated an integrated water-heater technology roadmap development workshop on February 25–27, 2004, in Baltimore, MD. Sponsored jointly by the Solar Energy Technologies Program and the Building Technologies Program, this workshop brought together the solar water heating, conventional water heating, and high-efficiency water heating industries for the first time. The water heating roadmap—in draft form at the end of FY 2004—will be used by DOE for long-term strategic planning.

The PV and SH&L Subprograms also jointly developed a new exhibit, "Your Home in the Sun," for the Solar Energy Technologies Program for display at the 2004 International Builders Show in Las Vegas, NV, January 19–22, 2004. With more than 100,000 industry professionals in attendance, this National Association of Home Builders (NAHB) show is the largest homebuilding show in the world. NREL Solar

Heating and Communications staff also developed a consumer's guide to solar water heating, *Heat Your Water with the Sun,* which complements the newly revised consumer's guide to photovoltaics, *Get Your Power from the Sun.*

4. Planned FY 2005 Activities

DOE will be conducting a Peer Review of the Solar Program, currently planned to be held in conjunction with the next Solar Program Review Meeting (November 7–10, 2005). Independent, expert panels of reviewers will assess all Solar Program research activities (at the national laboratories and with industry and university partners) and provide feedback to DOE management. Other significant plans for FY 2005 include:

- Publish proceedings of the October 2004 Solar Program Review Meeting and FY 2004 Annual Report (02/05).
- Start construction of the NREL Science and Technology Facility (03/05).
- Implement Stage-Gate Process for the Solar Program's research activities (09/05).
- Revise Multi-Year Technical Plan (08/05).

5. Major FY 2004 Publications

U.S. Department of Energy, *Solar Energy Technologies Program—Multi-Year Technical Plan, 2003-2007 and Beyond*, 168 pp., DOE/GO-102004-1775 (January 2004).

U.S. Department of Energy, *Solar Program Overview, Fiscal Years 2002 & 2003*, 36 pp., DOE/GO-102004-1938 (June 2004).

Solar Energy Industries Association et al., *Our Solar Power Future: The U.S. Photovoltaics Industry Roadmap Through 2030 and Beyond*, 16 pp. (September 2004).

6. University and Industry Partners

The following organizations partnered in the Project's research activities during FY 2004 (no cost share).

Organization/ Principal Investigator	Location, e-mail	Description/Title of Research Activity	FY 2004 ($K)
McNeil Technologies Kevin DeGroat	Springfield, VA kdegroat@Mcneiltech.com	Support for Solar Program roadmapping and expansion of the Systems-Driven Approach.	362.8
SENTECH, Inc. Jonathan W. Hurwitch	Bethesda, MD jwitch@sentech.org	Technical analysis support to NREL's Solar Energy Technologies programs.	89.5
Science Communications, Inc. Mark Fitzgerald	Highlands Ranch, CO markfitz@ispq.org	Evaluation and assistance support for NREL's PV-related certification and validation activities.	65
Shirley Neff, Consultant	Washington, DC shirleyneff@earthlink.net	Inputs and policy evaluation for the *U.S. PV Industry Roadmap*	61
Western Renewables Group Les Nelson	Rancho Santa Margarita, CA lnelson@westernrenewables.com	Support for program reviews and System-Driven Approach activities	90

Congressional Directed Projects

The three projects described in this section are earmarks under the Energy and Water Development Act. The projects, located in Massachusetts, New Jersey, and California, involve installing medium-sized PV systems and/or educating the public and community groups about the benefits of solar energy. It is anticipated that these PV systems and accompanying outreach activities will serve as models for other communities to emulate.

Some accomplishments related to these projects in FY 2004 are listed below.

Center for Ecological Technology

- Identified seven high-profile sites (schools, farms, institutions) for PV installations.
- Assisted staff at Williamstown Elementary School in selling Renewable Energy Certificates generated by the school's 24-kW PV system.

Hackensack University Green Building Medical Center

- Issued award in September 2004 to install a 20–30-kW PV system on or adjacent to the new Women's and Children's Pavilion.

Solar Energy Project in Yucca Valley, California

- Issued award in September 2004 to install a 50-kW PV system on the municipal government center, which houses a regional nature museum, community center, library, and offices.

Center for Ecological Technology

Performing Organization: Center for Ecological Technology, Inc.
Berkshire, MA

Key Technical Contact: Laura Dubester, Director, 413-445-4556, laurad@cetonline.org

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

FY 2004 Budgets: $392K (DOE), $198K (CET)

Objectives

- Provide objective practical information about solar energy options and technologies to diverse target groups through a variety of methods.
- Increase public awareness about the benefits of solar energy through tours and educational displays of PV systems installed at highly visible locations.
- Expand the expertise and infrastructure of solar installers, electricians, and building inspectors through installations at highly visible sites.
- Increase sustainability of local farms through increased use of solar electricity.
- Increase the understanding of solar principles among youth through classroom presentations, events, and activities.
- Provide technical assistance to organizations/groups that have potential host sites for PV installations.
- Increase the amount of solar energy in the Berkshire, MA, electricity mix.
- Increase demand for solar energy through new market opportunities.

Accomplishments

- Identified seven high-profile sites (schools, farms, institutions) for PV installations.
- Assisted staff at Williamstown Elementary School in selling Renewable Energy Certificates generated by the school's 24-kW PV system.
- Compiled information on local projects and new opportunities for solar energy for the Berkshire Renewable Energy Collaborative Website.
- Supported the Junior Solar Sprint as part of mission to educate schoolchildren about solar technologies.

Future Directions

- Foster successful installations of PV in the high-visibility areas identified in FY 2004.
- Conduct solar energy workshops, public forums, and solar tours at the PV installations.
- Work with western Massachusetts teachers to access state-of-the-art topics and techniques related to solar energy.

---

1. Introduction

This project is an earmark under the FY 2004 Energy and Water Development Act. Established in 1976, the Center for Ecological Technology (CET), a nonprofit organization, engages in work that demonstrates and promotes practical and affordable solutions to environmental issues. CET works in partnership with other organizations to provide educational and technical assistance to schools, communities, and businesses in western Massachusetts and other regions. CET was funded to conduct a solar initiative to identify and overcome the barriers to expanding the use of solar energy in the Berkshire/western Massachusetts region. Through public forums, workshops, tours, school programs, technical assistance, and special events associated with solar installations, CET plans to educate the public about solar energy technologies and promote their use in the region.

2. Technical Approach

2.1 Public Education, Technical Assistance, and Consumer Choice
CET, in partnership with the Berkshire Renewable Energy Collaborative, a group of educators and community and organizational leaders who play a unique and vital role in guiding and promoting renewable energy use in Berkshire region, conducts solar energy workshops, public forums and solar tours. The Center maintains a Website with region-specific and practical information about solar energy and produces informational displays for public events. In addition, CET provides solar energy education targeted to youth (by training teachers to integrate solar energy into curriculum), conducts after-school programs, and coordinates special events such as the Junior Solar Sprint. Finally, CET provides technical assistance to groups/people with potential sites for PV installations and provides interactive real-time displays for PV installations at schools and public buildings.

CET connects people to their source of energy and links education with action through GreenerWatts New England, which is offered by the Massachusetts Electric Company through its "GreenUp" program. This allows residents and small businesses to directly support local renewable energy. Organizations with small PV systems generally do not have anyone on staff with the knowledge to register and market their Renewable Energy Certificates (RECs), and, thus do not receive additional income that would result in a shorter payback period for PV systems. (RECs are tradable units that represent the commodity formed by unbundling the environmental attributes of a unit of renewable energy from the underlying electricity.) CET assists local electricity generators in certifying RECs. CET is also testing whether a "competition" among towns for the highest percentage of residents choosing renewable electricity is an effective way to promote solar energy. As an incentive, CET offers PV installations at feasible sites selected by the winning municipality.

2.2 Solar Installations
CET has funding from the Massachusetts Technology Collaborative to write down the cost of installing PV systems at highly visible locations in the Berkshire region where a solar project would provide environment, economic and educational benefits to the host and general public. CET also received support from the USDA to identify opportunities for energy efficiency and renewable energy through a Sustainable Agriculture Research and Education grant.

3. Results and Accomplishments

In the first two quarters of the earmark, CET staff concentrated mainly on identifying high-profile sites for PV installations, because their whole approach to outreach and education was based on identifying good sites and convincing hosts to support those installations. This took much technical assistance and outreach. Farmers were identified as hosts, as were schools, institutions, and municipalities. Seven sites were identified for solar PV installations, and technical assistance was provided to:

- Conte Community School, Pittsfield
- Gould Farm, Monterey
- Howden Farm, Sheffield
- Massachusetts College of Liberal Arts, North Adams
- McCann Technical Vocational School, North Adams
- Simon's Rock College, Great Barrington
- Williams College, Williamstown.

CET also worked with the Williamstown Elementary School to facilitate a contract with Conservation Services Group, Inc., for the purchase of the RECs generated by the elementary school's 24-kW PV system.

In addition, CET staff compiled information on local projects and new opportunities for solar energy to be incorporated into the Berkshire Renewable Energy Collaborative Website (www.BerkshireRenewable.org). This included appropriate applications of specific solar technologies, local conditions, costs, tax and other financial incentives, local examples, and links to other information.

CET contacted individuals and businesses for their availability to participate in the October Solar and Green Buildings Tour, and staff created informational displays for this and other public events.

CET staff also supported the Junior Solar Sprint, as part of their ongoing commitment to educate the public and schoolchildren about solar technologies.

4. Planned FY 2005 Activities

CET will rely heavily on the successful installations of PV in high-visibility areas to showcase the technology and to educate the public regarding solar energy. Weather permitting, they would like to see the PV installations completed in the first part of FY 2005, so that they could begin to orchestrate tours and workshops and other means of broadcasting the existence of these demonstration sites. CET will work with western Massachusetts teachers to access state-of-the-art topics and techniques related to solar energy. Teacher training about solar energy will enable teachers to bring solar lessons and activities into their classrooms.

5. Major FY 2004 Publications

There were no major publications, but several stories appeared in the local press regarding the grant activities.

6. University and Industry Partners

Conte Community School, Pittsfield
Gould Farm, Monterey
Howden Farm, Sheffield
Massachusetts College of Liberal Arts,
North Adams
McCann Technical Vocational School,
North Adams
Simon’s Rock College, Great Barrington
Williams College, Williamstown
Northeast Sustainable Energy Association
Massachusetts Technology Collaborative
Berkshire Bank
Berkshire Gas Company
U.S. Department of Agriculture
Berkshire Renewable Energy Collaborative
Massachusetts Electric Company
Conservation Services Group, Inc.

Hackensack University Green Building Medical Center

Performing Organization: Hackensack University Medical Center
Hackensack, NJ

Key Technical Contact: Robert M. Koller, Vice President, 201-996-3780, rkoller@humed.com

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

FY 2004 Budgets: $491K (DOE), $491K (Hackensack)

Objectives

- Install 20–30-kW PV system, as well as energy efficiency measures such as chiller plants with variable frequency drives and harmonic filters, high-frequency motors, solar window glazing, lighting/motion sensors, on or adjacent to the new Women's and Children's Pavilion.
- Help the Pavilion achieve certification by the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Program
- Incorporate innovative and eco-friendly enhancements in the 300,000-square foot building currently under construction.

Accomplishments

- Award was issued in September 2004.

Future Directions

- Hackensack is in the process of deciding what solar and associated energy efficiency upgrades they will install, as well as develop the final capacities for those components that will be incorporated into the final design for their LEED Medical Center.

---

1. Introduction

Hackensack University's Women's and Children's Pavilion plans to be the first hospital project in the nation to receive LEED certification. The Pavilion will feature products such as non-fiberglass building insulation and toxin-free paints and adhesives, which, along with other materials, fabrics, and furnishings, will make a healthier building and promote a safer environment. This is where a significant number of children with cancers and deficient immune systems will be treated everyday.

2. Technical Approach

The university intends to improve HVAC, plumbing, electrical and other operating systems to promote a healthier, more energy-efficient environment while reducing operating costs. Lighting and plumbing fixture sensors will be implemented to reduce electrical and water usage. PV installation will be demonstrated in garden, where it will be highly visible.

3. Results and Accomplishments

The award for the PV system at Hackensack University's Women's and Children's Pavilion was issued in September 2004.

4. Planned FY 2005 Activities

- PV system Installation
  - Determine the available space for the required components of a PV system installation.
  - Decide on the PV array layout.

- Obtain bids from PV system retailers and installation contractors for the purchase and installation of the PV system.
- Select PV system vendor and schedule installation.
- Facilitate PV system installation and testing.
- Apply for PV system interconnection agreement with local electric utility.

- Energy Efficiency Measures
  - Install harmonic filters to reduce the power factor and load on the utility.
  - Upgrade window glazing to premium, high-efficiency versions to mitigate the solar gain in the interior spaces.
  - Include other energy efficiency measures in coordination with DOE/GO, as determined practicable.

Solar Energy Project in Yucca Valley, California

Performing Organization:	Town of Yucca Valley Yucca Valley, CA
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@hq.doe.gov
FY 2004 Budget:	$245K, Cost Share (TBD)

Objectives
- Demonstrate the feasibility of local government using PV systems to provide clean electricity and cut electric utility bills.
- Install 50-kW PV system on the municipal government center, which houses a regional nature museum, community center, library, and offices.

Accomplishments
- Award was issued in September 2004.

Future Directions
- Yucca Valley's PV installation contractor will be developing the designs for the PV system, which will then be reviewed and approved by the town's engineering contractor before installation can begin.

---

1. Introduction

Located in the southwestern corner of the Mojave Desert and shielded by windward mountain ranges, the Yucca Valley area receives more than 320 days of sunshine per year, making it a prime location for the use of solar energy. Installation of a PV system on the civic center would reduce electric utility bills and provide significant benefits to the environment. The center uses 140,000 kWh per year at a cost of $52,000.

2. Technical Approach

Yucca Valley plans to install a 50-kW PV system at its town civic center to demonstrate the use of solar energy to regional commercial and residential consumers.

3. Results and Accomplishments

The award for the Yucca Valley PV system was issued in September 2004.

4. Planned FY 2005 Activities

Engineering and Design. Determine the required components for a 50-kW PV system and the PV array roof layout, as well as locations of inverters and wire runs to utility interconnection point. Determine the system structure requirements.

Procurement. Obtain bids from PV systems' retailers and installation contractors for the purchase and installation of the PV system. Select PV system vendor and schedule installation.

Installation. Facilitate PV system installation and testing. Also, apply for PV system interconnection agreement with local electric utility.

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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)
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
ASTM	American Society for Testing and Materials
ASU	Arizona State University
BES	Basic Energy Sciences (within U.S. DOE Office of Science)
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
CAD	computer-assisted design
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	catholuminescence
COSE	cost of saved energy
CPV	concentrating photovoltaics
CRADA	Cooperative Research and Development Agreement
c-Si	crystalline silicon
CSS	close-spaced sublimation
CVD	chemical vapor deposition
CY	calendar year
DC	direct current
DEG/SE	Davis Energy Group/SunEarth
DETL	Distributed Energy Technologies Laboratory (at Sandia National Laboratories)
DJ	dual junction
DLTS	deep-level transient spectroscopy
DMA	dynamic mechanical analysis
DNI	direct normal incident
DOD	Department of Defense
DOE	Department of Energy
DSP	digital signal processing

EERE	Energy Efficiency and Renewable Energy (U.S. Department of Energy office)
EFG	edge-defined, film-fed growth
EM&D	Electronic Materials & Devices
EPA	Environmental Protection Agency
EPS	environmental portfolio standard
EPV	Energy Photovoltaics
ES&H	environmental safety and health
EVA	ethylene vinyl acetate
FF	fill factor
FSEC	Florida Solar Energy Center (at University of Central Florida)
FY	fiscal year
GB	grain boundary
GIS	geographical information system
GIT	Georgia Institute of Technology
GO	Golden Field Office (U.S. Department of Energy)
GOES	Geostationary Operational Environmental Satellite
GPRA	Government Performance and Results Act
GSE	Global Solar Energy
GW	gigawatt
HALT	highly accelerated lifetime testing
HBCU	Historically Black Colleges and Universities
HP	Hewlett Packard
HQ	headuarters
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
IREC	Interstate Renewable Energy Council
IR	infrared
IRR	internal rate of return
ISET	International Solar Electric Technologies
ISO	International Standards Organization
ISP	Institute for Sustainable Power
ITN/ES	ITN Energy Systems
J_{sc}	short-circuit current
J-V	current voltage
kW	kilowatt
LACSS	large-area, continuous-solar simulator
LCA	life-cycle analysis
LEC	levelized energy cost
LED	light-emitting diode
LOI	letter of interest
MBE	molecular beam epitaxy or mean bias error
MBMDPE	mechanical creep of metallocene-based multi-density polyethylene
MDC	McDonnell Douglas Corporation
MEG	multiple exciton generation

MOCVD	metal organic chemical vapor deposition
MSR	Million Solar Roofs
MTBE	mean time before failure
MURA	Minority University Research Associates
MW	megawatt
MYTP	Multi-Year Technical Plan (issued by the DOE Solar Energy Technologies Program)
NABCEP	North American Board of Certified Energy Practitioners
NAHB	National Association of Home Builders
NCPV	National Center for Photovoltaics
nc-Si	nanocrystalline silicon
NEC	National Electrical Code
NEMS	National Energy Modeling System (of the International Energy Agency)
NETL	National Energy Technology Laboratory
NGO	non-governmental organization
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
NYSERDA	New York State Energy Research and Development Authority
OATS	Outdoor Accelerated-weathering Testing System
ORNL	Oak Ridge National Laboratory
OTF	Outdoor Test Facility (National Renewable Energy Laboratory))
OWIP	Office of Weatherization and Intergovernmental Programs
PECVD	plasma-enhanced chemical vapor deposition
PERT	Performance and Energy Ratings Testbed
PIER	Public Interest Energy Research (program of the California Energy Commission)
PNNL	Pacific Northwest National Laboratory
PV	photovoltaics
PVD	physical vapor deposition
PVPS	Photovoltaic Power Systems Programme (of the International Energy Agency)
PVSAM	PV Systems Analysis Model
PVSC	Photovoltaic Specialists Conference
QD	quantum dot
QE	quantum efficiency
RCPCD	resonant-coupled, photoconductive decay
R&D	research and development
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
RMSE	root mean square error
ROI	return on investment
RPS	renewable portfolio standard
RUS	Rural Utilities Service (of the U.S. Department of Agriculture)
SAIC	Science Applications International Corporation

SBC	systems benefit charge
SBIR	Small Business Innovative Research
SDA	Systems-Driven Approach
SDHW	solar domestic hot water
SEGS	Solar Energy Generating Systems
SEIA	Solar Energy Industries Association
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
SHJ	silicon heterojunction
SHW	solar hot water
SKPM	scanning Kelvin probe microscopy
SMUD	Sacramento Utility District
SNL	Sandia National Laboratories
Solar PACES	Solar Power and Chemical Energy Systems
SPIE	International Society for Optical Engineering
SRCC	Solar Rating and Certification Corporation
SSI	Shell Solar Industries
S&TF	Science and Technology Facility
SWRES	Southwest Regional Experiment Station (at New Mexico State University)
SWTDI	Southwest Technology Development Institute (at New Mexico State University)
SUNY	State University of New York
TA	technical assistance
TBD	to be determined
TCO	transparent conducting oxide
TEM	transmission electron microscopy
TES	thermal energy storage
TMY	typical meteorological year
TOU	time of use
TPD	temperature-programmed desorption
TVA	Tennessee Valley Authority
UHV	ultra-high vacuum
UL	Underwriters Laboratories
UN	United Nations
UPS	ultraviolet photoelectron spectroscopy
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
UV	ultraviolet
VB	valence band
V_{oc}	open-circuit voltage
VSHOT	Video Scanning Hartmann Optical Test
WGA	Western Governors' Association
WOM	WeatherOmeter
WREC	World Renewable Energy Congress
WRR	World Radiometric Reference
XPS	X-ray photoelectron spectroscopy
YDR	Yield, Durability, and Reliability
ZEH	Zero Energy Home

Cover Photos (clockwise, from top):

With a combined output of 364 megawatts, the Solar Electric Generating Systems' concentrating solar power facility in southern California constitutes the world's largest solar power plant. *Credit: Kramer Junction Company, PIX11070*

Thirty-thousand square feet of PV panels grace the roof of the Moscone Convention Center in downtown San Francisco. Installed by PowerLight Corporation, this is the first project resulting from two voter-backed initiatives to finance renewable energy in San Francisco's commercial, residential, and government-owned buildings. At their peak, these panels will generate 675 kilowatts of electricity. *Credit: PowerLight Corp., PIX13339*

Researchers at NREL's Outdoor Test Facility use state-of-the-art laboratories and test beds to measure the performance and reliability of PV systems. *Credit: Warren Gretz/PIX10751*

The owners of this Colorado home take advantage of a solar water heating system on the roof. This drainback system has a 120-gallon storage tank. *Credit: Industrial Solar Technology Corp., PIX12964*

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