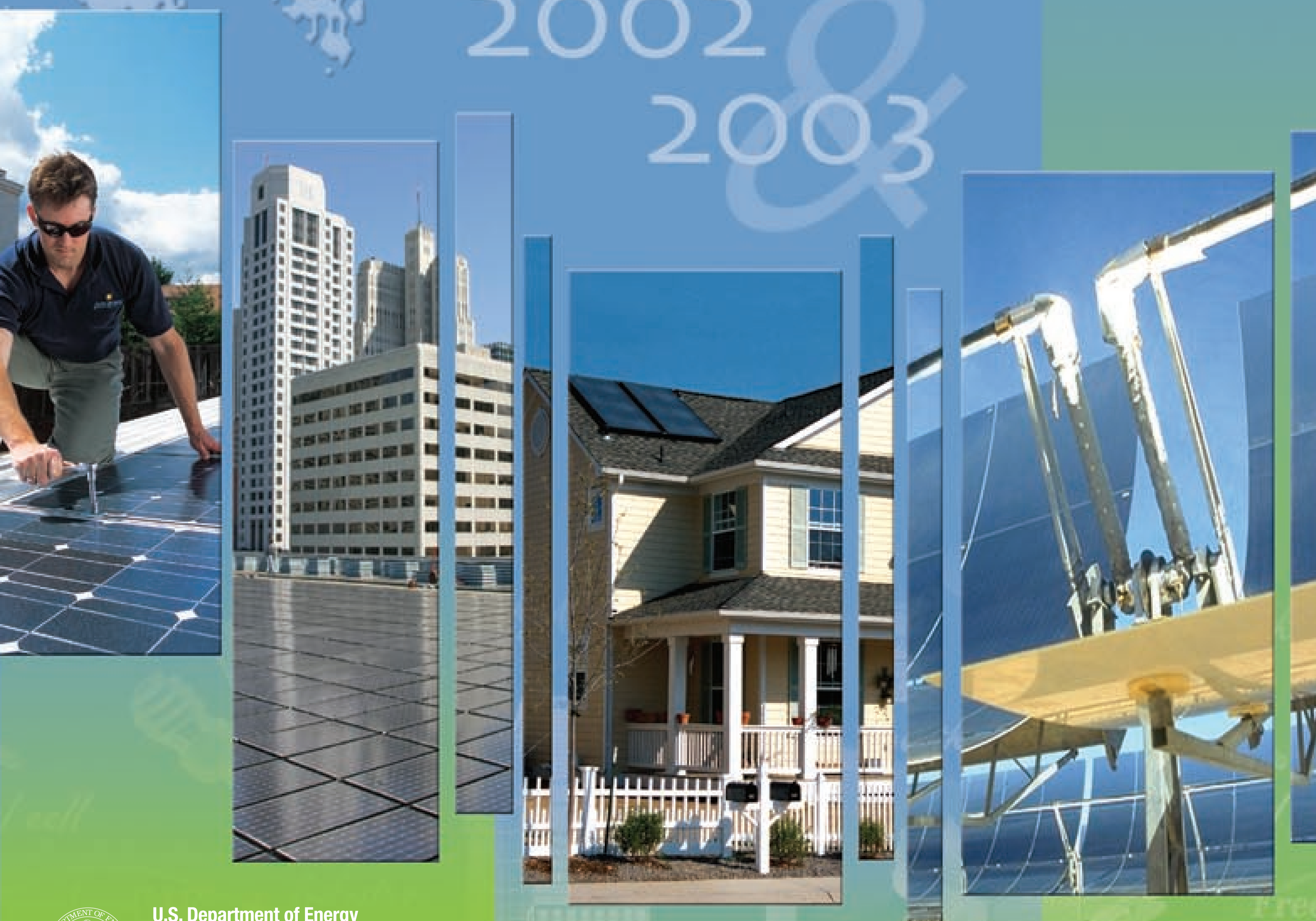
Solar Program Overview

fiscal years 2002 & 2003



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

Program Highlights

Photovoltaics Subprogram

Fundamental and Exploratory Research 6

- Achieved a 36.9%-efficient triple-junction terrestrial concentrator cell
- Demonstrated a 19.2%-efficient CIGS thin-film cell
- Gained approval for design of Science and Technology Facility
- Provided measurements and characterization support to more than 70 organizations.

Advanced Materials and Devices 13

- Achieved 12.8%-efficient CIS module
- Received R&D 100 award with First Solar, Inc., for manufacturing of CdTe PV modules
- Established Thin Film Module Reliability National Team to coordinate research on reliability of thin-film modules
- Decreased costs by more than 55% for participants in PV Manufacturing R&D projects
- Readied new subcontracts for award under *PV Manufacturing R&D—Large-Scale Module and Component Yield, Durability, and Reliability*
- Reported long-term exposure data on 20 CIS modules to manufacturers to help improve module durability
- Created an educational industry-interactive Web site titled *Cadmium Use in Photovoltaics*.

Technology Development 21

- Increased sources of data for reliability database
- Approved engineering designs for prototypes under *High-Reliability Inverter Initiative*
- Transferred dark I-V testing to PowerLight Corporation to aid quality measurement during production
- Supported inclusion of PV systems on the Rural Utility Service's approved list of materials and within the National Voluntary Practitioner Certification Program and the Navajo Electrification Demonstration Program
- Conducted the Solar Decathlon, American Solar Challenge, and Renewable Energy Academic Partnership Conference.

Solar Thermal Subprogram

Concentrating Solar Power 26

- Developed prototype parabolic trough collector with Solargenix Energy. Tests at the National Solar Thermal Test Facility (NSTTF) at Sandia validated optical accuracy and thermal performance
- Developed and operated the Mod 1 prototype of the Advanced Dish Development System (ADDS) with Stirling Energy Systems with 91.4% availability during field tests at the NSTTF
- Demonstrated closed-loop tracking and automated operation in grid-connected mode of the Mod 2 10-kW dish
- Demonstrated PV as receiver (dense-packed array) in dish concentrator with tests at the High-Flux Solar Furnace at NREL
- Formed the *1,000 MW CSP Project Team* in response to Congressional interest to stimulate the deployment of CSP in the Southwest.

Solar Heating and Lighting 30

- Provided testing and analysis to solar water heating industry to identify and solve problems, such as corrosion, occurring in the field
- Began field tests of two designs for low-cost solar water heating systems using polymer materials
- Began tests of a prototype hybrid solar lighting concept.

Cover photos (from right to left): With a combined output of 354 megawatts, the Solar Electric Generating Systems' CSP facility in southern California constitutes the world's largest solar power plant (Sandia, SNL1428-5); The owners of this Colorado home take advantage of a solar water heating system on the roof (Industrial Solar Technology Corp., PIX12964); 30,000 square feet of PV panels grace the roof of the Moscone Convention Center in San Francisco (PowerLight Corp., PIX13340; A PV system is integrated into an awning over a back porch in California (AstroPower, PIX12345); Crowds flocked to the Solar Decathlon, an event that showcased solar homes designed and built by college students (Warren Gretz, NREL, PIX11779); Two megawatts of utility-scale PV generation are located at the Prescott, Arizona, airport (Arizona Public Service, PIX13338)

The Solar Energy Technologies Program

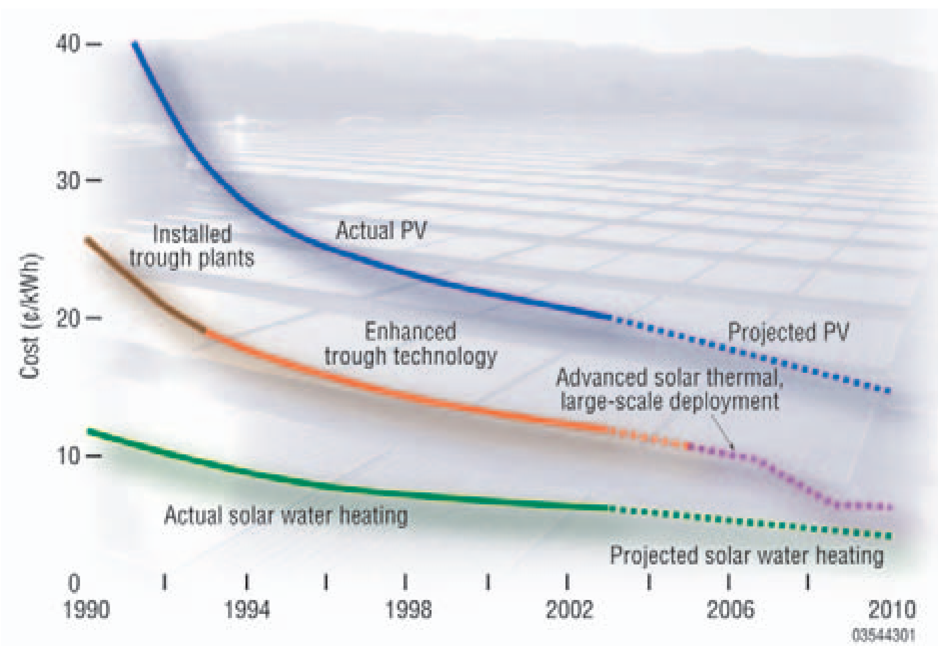
The sun's energy holds tremendous potential to diversify our energy supply, reduce our dependence on imported fuels, improve the quality of the air we breathe, and stimulate our economy by creating jobs in the manufacture and installation of solar energy systems. To reap these benefits for our nation, the U.S. Department of Energy (DOE) manages a Solar Energy Technologies Program directed toward specific, measurable results. In partnership with universities and industry, the Solar Program conducts research and analysis to make solar energy a greater part of our nation's economy.

Here we report some of the impressive results of fiscal years (FYs) 2002 and 2003, both to account for taxpayer resources invested and to outline the continuing activities necessary to reach our goal of having cost-effective solar energy technologies in widespread use throughout our nation.

Essential to carrying out a complex research and development (R&D) program is careful planning. In FY 2003, we drafted the first *Solar Energy Technologies Program Multi-Year Technical Plan*, which charts a five-year planning cycle for Program activities and highlights how a systems-driven approach is being used to achieve short- and mid-term results and set the research direction for achieving long-term goals. This document, along with information about Program activities and about solar energy technologies in general, can be found on the Solar Program Web site (*www.eere.energy.gov/solar*).

We manage the activities of the Solar Program through the efforts of staff at DOE and its national laboratories, including the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (Sandia), Oak Ridge National Laboratory (ORNL), and Brookhaven National Laboratory (BNL). This talented group of scientists, engineers, and managers work together in organizational structures we call virtual laboratories. Through cooperation, communication, and teamwork among their many participants, the National Center for Photovoltaics (NCPV) serves as the virtual laboratory for the Photovoltaics Subprogram, and Sun♦Lab is the virtual laboratory for the Concentrating Solar Power Subprogram. For each virtual lab, a single team of managers from NREL and Sandia directs day-to-day program activities. Together with DOE managers, they formulate a long-term vision for the programs, develop yearly operating plans, and negotiate cooperative agreements with the Solar Program's industrial partners.

This solar-powered house was designed and built by students from the University of Missouri-Rolla for the Solar Decathlon competition in Washington, D.C., in fall 2002. This event, sponsored by the Solar Program and others, showcased the ingenuity of U.S. college students in applying renewable energy and energy efficiency technologies for living and working environments.



With improved technology supported by DOE, the cost of solar energy in the United States has declined steadily. The projected costs (shown as dotted lines in the graph) are based on continuing the proposed budget support for the Solar Program.

A Message from the Program Manager

We are witnessing yet another year of dramatic growth in the worldwide solar energy industry. In 2003, annual revenues from solar power equipment and installation reached $4.7 billion. This impressive growth is founded on decades of research and development at our universities, laboratories, and in industry. Yet to make a bigger difference to our nation's energy economy, we can and must do so much more. To this end, the Solar Program is mobilizing the nation's resources to develop a portfolio of reliable and affordable solar energy technologies in line with guidelines in the *President's National Energy Policy* (May 2001).

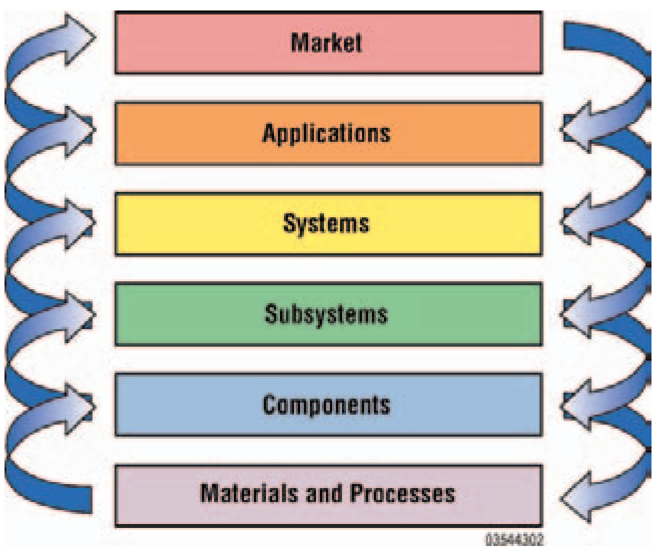
Our integrated research program works for the wider use of photovoltaic (PV) and solar thermal approaches to solar energy conversion. PV and solar thermal power have many common challenges in entering markets and developing cost-competitive applications, systems, and subsystems. For example, all solar technologies that are integrated into building roofs or installed on roofs have common challenges in satisfying builder and owner preferences and in interconnecting with the building's energy system.

To understand these challenges and to identify the most important research required to create effective systems, the Solar Program uses a systems-driven approach that relates materials, processes, components, products, applications, data from fielded systems, and markets for the technologies.

The overriding benefit of the systems-driven approach is the ability to see how changes in one component might affect the application or market for the entire system. For example, when we develop a new low-cost polymer for solar water heaters, we open up completely new markets for the systems. On the other hand, changes in a market can change component requirements. For example, new national interconnection standards may change requirements for components of PV systems supplying power to the utility grid. Our systems-driven approach to planning and managing the Solar Program helps identify common elements that impact R&D activities. This management style, driven by results rather than by processes, is key to building on the accomplishments of our program reported here.

Raymond A. Sutula

Raymond A. Sutula, Manager
Solar Energy Technologies Program



The systems-driven approach is being used throughout the Solar Program. At the technology level, this approach can help identify common research concerns, avoid duplication of effort, and explore how advances in an area such as subsystems might change the assumptions or requirements for systems, applications, or markets.

Ambitious Goals, Strong Working Relationships

The goals of the Solar Program align directly with the *National Energy Policy* goals. As part of the DOE Office of Energy Efficiency and Renewable Energy (EERE), the Solar Energy Technologies Program works with other federal institutions to develop PV and solar thermal energy technologies. The Solar Program works with the U.S. Department of Agriculture, Department of Defense, Federal Emergency Management Administration, Office of Homeland Security, and others. For example, in early 2004, the Defense Advanced Research Projects Agency awarded a contract for basic research to develop new materials for hybrid PV cells. The U.S. Army Soldier Systems Center, NREL, and other PV Subprogram subcontractors will participate in these efforts. By working with other government institutions, the Solar Program conveys and collects valuable information about how solar technologies can make the best contribution to our nation's energy portfolio.

The Solar Program also works closely with other DOE efforts to achieve EERE goals. For example, the Solar Heating and Lighting Subprogram performs R&D and works closely with the Building Technologies Program to overcome barriers to acceptance of solar thermal technologies and to increase their deployment. Solar water-heating systems and PV systems have been installed by some teams participating in the Building Technologies Program's Zero Energy Buildings and Building America activities. These teams have been supplying valuable feedback on product specifications including pricing, aesthetics, and installation practices. In other work, cooperative research is also under way through hybrid solar lighting, with the Energy Efficiency Science Initiative and the DOE Fossil Energy Program.

Through improved technology we can ensure that America will lead the world in the development of clean, natural, renewable and alternative energy supplies. – President's National Energy Policy

An important part of the Solar Program is its relationship with industry. Through competitive solicitations, cooperative research and development agreements (CRADAs), conferences, and publications, the Solar Program brings the perspectives and resources of the solar industry into the planning and implementation of the R&D activities.

The highlights presented in this report are a sample of the accomplishments of the previous two fiscal years. They indicate the breadth and depth of the activities under way and explain our optimism for even greater accomplishments in the years ahead.

Warren Gretz/PIX12514

NCPV Director Larry Kazmerski (left) presents the 5th NCPV Paul Rappaport Award to the 2002 Solar Decathlon. Accepting the award, on behalf of the hundreds of students who participated in this event, are DOE Solar Program Manager Ray Sutula and DOE PV Team Leader Richard King.

Warren Gretz/PIX12513

At the Solar Program Review Meeting in 2003, Frank Wilkins (left), Team Leader of the Solar Thermal Subprogram, recognized Hank Price of NREL for his work in analyzing parabolic trough systems. Scott Jones (not shown) of Sandia was honored for contributions to power tower systems.

USING PV TECHNOLOGY TO MAKE ELECTRICITY

There is more than enough energy from the sun falling on the United States to meet our electricity needs. Each hour, enough sunlight strikes the earth to meet the world's energy needs for an entire year. We can tap this solar energy using photovoltaics (PV), the direct conversion of sunlight to electricity using semiconductor materials. Rooftops on existing buildings and homes offer ideal locations for PV.

Since 1953, when the first practical solar cell produced a few thousandths of a watt of power with a conversion efficiency of about 5%, PV cells and modules have become a familiar part of our lives, powering everything from homes, to satellites, to emergency roadside telephones. This progression from laboratory to spacecraft to roadside began in the 1970s, when the federal government started working with universities and industry partners to harness PV for energy needs on earth. The goal of the federal program has always been to increase the conversion efficiency and reliability of solar cells in order to reduce the cost of electricity generation. In addition to research to improve cells made of silicon, the past 30 years have seen discoveries in thin-film materials—amorphous silicon (a-Si), copper indium diselenide (CIS), and cadmium telluride (CdTe). In the 1990s, III-V multijunction devices took center stage with their champion efficiencies. All of these technologies have been incorporated in some of today's commercial products.

By 2003, commercial PV cells averaged 15% to 20% conversion efficiency, and our researchers demonstrated a laboratory cell with nearly 37% efficiency. With improvements in technology and manufacturing, the cost of PV modules has dropped from \$55 per watt in 1973 to \$3 to \$4 per watt in 2003 (2003 dollars). Annual production of PV cells in 2003 rose to about 744 megawatts (MW) of power capacity.

RICHARD KING, TEAM LEADER, PHOTOVOLTAICS SUBPROGRAM

The primary purpose of the DOE Photovoltaics Subprogram is to accelerate the development of solar electricity as a national and global energy option. In 2002 and 2003, we saw considerable progress. The market for PV grew by 30% for the third and fourth years in a row, and, for the first time, sales of systems for connection to the utility grid equaled sales for remote power applications. This growth and the impressive advancements in manufacturing and R&D are in line with the strategy and goals of the *U.S. Photovoltaic Industry Roadmap* developed in 1999.

The PV Subprogram has met or exceeded the goals and milestones set by our annual and multi-year planning process for FYs 2002 and 2003. These accomplishments include new record efficiencies: 36.9% for the triple-junction terrestrial concentrator cell and 19.2% for a CIGS thin-film cell. These laboratory records and the increased understanding of solar cell processes down to the atomic level led to improvements in the efficiencies of modules and cells coming off the manufacturing line. At the same time, module-manufacturing costs have decreased by 55% for participants in the PV Subprogram's PV Manufacturing R&D Project. Building on these accomplishments, we will work aggressively to meet our planned goals and milestones in FY 2004.

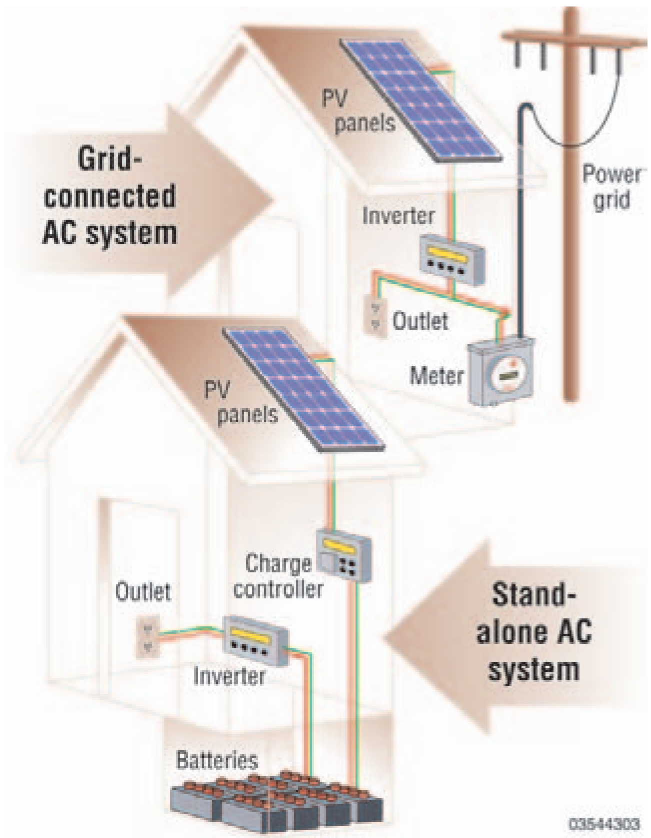
Warren Gretz/PIX11822

Despite this progress, costs must come down even more before PV can make a significant contribution to our energy economy. A major goal of the Solar Program is to reduce the cost of electricity from PV systems from about \$0.25/kilowatt-hour (kWh) in 2003 to \$0.18/kWh in 2005. To bring costs down, the Program conducts an aggressive R&D effort aimed at increasing efficiencies, improving reliability and system life, and improving manufacturing processes.

PV SUBPROGRAM STRUCTURE

The PV Subprogram carries out these activities through the National Center for Photovoltaics (NCPV), an alliance of organizations working with the U.S. PV industry to maintain our global leadership position. Several national laboratories—NREL in Golden, Colorado; Sandia in Albuquerque, New Mexico; and BNL in Upton, New York—are key participants in these efforts.

Our PV Subprogram, in conjunction with the NCPV, supports world-class scientists at the national laboratories with the latest equipment, performing research aimed at our national energy goals. We use efficiency—the percentage of energy from sunlight falling on a PV device that is converted to



*A **solar electric system** includes several key components that work together to deliver electricity to the user. **Cells** are composed of layers of semiconductor and other materials that produce electric current in response to sunlight. Individual cells are connected in strings to make up the **PV module** that is sealed from the weather with encapsulants. Module electrical wires are connected by **electrical junction boxes**. PV modules generate direct current (DC) electricity that can be stored in **batteries**. **Charge controllers** keep batteries from overcharging or undercharging. If alternating current (AC) is needed, such as for conventional appliances or for interconnection to a utility grid, an **inverter** or **power conditioner** is necessary.*

electricity—as one measure of our progress with materials, devices, and systems. The champion efficiencies result from materials and devices made in the laboratory where the very latest equipment and highly trained personnel control every step of every process.

Developing PV products that can compete with other forms of electric generation begins with basic research in the laboratory, then examines advanced materials and devices, continues through manufacturing R&D, and extends to technology development and the marketplace. Once in the market, information about performance and reliability provides important feedback to all the previous activities.

Teams, Peer Review, and Publications

Some of the research activities are coordinated by national teams composed of in-house researchers from NREL and Sandia, U.S. industrial partners, and university researchers with expertise in a specific PV material. Industry partners first suggested this approach, which was adopted in 1993. Teams are added as technologies or issues arise. About 40 researchers are on each team, doing the research and reporting on it about every nine months. In FY 2003, there were research teams for CdTe materials, CIS materials, a-Si and thin silicon materials, environmental safety and health, and thin-film module reliability. The PV national teams include the nation's best research and engineering talent drawn from industry, universities, and the national laboratories.

Peer review of research results and management strategy is basic to the PV Subprogram, and we continue to receive high marks for our efforts. In 2003, an independent panel selected by DOE conducted a formal review of the PV Subprogram. The reviewers included representatives from the National Aeronautics and Space Administration, National Institute of Standards and Technology, Electric Power Research Institute, Rutgers University, and University of Massachusetts at Amherst. To quote from this report, "The Thin Film Partnership and Systems Reliability research efforts examined during this review are outstanding accomplishments for DOE that are emblematic of the high standards and exceptional capabilities that the panel found during the peer review of the entire program in 2001."

The primary purpose of the DOE Photovoltaics Subprogram is to accelerate the development of PV as a national and global energy option.

Cooperation with other institutions and programs maximizes the impact of our results by moving discoveries and developments to those who can make best use of them. For example, papers published by NCPV researchers in refereed journals, such as *Applied Physical Letters, Solar Energy Materials and Solar Cells, Journal of Physical Chemistry*, and others demonstrate the high caliber of work and level of influence the PV Subprogram is having on the field. In the last six months of FY 2003, the NCPV had more than 500 publications in journals and conference proceedings. In addition, staff members made 92 presentations at technical meetings, including 26 invited talks.

PV Fundamental and Exploratory Research: Pushing the Frontiers

The PV Subprogram supports fundamental research to understand the limitations of current and next-generation PV technology. Building on this understanding, researchers then work to push PV technologies to the limit. They conduct exploratory research to identify strategies to "leapfrog" or jump over and avoid protracted R&D to completely new technologies. These breakthrough technologies could make a dramatic impact on energy markets.

The PV Subprogram supports two main areas of basic research. The first explores defects and structures of electronic materials and devices to discover ways to increase efficiencies and to validate novel fabrication techniques. The second applies material and device-processing science to develop new tools for deposition, processing, and characterization of electronic materials. These tools will allow us to integrate processes and diagnostics in any number of ways, thus providing the opportunity to study research problems that were previously difficult or even impossible to pursue. Both areas involve closely coordinated efforts among scientists at the national laboratories, at universities, and in industry.

This effort to explore unconventional ideas for converting sunlight into electricity has met and exceeded its overall goals…

Basic and University Research: Organic Semiconductors, Nanotechnology, Third-Generation Solar Cells, and Creative Students

To help stimulate creative ideas and move them into the development process, the PV Subprogram has awarded contracts under the *Future Generation PV* and *PV Beyond the Horizon* projects. Beginning in 1999, contracts to 29 university teams and four companies have explored new concepts to better understand their potential. These efforts have sparked the interest of industry, and some subcontracts have resulted in start-up companies.

Warren Gretz/PIX10822

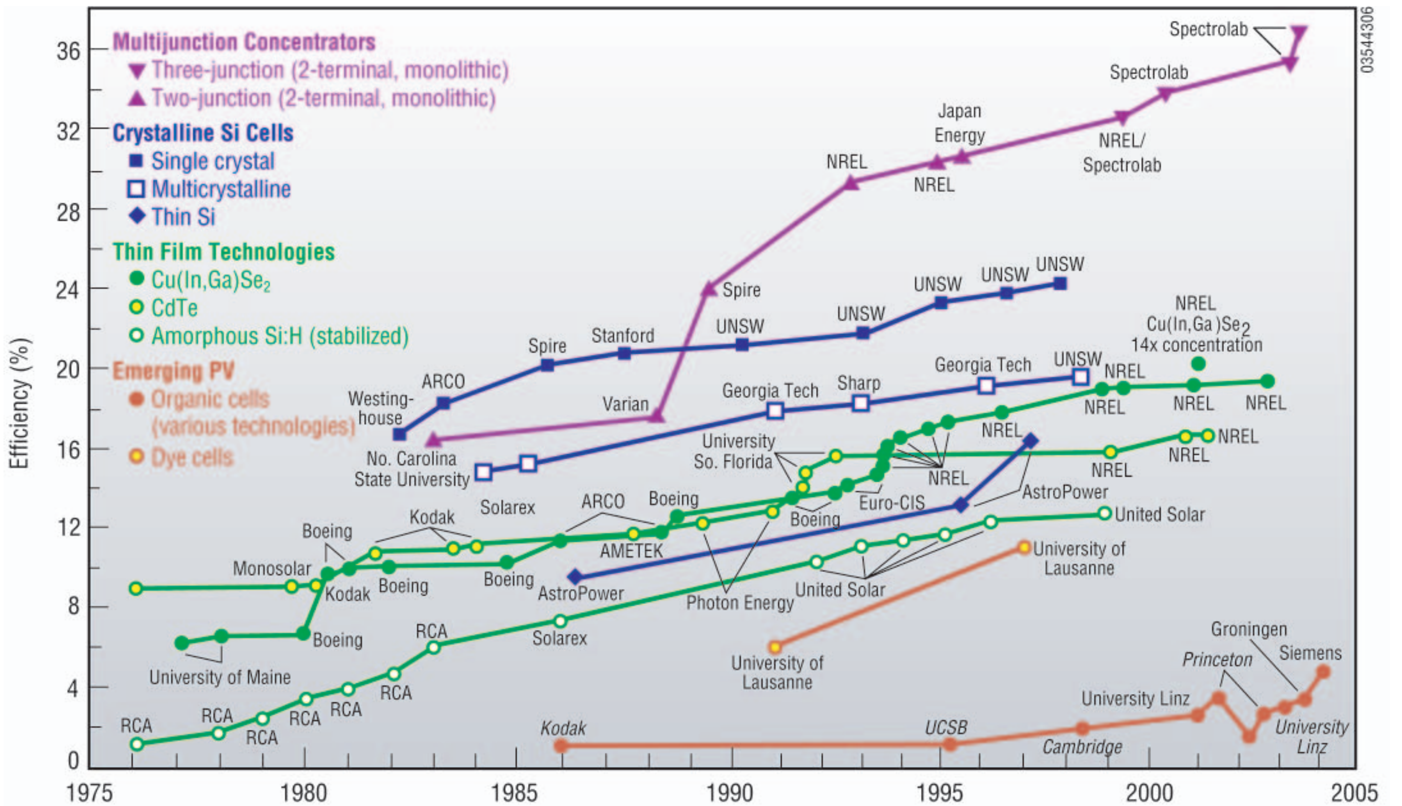
An NREL research team holds the world efficiency record for a cadmium telluride PV cell. Innovations include a CdSn transparent conducting oxide layer (for superior conductivity, strong optical transmittance, and a smoother surface) and a ZnSn buffer layer (for improved performance and reproducibility). Shown above are Xuanzhi Wu (left) and James Keane.

This effort to explore unconventional ideas for converting sunlight into electricity has met and exceeded its overall goals and objectives by identifying a number of very promising new approaches to solar cells. Results have been presented at two conferences sponsored by DOE and NREL in FYs 2002 and 2003, Future Generation Photovoltaics and Photovoltaics for the 21st Century II. At these conferences, international experts and the DOE contractors presented research on new materials or processes for generating electricity from the sun. Peer reviews of research results ensured high-quality contract performance.

The approaches explored under basic and university research include high-efficiency concepts for which costs need to be reduced—or low-cost concepts for which efficiency needs to be increased. Projects have also contributed to some of the more mature technologies in the PV Subprogram. For example, several universities have worked to understand the Staebler-Wronski effect in amorphous silicon and develop ways to ameliorate it. Three projects explored innovative deposition techniques that can be used for thin-film PV modules, and at least one subcontractor may bring its idea to commercial reality through subcontracts in other parts of the subprogram such as PV Manufacturing R&D.

Organic and Nanotechnology Solar Cells

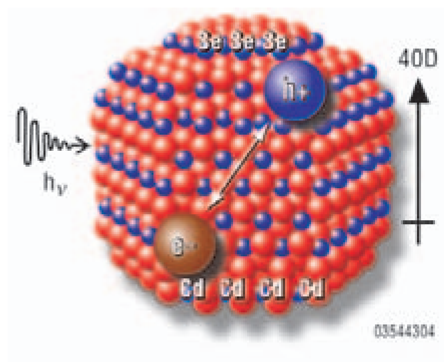
One approach addressed by six DOE-funded projects explores using organic semiconductors in solar cell technology. Organic semiconductors, recognized in the 2000 Nobel Prize for Chemistry, hold promise as building blocks for organic electronics, displays, and solar cells. In conventional PV technologies (silicon and thin-film materials), light creates separated electrons and holes that are swept away by an internal electric field produced by a p-n semiconductor junction. In an organic solar cell, light creates a bound electron-hole pair called an exciton, which separates into an electron on one side and a hole on the other side of a material interface within the device.



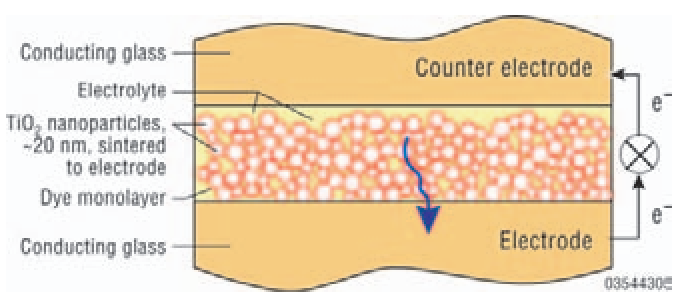
This graph of measured solar cell efficiencies reflects the significant progress that has been made in fabricating devices from 1975 to the present.

One result of this different process is that organic solar cells can be about 10 times thinner than thin-film solar cells, which are themselves about 100 times thinner than crystalline-silicon solar cells. Organic solar cells could be manufactured in a process something like printing or spraying the materials onto a roll of plastic. Consequently, organic solar cells could lower costs in three ways—low-cost materials, reduced material use, and high-volume production techniques.

The PV Subprogram has funded work on organic solar cells at a variety of universities, including early efforts at the University of California at Berkeley and Vanderbilt University for quantum dots (a nanotechnology) embedded in an organic polymer. Later projects included work on heterojunction small-molecule solar cells at Princeton University, liquid-crystal (small-molecule) cells at the University of Arizona, polymer cells at the University of California Santa Cruz and NREL, and small-molecule chromophore cells at Johns Hopkins and North Carolina State University. Work will be completed in FY 2004 with the goal of increasing the efficiency of organic solar cells to 4%. New efforts are planned to begin in 2004 to increase the efficiency from 4% to 7.5% by 2007.



Researchers at Vanderbilt University are investigating PV photosystems based on semiconducting nanocrystals. The size-tunable bandgap, large absorption coefficient, intrinsic electron-hole-pair separation, long exciton lifetime, and chemical robustness make these nanocrystals an ideal PV material.



A schematic of a dye-sensitized solar cell, which uses nanoparticles of titanium dioxide as the semiconductor, is shown above. A group from the California Institute of Technology is working on an all-solid-state device to overcome problems associated with a liquid electrolyte.

Nanotechnology for PV is exciting because the optical and electronic properties of the materials can be tuned by controlling particle size. This novel class of semiconductor material, including quantum dots, lies between the single-atom and solid-state forms of matter. Nanostructured solar cells are likely to be extremely thin because they are also excitonic. They may be easy to manufacture when the nanoparticles are produced by means of chemical solution.

Dye-Sensitized Solar Cells

Dye-sensitized solar cells have foundations in photochemistry rather than in the solid-state physics that support research in today's silicon or thin-film solar cells. In these simple cells, titanium dioxide (TiO_2) serves as a porous matrix holding organic dye molecules. The dyes are sensitive to the solar spectrum and after the dye absorbs photons, electrons are injected into the TiO_2. Dye-sensitized solar cells are extremely attractive because of their near 11% conversion efficiency and the low cost of the constituent materials; TiO_2 is a common material used in paints and toothpaste. In addition, the manufacturing process could be quite simple compared to other PV technologies. At the Photovoltaics for the 21st Century II conference, more than a dozen experts favorably assessed progress on this technology by the DOE Solar Program. Work on dye-sensitized solar cells will continue at NREL and at selected universities in 2004.

A direct result of work supported by the PV Subprogram is the commercialization effort of a new U.S. company, Konarka. Having gathered investor support, the company began developing the dye-sensitized solar cell technology for use on flexible substrates in 2003. Work supported by DOE in 2004 at several universities will help Konarka by increasing the understanding of transparent conducting coatings for their cells and exploring a new version of their dye cell that has an organic electrolyte.

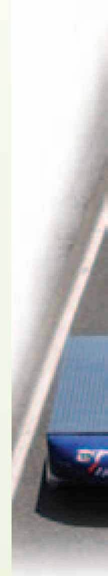
The Solar Program Inspires Our Youth

Continued progress in basic research and technology development demands a good supply of talented new scientists coming from our universities. To provide research experience and to spark the interest of talented students, the Solar Program helps sponsor several projects for undergraduate and graduate students in the field of solar energy. The most visible of these projects was the 2002 Solar Decathlon, a challenging competition for college student teams to design, build, and operate a small home powered only by solar energy systems. Students in many academic disciplines worked together on each team to bring their houses to the competition on the National Mall in Washington, D.C. All of the houses in this Solar Village showcased the latest energy-saving products, advanced building techniques, and renewable building materials. All houses used both photovoltaic and solar thermal technologies. Plans for the next Solar Decathlon, to be held in the fall of 2005, are under way, with 19 teams selected and briefed on the contest procedures.

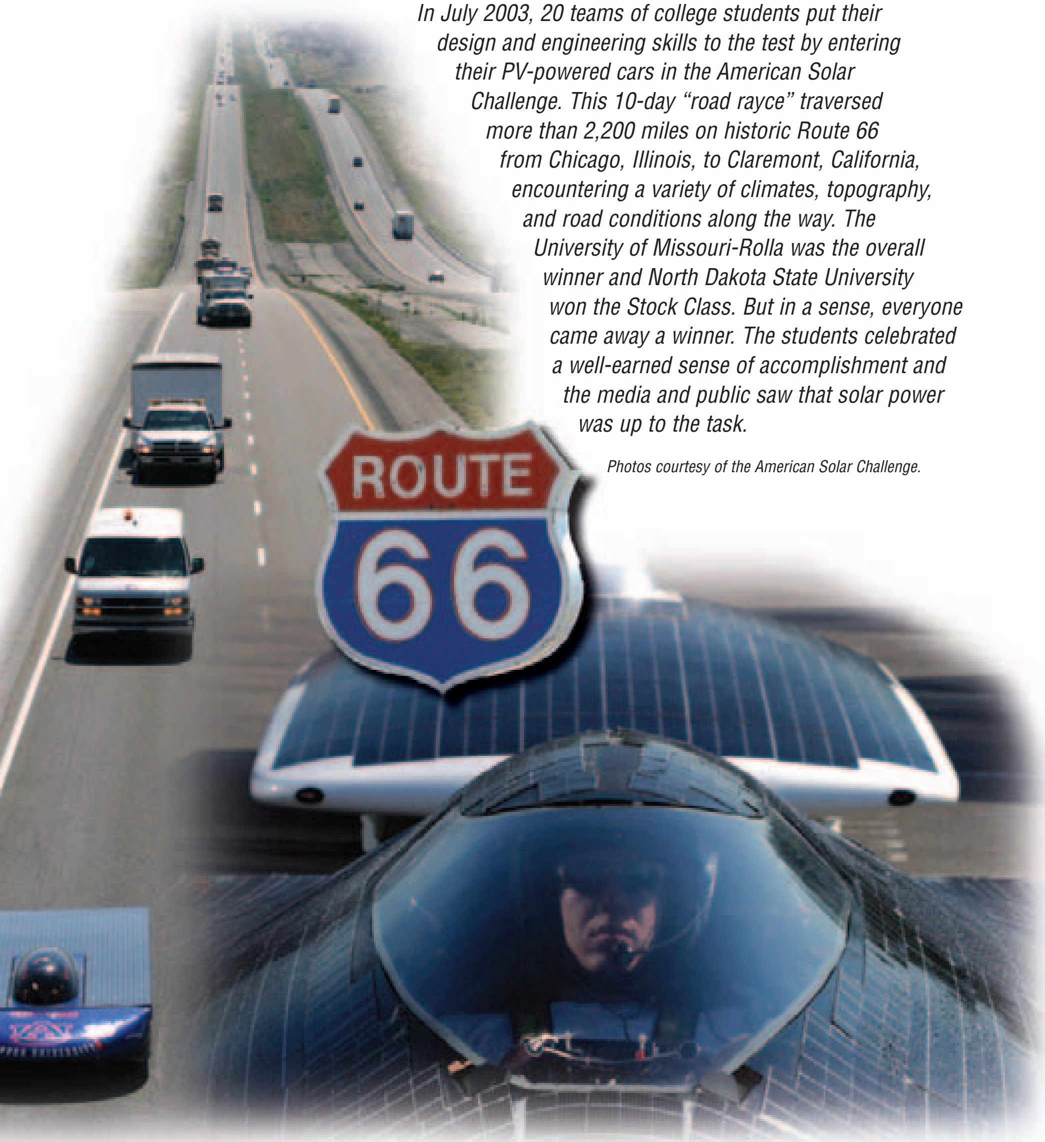
Once again, in the summer of 2003, the nation was intrigued by the American Solar Challenge, an intercollegiate competition to design, build, and race solar-powered cars across the United States. NCPV staff has helped organize this biennial competition since its inception in 1990.

Another important project to encourage students to study solar energy is the DOE-NREL HBCU (Historically Black Colleges and Universities) Photovoltaic Research Associates Program, which includes the Renewable Energy Academic Partnership (REAP). Begun in 1995, this program reached out to students in colleges with large populations of minority students, who are typically underrepresented within science careers. A variety of research projects in PV have been funded at these schools, many of them linked to different parts of the Solar Program. The annual REAP Conference in 2003 featured presentations on the most recent research projects of these students and their professors. Twelve students from these schools worked on a variety of PV projects at NREL as summer interns in 2003. In FY 2003, the Minority University Research Associates (MURA) program was announced to more than 250 minority-serving institutions. This is a successor to, and expansion of, the HBCU Program and will run through 2004 and beyond.

The projects of the Solar Energy Technologies Program further benefit students through the efforts of the national laboratories, including NREL, Sandia, and ORNL. These organizations all have agreements with universities to employ students on research projects funded by DOE and others.



The measurements and characterization activity cuts across all strata of the PV Subprogram from basic R&D to module and system performance to solar resource assessment and characterization of materials and devices.



In July 2003, 20 teams of college students put their design and engineering skills to the test by entering their PV-powered cars in the American Solar Challenge. This 10-day "road rayce" traversed more than 2,200 miles on historic Route 66 from Chicago, Illinois, to Claremont, California, encountering a variety of climates, topography, and road conditions along the way. The University of Missouri-Rolla was the overall winner and North Dakota State University won the Stock Class. But in a sense, everyone came away a winner. The students celebrated a well-earned sense of accomplishment and the media and public saw that solar power was up to the task.

Photos courtesy of the American Solar Challenge.

Third-Generation Solar Cells

Researchers around the world are looking for ideas with the potential of converting solar energy into electricity with efficiencies between 60% and 85%. Referred to as "third-generation PV" by Martin Green, who developed the highest-efficiency crystalline silicon solar cells in the 1980s, many of these ideas have been around for decades but lacked enabling technologies to move beyond theory. For example, the idea of a multijunction solar cell that is sensitive to several different colors of the solar spectrum was made possible years after its inception by a technology breakthrough in the 1980s. The resulting high-efficiency III-V solar cells (referring to elements in groups III and V of the periodic table) have demonstrated efficiencies today approaching 37%.

The PV Subprogram has been contributing to this search by funding universities to conduct fundamental and exploratory research to bring theories closer to the reality of materials and devices that can be tested in the laboratory. One success story has been the work of several universities to explore new III-V compounds (particularly GaInNAs as a potential third-junction material) for even higher four-junction solar cell efficiencies.

Several of these projects explored fabricating multijunction III-V solar cells on cheaper substrates. Successes of this work were continued by other elements of the PV Subprogram, such as the High-Performance PV Project (see page 10). In 2004, a new university project will explore a different third-generation concept for getting multiple charge carriers per photon, this time in an organic solar cell.

In FY 2003, a request for research proposals from universities under the Future Generation PV Project attracted an exciting group of proposals for research into high-efficiency organic solar cells, third-generation concepts, high-efficiency III-V solar cells on low-cost substrates, and innovative crystalline silicon concepts. Some of this work may begin in FY 2004.

MEASUREMENTS AND CHARACTERIZATION: TRACKING OUR PROGRESS

Every activity of the PV Subprogram relies to some extent on the resources of the NCPV measurements and characterization effort at our national laboratories—NREL, Sandia, and BNL. These measurements and characterization teams help researchers measure progress and better understand the behavior of materials and devices. Measurements include electro-optical characterization, microscopy, surface analysis, and more. The teams also develop and implement new and specialized measurement techniques, allowing researchers to test and analyze thousands of materials and device samples each year. This effort also helps devise diagnostic tools to advance manufacturing R&D.

The measurements and characterization activity cuts across all strata of the PV Subprogram from basic R&D to module and system performance to solar resource assessment and characterization of materials and devices. In FY 2003 alone, the NCPV measurements and characterization effort provided support to more than 70 participants in industry, universities, and national laboratories.

High-Performance PV: Record efficiencies, lower costs, and new prototypes

The High-Performance PV Project explores the ultimate performance limits of existing PV technologies, seeking to nearly double 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 precommercial multijunction concentrator modules able to convert more than one-third of the sun's energy to electricity.

High-performance PV with concentrators is being developed for markets at least 10 years in the future. One attraction is the possibility of generating low-cost electricity by using small, highly efficient solar cells with large, inexpensive concentrating lenses or mirrors. The PV Subprogram awarded 2-year subcontracts under the High Performance PV Project, "Identifying Critical Pathways," in FY 2001. These contracts to university and industry contractors complemented work by NCPV in-house scientists in the areas of thin-film multijunction cells and high-efficiency III-V multijunction cells.

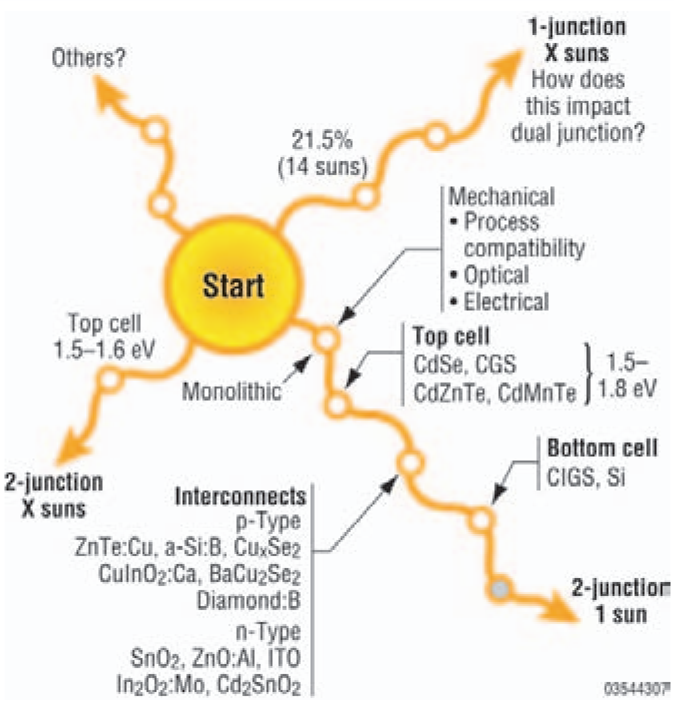
Multijunction solar cells achieve higher efficiencies by using a broader portion of the solar spectrum and by achieving more efficient conversion of individual photons. Therefore, research is aimed at improving materials and processes to maximize performance and offer low-cost manufacturing potential.

The Science and Technology Facility

From Atoms and Molecules to Processes and Products

In current research programs, resources to conduct fundamental research, applied research, prototype manufacturing, and full-scale manufacturing are separated, both physically and organizationally. This arrangement has limited the rapid movement of research technology and relevant intellectual property from R&D to U.S. industry. The planned Science and Technology Facility is designed to speed the transition from fundamental R&D to full-scale manufacturing by adding laboratories for process-integration research, diagnostic development, and process simulation right next to existing research capabilities of the Solar Energy Research Facility at NREL. After construction in FY 2006, the new laboratories will be used for work on PV, energy sensors, and energy storage. However, the flexible design of the facility means that laboratories can be converted quickly and at minimal cost to conduct R&D in new areas, as required by the U.S. energy research programs.

Moving toward the goal of higher efficiencies, the new world-record conversion efficiency (36.9% at up to 600 suns concentration) was achieved under a High-Performance PV subcontract by Spectrolab, Inc. This result builds on the NREL-patented two-junction device licensed to Spectrolab. The company modified the two-junction device into a triple-junction solar cell. The champion cell, measuring about one-quarter of a square centimeter in area, was fabricated and tested at Spectrolab and then measured at NREL under standard reporting conditions. Adding another junction (the third of four junctions) to this device using material with a bandgap of 1 electron volt (eV) would raise the theoretical efficiency to 50%. Cells such as these could dramatically reduce the cost of generating



Subcontracts issued under the new solicitation, "Exploring and Accelerating Pathways Toward High-Performance PV," investigate these pathways to high efficiency for thin-film polycrystalline tandem cells.

electricity from solar energy. Another High-Performance PV subcontractor, Amonix, Inc., is working to integrate these high-efficiency cells into a Fresnel-lens-based, high-concentration module.

A promising approach to increasing efficiency and lowering the cost of solar cells made from polycrystalline thin films involves combining materials in monolithic two-terminal tandem cells. Researchers at the NCPV demonstrated a prototype tandem arrangement using Si as the bottom absorber and $CuGaSe_2$ (CGS) as the top-cell absorber. The CGS top cell was grown by elemental evaporation following the NREL-patented 3-stage process. The interconnect junction consisted of an n^+ interconnect transparent oxide, and initial measurement showed excellent voltage addition of about 1.3 V and efficiency of about 5.1%. With an improved CGS top cell, the next research step will examine an all-thin-film polycrystalline Si/CGS tandem combination that could offer a viable route to a low-cost, high-voltage cell.

Obtaining high-bandgap top-cell materials is critical to the development of tandem PV cells. The Institute of Energy Conversion at the University of Delaware developed one such potential top cell based on CIGS, with the best performance obtained for low-S and high-Ga contents. Cells were tested with an anti-relective coating at NREL and were >10% efficient.

In FY 2003, the PV Subprogram made 3-year subcontract awards under the High-Performance PV Project, "Exploring and Accelerating Pathways Toward High-Performance PV." Forty-six letters of interest were received, and from these, 14 organizations including universities and companies began work in FY 2004. Seven of the subcontracts involve polycrystalline thin-film tandem cells, and the other seven concern III-V multijunction concentrators.

CRYSTALLINE SILICON: INSIGHTS, NEW PROCESSES, AND ENHANCED ANALYTICAL TOOLS

Crystalline silicon, the first material used to make commercial solar electric devices, is still used in nearly 90% of the PV systems being installed today. Nevertheless, there is much more to learn about the basic science of silicon as it relates to solar cells. In keeping with the PV Subprogram strategy of peer review and developing a coordinated research approach, about 40 scientists from universities, NCPV, and industry perform shared research important to the future of this technology. These researchers explore defects and structures of electronic materials and devices to discover ways to increase efficiencies and to validate novel processing techniques. They also apply material and device processing science to develop new tools for deposition, processing, and characterization of electronic materials.

In 2003, three universities, NREL, and representatives from the PV industry joined the National Science Foundation Silicon Wafer Engineering and Defect Science (SiWEDS) consortium. Originally created for the integrated-circuit industry to conduct exploratory research into crystalline silicon, SiWEDS is generating information on research topics that are also relevant to the PV industry.

GEORGIA INSTITUTE OF TECHNOLOGY—CENTER OF EXCELLENCE

The DOE-funded University Center of Excellence in Photovoltaics at the Georgia Institute of Technology has contributed to the understanding of silicon-based solar electric cells since 1992. The faculty and students at Georgia Tech have fabricated devices that set several world records for conversion efficiencies. In addition, Georgia Tech works with industry to improve manufacturing techniques. For example, the rapid thermal processing methods they pioneered are faster than conventional furnace diffusion and oxidation of silicon wafers by a factor of five or more.

Crystalline Silicon University Research Project

To integrate industry research needs with the expertise at our leading research universities, the PV Subprogram initiated the Crystalline Silicon University Research Project in 2001 to involve university teams in topics of concern to the PV industry. Subcontracts were awarded to seven universities; they included collaboration with industry wherever appropriate. The contractors formed teams to explore four topics identified by industry: mechanical strength and yield; the production of better materials; hydrogen passivation and silicon nitride coatings; and contacts and selective emitters.

As part of the PV Subprogram's results-oriented approach, a review panel was convened to assess the impact of these university/industry collaborations after the first two years of effort in 2003. With one year left on most of these projects, the review panel applauded the work so far as providing necessary tools, analysis, and diagnostics that are very relevant to industrial concerns. Six of the nine reviewers were from the PV industry.

Facilitating exchange of research results, DOE sponsored the 13th Workshop on Silicon Solar Cell Materials and Processes in 2003. More than 100 scientists and engineers from around the world attended the conference, including representatives from 22 companies and 22 research institutions. Presentations and discussion sessions addressed crystal growth, new cell structures, new processes and process characterization techniques, and cell-fabrication approaches suitable for future manufacturing demands. Ongoing collaborations such as these are crucial to the design and conduct of the DOE PV Subprogram.

A major objective of the PV Subprogram is to move research procedures and tools to industry as quickly as possible. A prime example of the effective use of the patent, license, and technical-assistance strategy of the program is the transfer of the PV Reflectometer. This reflectometer, developed and patented at NREL, measures surface roughness, thickness of antireflective coatings, fraction and height of metallization, wafer thickness, and reflectance of back surfaces in less than one second without ever touching the materials. An equipment manufacturer, GT Solar Technologies, has licensed the PV Reflectometer and plans to commercialize the technology, which is perfectly suited for the characterization of photovoltaic materials and finished solar cells in a production-line environment.

Another tool developed in the PV Subprogram and licensed to GT Solar Technologies is PVSCAN (photovoltaic scanner), a high-speed, optical scanning system designed for the characterization of PV materials and finished solar cells. This tool won an R&D 100 award in 2001 from *R&D Magazine* as one of the 100 best R&D advances for the year. GT Solar Technologies will market PVSCAN to help crystal growers achieve a high-quality (low defect density) material. The tool can also help solar cell process engineers develop fabrication processes for higher-efficiency devices.

Additional Achievements in Photovoltaics R&D

Organization	Achievement	Significance
NREL	Completed experiments using combinatorial materials science	Rapid exploration of materials for device structures
NREL	Identified signature for minority-carrier lifetime defect in GaInNAs	Possible third junction in a four-junction device aimed at 40% efficiency goal
Rutgers University/ NREL	Detected novel properties in ZnTe/tetracene structure	Hybrid organic-inorganic superlattice could be useful in solar cells and LED devices
University of Toledo	Used ZnO to fabricate a 14%-efficient, all-sputtered CdS/CdTe cell	Major improvement in efficiency; sputtering technique could expand the range of material options for tandem cells
Unisun	Developed a process for non-vacuum transparent conducting coating	Complements a complete nonvacuum CIGS solar cell process cofunded by California Energy Commission
NREL	Demonstrated a mechanical stack with CGS on CIS, 9.5% efficiency	Highest efficiency for this structure
Princeton University	Achieved 3.6% organic solar cell and published results in *Nature*	Higher efficiency is critical to the future of organic solar cells
Ohio State University	Developed a SiGe buffer layer on Si substrate	Permits deposition of III-V solar cells on low-cost Si
NREL	Identified a hole barrier preventing recombination at CIGS grain boundaries	Explained why polycrystalline CIGS works better than single-crystal material
Sandia	Developed and patented maskless plasma texturing using reactive ion etching for multicrystalline silicon cells	Increases cell performance over untextured or planar and wet-textured cells by up to 6%

PV Advanced Materials and Devices

Once record conversion efficiency is achieved in the laboratory, the next step is to explore how this improved material or device can be produced outside of the laboratory. Taking technology from the laboratory to the production line falls under the Advanced Materials and Devices element of the PV Subprogram.

Thin Films: Higher efficiencies, recycling, new national team

Making PV devices by applying thin layers of semiconductor material to an inexpensive substrate holds great promise for reaching the long-term goal of cost-competitive electricity from PV. Over the past decade, the work of scientists at the NCPV in collaboration with universities and industry in the Thin Film PV Partnership has steadily driven up the efficiency of thin-film devices. Better still, this thin-film PV technology has recently entered the marketplace.

However, to reach our cost goals, issues remain of increasing device efficiencies, increasing module reliability, and developing deposition and manufacturing capabilities for large-scale production. The PV Subprogram has focused the efforts of the Thin Film PV Partnership, the NCPV, and the national teams on these issues for four of the most promising thin-film technologies—copper indium diselenide, cadmium telluride, amorphous silicon, and thin-film silicon. An additional national team was started in 2002 to address thin-film module reliability issues.

Copper Indium Diselenide (CIS)

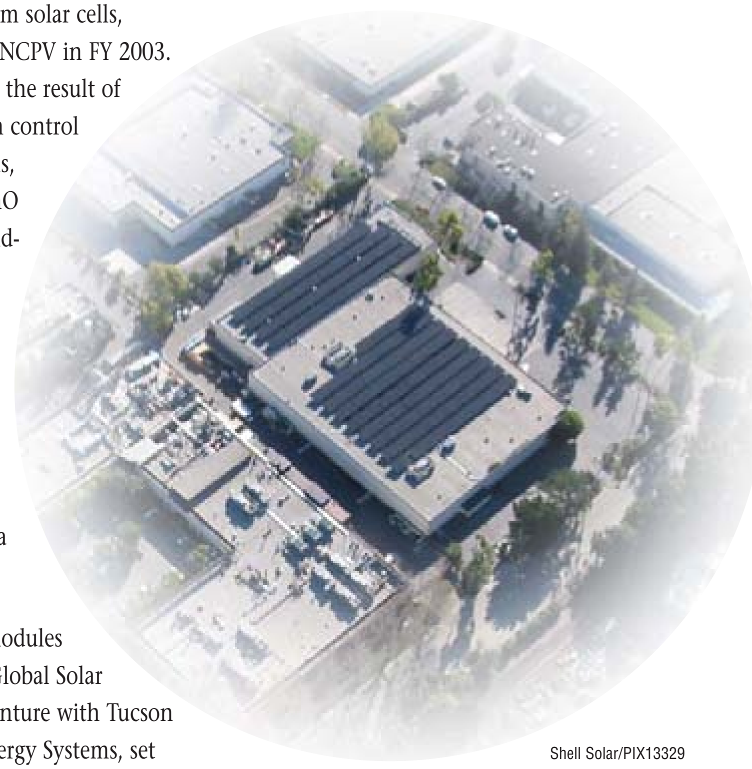
Copper indium diselenide thin-film manufacturing benefits from economies of scale, technology improvements, and having fewer special handling requirements than the process for making PV modules from silicon. For these reasons, CIS may one day undercut the cost of production for silicon PV. Achieving higher efficiencies for thin-film solar cells and translating these results to large-scale production of modules is a major planning goal of the PV Subprogram.

In FY 2003, Shell Solar Industries achieved two major planning goals as part of its subcontract with the Thin Film PV Partnership. While doubling production capacity from one to two MW, the company also achieved a new world-record efficiency for a thin-film CIS-based module. The 46.5-W power module measuring 4 ft^2 (3626 cm^2) was 12.8% efficient as verified at NREL. Optimizing each layer of the module and improving fabrication processes resulted in this record efficiency for a monolithically integrated thin-film module.

Higher efficiencies and lower costs for CIS with added gallium (CIGS) are possible with a fabrication technique called evaporation. Using this technique, a new world-record efficiency for CIGS thin-film solar cells, 19.2%, was verified at the NCPV in FY 2003. The improved efficiency is the result of mastering the composition control and uniformity of the films, improving the CdS and ZnO processes, engineering bandgap at the absorber interfaces, and improving antireflective coating and grids. The improved efficiency is the latest result of careful and rigorous research by the NCPV CIS National Team to achieve a major planning goal.

Lightweight, flexible PV modules have many applications. Global Solar Energy (GSE), in a joint venture with Tucson Electric Power and ITN Energy Systems, set a record in 2003 by delivering a module to NREL that tested at a record 9.2% efficiency. This met a major milestone of the Solar Program to move toward more-efficient devices for this application. The device structure is ITO/CdS/CIGS/Mo/SS, and the CIGS is deposited by the physical vapor deposition method. GSE supplies these lightweight, flexible solar power packs to the U.S. Army and the Marine Corps.

In some cell designs, a layer of cadmium has contributed to the efficiency, but another goal of the program is to develop high-efficiency cells that do not include cadmium. The CdS window layer also limits the current that can be collected in the solar cell. In 2003, NREL researchers fabricated a cadmium-free CIGS device with a record measured efficiency of 18.6%. This work was conducted in collaboration with Aoyama Gakuin University in Japan. Future work with industrial partners will translate this important result to large-scale U.S. production of more-efficient modules.



Shell Solar/PIX13329

Shell Solar installed this 245-kW thin-film CIS PV system on its factory in Camarillo, California. The average aperture-area efficiency of the modules is between 11% and 11.5%.

Cadmium Telluride (CdTe)

Cadmium telluride thin-film material has the advantage of a bandgap that is well matched to the solar spectrum and a high absorption coefficient such that even one micron of the absorber film is sufficient for solar cell fabrication. Several U.S. manufacturers have applied the development work performed in collaboration with the PV Subprogram to the manufacture and sale of products using this technology.

A key challenge for industry is to develop and implement manufacturing techniques for this promising material. The PV Subprogram and a subcontractor, First Solar, Inc., were recognized for achievement in this area by *R&D Magazine*, which presented the prestigious R&D 100 award to the team as one of the top 100 R&D achievements of the year.

The award was for the continuous-feed, automatic, nonstop production line for manufacturing CdTe PV modules developed by First Solar (Toledo, OH) with funding from the Thin Film PV Partnership. This is the 18th R&D 100 award associated with the PV Subprogram over the years. In addition to receiving the award, First Solar has applied results of its research subcontract, "High-Rate Vapor Transport Deposition for CdTe PV Modules," awarded by the Thin Film PV Partnership to reduce the price of its product by 30%. Such cost reduction of commercial modules is an important milestone for the PV Subprogram.

Jim Yost/PIX13218

First Solar, Inc., and NREL, through the Thin Film PV Partnership, earned an R&D 100 award in 2003 for a faster, less costly process for manufacturing CdTe PV modules. Shown above (from right) are Ken Zweibel, a project leader who manages the Thin Film PV Partnership along with Harin Ullal and Bolko von Roedern.

Tucson Electric Power/PIX13327

Tucson Electric Power's 3.4-MW Springerville solar field is the fourth largest installation of PV modules in the world. Using $6 million per year from a provision of Arizona's Environmental Portfolio Standard (which requires utilities to install more renewable energy systems such as solar), Tucson Electric buys PV systems made of crystalline silicon and promising thin-film technologies. In addition to generating electricity, the Springerville solar field also serves as a useful laboratory for identifying ways to improve thin-film module design.

A new approach to improved manufacturing and lower cost has been developed at NREL to prepare CdTe cells on low-cost commercial soda-lime glass/SnO_2 substrate. The best cell so far had an efficiency of 14.4%. The new process takes advantage of two patented films. The NREL team has begun collaboration with First Solar to demonstrate the new process in a manufacturing setting.

Licensing and technical assistance will follow if the process is adopted for production of CdTe modules.

Recognizing the challenges presented by the routine use of cadmium, the PV Subprogram has invested considerable resources and worked with BNL to develop safe procedures and information for decision makers about handling cadmium for solar cells. In 2003, this information was consolidated in a new Web site, *Cadmium Use in Photovoltaics* (*www.nrel.gov/cdte*), which serves as a clearinghouse and forum for discussing related environmental issues.

The PV Subprogram recognizes that recycling materials is an important way to increase the environmental benefits of PV. With technical assistance from the subprogram, First Solar, the largest producer of cadmium telluride PV modules, now recycles all of its cadmium manufacturing waste at its Perrysburg, Ohio, plant, including modules that do not meet product specifications. With assistance from DOE, BNL, and NREL, the company adopted an aggressive approach to cadmium handling, which minimizes all aspects of exposure and any related environmental, safety, and health issues. Much of the waste cadmium is reused in the manufacture of NiCd batteries. Recycling is cheaper than disposal at a hazardous waste site.

Amorphous Silicon (a-Si)

Amorphous silicon PV modules accounted for about 10% of the PV market in 2003. Commercial modules of a-Si average about 7% efficiency, yet they are competitive with crystalline silicon modules in some applications because of lower manufacturing costs. One way to reduce the cost of electricity for a-Si modules is to increase cell and module efficiency; another is to increase deposition rates of PV materials during manufacture.

These ways to reduce costs could result from effective research in nanocrystalline materials. Prior to 2002, nanocrystalline solar cell device work was making news in Germany, Switzerland, and Japan. In 2002, the a-Si Thin Film National Team added thin-film silicon activities to its agenda. By the close of 2003, many devices had been tested in the United States, and efficiencies matching those achieved abroad were reported.

Institute of Energy Conversion—Center of Excellence

The Institute of Energy Conversion (IEC), University of Delaware, has been a DOE University Center of Excellence in Thin Films since 1992. IEC continues to provide cutting-edge equipment and expertise to the PV research and development community. For example, in 2003 researchers contributed to achieving a key milestone of the High-Performance PV Project by developing a potential wide-bandgap cell based on $Cu(InGa)(SeS)_2$; the best performance was obtained with low-S and high-Ga content. Cells were tested with an antireflective coating at NREL and were greater than 10% efficient, an important milestone for the PV Subprogram. IEC will continue its work under the next phase of the High-Performance PV Project on research to develop a wide-bandgap solar cell in the thin-film tandem structure. This has been identified as the single most critical issue for developing very high efficiency thin-film tandem solar cells as a follow-on to today's single-junction thin-film PV. IEC's best CIG-alloy cell has a verified efficiency of 17%. In addition to such efforts to increase cell efficiencies, IEC will support other subcontractors by preparing and providing CIGS films and devices for testing and characterization.


FSEC/PIX13334

The outdoor test facility at the Florida Solar Energy Center provides valuable data to the Solar Program about PV array and system performance under hot and humid operating conditions.

The most recent research results were reported at the 16th meeting of the Amorphous Silicon/Thin Film Silicon National Team. The first day was devoted to thin-film Si solar cells, which often feature nanocrystalline Si made by low-temperature deposition using techniques developed for a-Si. One company, United Solar, incorporated nanocrystalline cells into multijunction structures that have an a-Si top and a nanocrystalline bottom. These cells achieved initial efficiencies up to 13%.

Another company, MVSystems, reported nanocrystalline thin-film Si cells that were 7% to 9% efficient using plasma-enhanced vapor deposition, which holds the promise of increased deposition rates without reductions in material quality.

For several years now, another approach to high deposition rates, hot-wire chemical vapor deposition (CVD), has been developed and applied at NREL and the Institute of Energy Conversion (IEC) at the University of Delaware. This rapidly maturing technology was the focus of the Second International Conference on Hot-Wire CVD hosted by NREL in 2003. More than 100 scientists from around the world exchanged detailed information on processes and discussed solutions to deposition-related processing issues. The highlights of this technology continue to be deposition at high rates and at a temperature that does not damage substrates.

In other work on a-Si, the University of Toledo achieved a cell with 10.4% stabilized efficiency using a new p-layer with a single-junction a-SiGe cell. Researchers there also measured an a-Si/a-SiGe tandem cell with 12.5% initial efficiency.

Module reliability has been identified as an important research issue by the thin-film national teams. As a result, a new team was assembled in 2002 to discuss and propose research in this area. The Thin-Film Module Reliability National Team with about 60 members had met three times by the close of 2003. On recommendations of the national team, the Thin Film PV Partnership shifted some of its FY 2004 funding toward resolving module-level reliability issues. For example, two contracts were awarded for outdoor testing and monitoring of new thin-film module technologies in hot and humid climates to identify and fix durability issues before the modules are commercialized on a large scale. All major U.S. companies manufacturing thin-film modules supplied modules with their most advanced packaging designs for testing. The results of these tests will help guide any product revisions to improve reliability.

PV Manufacturing Research and Development

Since Congressional funding for the PV Manufacturing R&D Project began in 1991, the DOE PV Subprogram has conducted R&D projects in partnership with the U.S. PV industry. Over this period, the PV Manufacturing R&D Project has issued seven solicitations for partnerships that have resulted in more than 50 subcontracts, including 10 that were active at the close of FY 2003. Between 1992 and 2002, these cost-shared R&D projects have increased production capacity among the 15 U.S. participants more than 16-fold and have reduced the direct manufacturing cost of PV modules for participants by more than 55%.

By comparing customer savings to the government investment and comparing manufacturer savings to their cost-share investment, an analysis of the PV Manufacturing R&D Project showed that these investments have more than paid for themselves by reducing costs to consumers and expanding the U.S. industrial base. In fact, according to an analysis of data submitted by participants, the recapture of the public's investment in this research by the close of 2002 stood at 355% since the project's inception.


PowerLight Corporation/PIX12398

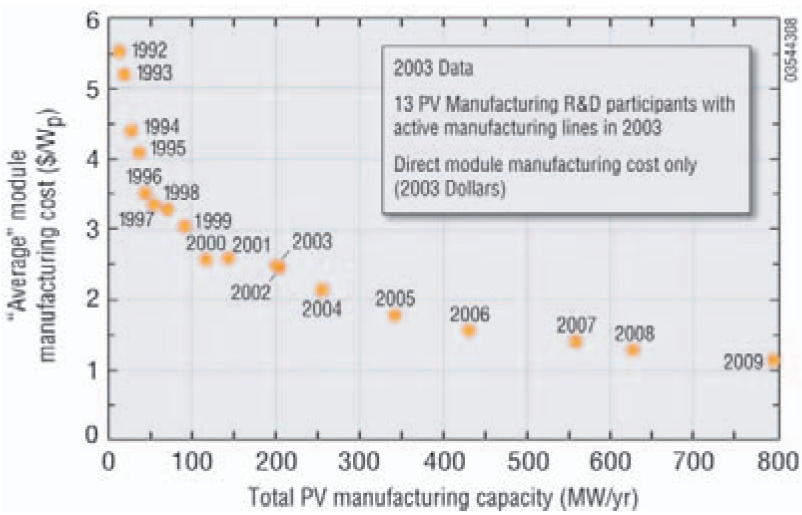
PowerLight Corporation installed the largest roof-mounted system in the United States, nearly 1.2 MW in size, at the Santa Rita jail in California. The system comprises mainly crystalline silicon modules, which are tied to the electric grid through four large inverters. This large system uses several different module materials and thus provides an excellent opportunity to compare the long-term reliability of different PV technologies. NCPV engineers collected baseline performance data on all 12,244 PV modules soon after installation.

The U.S.-based PV industry is planning for a domestic industry that can meet a significant portion of the nation's electricity needs. In 2001, the first *U.S. Photovoltaic Industry Roadmap* set a goal to scale up U.S. PV manufacturing capacity to 7 gigawatts by 2020. Manufacturing capacity in 2002 was 270 MW, so making this goal a reality will demand continued investment in manufacturing R&D.

The PV Subprogram's continued manufacturing R&D will help make the national goal of plentiful, low-cost PV a reality. The latest procurement is focused on increasing yield, durability, and reliability and will further reduce costs and improve manufacturing processes so that increased capacity will follow. The PV Manufacturing R&D Project issues competitive, cost-shared contracts to individual manufacturers for research that builds on their own unique approaches to manufacturing. Projects address promising PV technologies and include research on crystalline silicon, thin-film devices, and concentrator technologies. Research is conducted to increase module reliability and to improve integration, manufacturing, and assembly of systems; balance-of-systems components; packaging of systems and system components; and methods for quality control and storage of components.

At the close of FY 2003, major technical progress was reported on the first phase of contracts awarded for the solicitation, *In-Line Diagnostics and Intelligent Processing*, which is aimed at larger and more accelerated scale-up of manufacturing, as well as the other objectives of the PV Manufacturing R&D Project. For contractors to continue through the three phases of their projects, tasks and milestones for each phase must be completed. Some highlights of the Phase I review follow.

Under its subcontract, Energy Conversion Devices explored possible process improvements for a 30-MW amorphous silicon manufacturing facility at lower-tier United Solar



Since 1992, production capacity of participants (13 companies with active manufacturing lines in 2003) in the PV Manufacturing R&D Project has grown from 13 to 201 megawatts. And direct production costs (in 2003 dollars) decreased from $5.47 to $2.49 per peak watt.

Ovonic Corporation. The work developed control, monitoring, and diagnostic systems that allow quality assurance and quality control during production of each of nine layers of the PV device. For example, Energy Conversion Devices developed a closed-loop thickness control system for the deposition of ZnO, ITO, and a-Si layers within the United Solar Ovonic production line. Application of a PV capacitive diagnostic system allowed the measurement of the current-voltage (I-V) characteristics of component cells in the triple-junction device. Improvements in cleaning processes applied to the substrate increased production yield. With these advancements in place, the company will begin Phase II work in FY 2004.

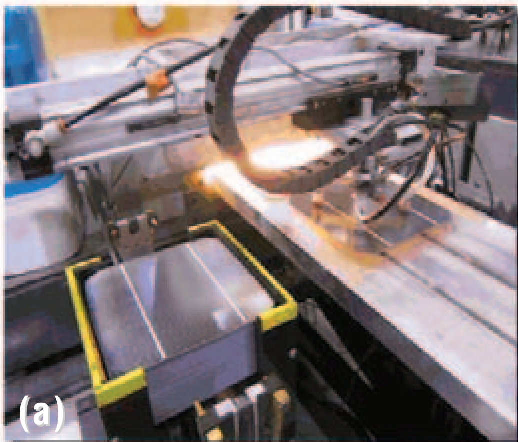
Energy Photovoltaics, Inc., also makes amorphous silicon thin-film PV modules. During its subcontract, the company has increased the stabilized power output of its modules by 10% and reduced the cost of modules by 20%. These results meet or exceed the goals of the subcontract, so the company will begin work on the next phase of the subcontract in FY 2004.

The PV Subprogram's continued manufacturing R&D will help make the national goal of plentiful, low-cost PV a reality.

ITN Energy Systems, Inc., is performing manufacturing R&D to support the CIGS production systems of Global Solar Energy. Under its subcontract, ITN has developed diagnostic tools for use in the processing line at Global Solar Energy to assess the relationship between processing conditions and the properties of the resulting products. Using a combination of in-line sensors and process controls, the company demonstrated process improvements, which increased the uniformity, yield, and throughput of CIGS deposition. For example, the company reduced variability in the thickness of the copper layer by 71%. Manufacturing technology for ultra-thin multicrystalline silicon solar cells is being developed by BP Solar. Under its subcontract, the company increased its ingot size from 250 kg to over 300 kg, which increased yield and reduced casting cycle time by 14%. Material use was improved when the wire saws reduced saw-room losses by 30%. Work continues to develop equipment for demounting and subsequent handling of very thin silicon wafers and to help increase production capacity of the silicon industry for lower-cost solar-grade silicon feedstock.

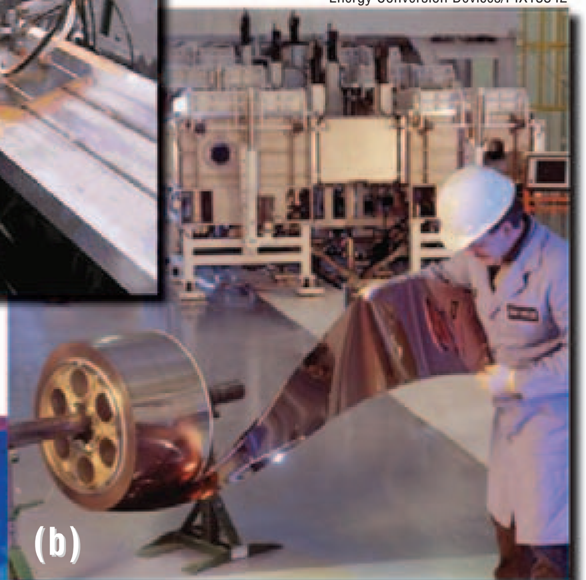
RWE Schott Solar, Inc., cuts wafers from silicon material produced in the unique edge-defined, film-fed growth (EFG) system, which produces a thin-walled octagonal cylinder of crystalline silicon material. The cylinders are 6.5 meters long and have a face width of 10 cm. These faces are cut with lasers to make silicon wafers for manufacturing PV modules. Under its PV Manufacturing R&D Project subcontract, the company completed design and prototypes of a module that replaces a fraction of the solar cells with lower-cost reflecting materials. This reflector-module concept could reduce the cell area required by 40%.

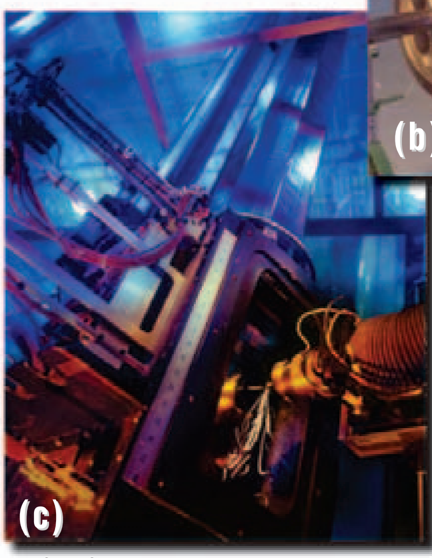
Evergreen Solar has developed an innovative and unique approach to manufacturing crystalline silicon wafers through the string-ribbon growth process. Under its subcontract with the PV Manufacturing R&D Project, the company moved a dual-ribbon growth system, known as Project Gemini, from R&D concept to pilot phase to production. This system produced cells with promising efficiencies, the best measuring 14.6%. One element of the system, a new contact-printing machine, increased yields by 3% and throughput by 70%. Work will continue to demonstrate reliability of the frameless, monolithic modules produced with this material.



AstroPower

Energy Conversion Devices/PIX13342





RWE Schott Solar/PIX13343

PV manufacturing processes in the United States have grown increasingly sophisticated since the PV Manufacturing R&D project commenced in 1991. These photos show (a) AstroPower's production line, (b) amorphous silicon deposition machine, built for United Solar Ovonic by Energy Conversion Devices, and (c) RWE Schott Solar's system for producing octagonal cylinders of crystalline silicon material for slicing into wafers.

PowerLight Corporation incorporates crystalline silicon or thin-film PV components into its PowerGuard® roofing tiles. In FY 2003, the company installed more than 1.5 MW of this product, which provided valuable feedback to the work conducted under a PV Manufacturing R&D Project subcontract. For example, with improvements in overall factory quality control, the company delivered 4,664 tiles to a customer, and all performed at or above specification. One element of this quality control established under the subcontract is testing PV modules before they are integrated into the roofing product. This and other efforts have reduced costs by 18%.

Under a PV Manufacturing R&D Project subcontract, Sinton Consulting, Inc., developed an in-line monitoring tool that measures minority-carrier lifetime during manufacture of single-crystal and polycrystalline wafers and cells. To date, PV manufacturers have purchased six of these WCT-100 tools. The WCT-100 in-line diagnostic equipment measures minority-carrier lifetime as an indicator of cell performance and serves as a quality check. Unacceptable materials are pulled from the manufacturing line before incurring the expense of converting the wafer to a cell, thus substantially increasing cell yield. Early feedback from industry to Sinton Consulting suggests that the equipment saves enough to pay for itself in less than one month.

The materials that encapsulate PV modules to protect them from the outside elements must be especially durable to ensure continued high performance of PV systems. As a prime example of the systems-driven approach to research in the Solar Program, Specialized Technology Resources, Inc., under a PV Manufacturing R&D Project subcontract, is working closely with PV module manufacturers including BP Solar, Energy Photovoltaics, Inc., and Shell Solar Industries to develop encapsulants for specific module types and end-use applications. In FY 2003, the company performed interfacial characterization of the glass surfaces to which the encapsulants must bond. To address issues of cost, Specialized Technology Resources, Inc., investigated ways to optimize extrusion techniques for large-scale manufacturing of encapsulants based on ethylene vinyl acetate (EVA) that cure fast and are flame retardant. As this work progresses, the company will continue work with manufacturers to test materials on specific module types for targeted end-use applications.

The PV Subprogram issued a request for Letters of Interest for the next solicitation, *PV Manufacturing R&D—Large-Scale Module and Component Yield, Durability, and Reliability*. The 29 responses from industry represented a 30% increase versus responses to previous solicitations. The subcontract awards will be divided into two categories: PV System and Component Technology, and PV Module Manufacturing Technology. Awards are expected in FY 2004 for research extending over three years and will be cost-shared with industry.

PV Module Performance and Reliability

To reach the PV Subprogram goal of cost-competitive products with a 30-year service life, PV systems must withstand year-round weather conditions including intense sunlight, high humidity, driving rain, snow, wind, and hail, as well as temperatures ranging from well below zero to midday summer heat. During years of exposure to these conditions, consumers reasonably expect modules to generate the same amount of electricity each year with few, if any, unexpected maintenance costs or down-time events.

To help manufacturers and system designers meet these consumer expectations, the PV Subprogram provides a unique combination of testing and analysis services for prototype and commercial PV modules and systems. With data from these tests, PV manufacturers can pinpoint problems and build on strengths. When overriding issues emerge, the PV Subprogram may sponsor targeted research to advance the industry as a whole. This activity to measure and improve the performance and reliability of commercial PV systems relies on the specialized testing and analysis capabilities at NREL, Sandia, the Southwest Technology Development Institute (SWTDI), the Florida Solar Energy Center (FSEC), and the PV Testing Laboratory at Arizona State University. Because no single manufacturer could invest in such comprehensive testing equipment and expertise, this is an important way that the Solar Program accelerates the development of reliable PV systems.

Tracking Long-Term Durability

After years in the field, one effect of long-term exposure to weather can be the intrusion of moisture into PV module and cell structures. If moisture makes its way into a module, it causes current drain and/or corrosion of solder joints, which reduces the electrical efficiency of the PV system. To learn more about water intrusion and other processes that reduce the electrical efficiency or cause complete failure of PV systems, the PV Subprogram has conducted reliability tests since 1991.

In 1997, the Module Long-Term Exposure Project was initiated in cooperation with PV manufacturers. Under this project, more than 80 modules from five manufacturers have undergone initial baseline testing at Sandia and have then been installed at FSEC and SWTDI to undergo monthly measurements during operation outdoors. These measurements can be very helpful to manufacturers. For example, in 2003, a group of 20 modules made from CIS thin-film material was returned to the manufacturer for in-depth analysis. After three years of exposure, performance of these modules had decreased more than predicted. In 2002 and 2003, more thin-film modules were installed at FSEC, after baseline testing at Sandia, to measure any effects of operation in the hot and humid environment of the FSEC test center.

At NREL, seven grid-tied, 1- to 2-kilowatt (kW) systems are maintained to test module made of varied materials for long-term performance and reliability. To expand understanding of long-term exposure to weather and ultraviolet light, and new long-term test program began in 2003.

Verifying Performance

Consumer confidence in the projected electrical output of PV systems is an important element to be cultivated in the growing market for PV systems. Aside from the continuous work of NCPV staff to fine-tune national standards and certification programs, the PV Subprogram's testing facilities generate unbiased reports on the electrical performance and reliability of prototype and commercial PV modules and systems. These confidential test reports are given to manufacturers about their products, but can be released by the companies if they choose. This work verifies projected electrical output and annual energy production.

Module performance can be measured in several ways. At NREL, researchers measure performance outdoors under natural sunlight tests or in the laboratory using solar simulators. In 2003, a new pulse-analysis spectrometer system will allow faster and more accurate flash spectrum analysis in the laboratory.

Outdoors, more than 30 modules can be monitored over weeks, months, or years; and more than 50 modules can be tested for short-term performance under prevailing weather conditions. Stand-alone systems for remote homes and streetlights are also being monitored.

Jim Yost/PIX13219

Jim Yost/PIX13220

NREL's Outdoor Test Facility is used to verify, characterize, and model performance and improve PV performance and reliability. From top: The Outdoor Accelerated-Weathering Tracking System with Tom McMahon and the High-Voltage Test Bed with Joseph del Cueto.

PowerLight Corporation/PIX13339

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 efforts in San Francisco's commercial, residential, and government-owned buildings. At their peak, these panels will generate 675 kilowatts of electricity. When combined with other newly installed energy efficiency measures, this solar power should save the convention center about $210,000 a year.

At Sandia, module performance measurements, as well as measurements of arrays with several PV modules, are conducted under actual outdoor operating conditions. In 2003, test engineers characterized dozens of modules for three different manufacturers because the accuracy of their nameplate ratings was in doubt after discrepancies arose among tests at other laboratories.

Predicting performance based on measurements can be helpful for system designers. Module performance models have been under development for several years and use a database of measured performance parameters being assembled at Sandia. The database contained more than 165 commercial modules and arrays at the close of 2003.

Improving Durability: Systems-Driven Approach

When the testing and analysis activities point to a common durability issue, the PV Subprogram, through the systems-driven approach to program management, responds by initiating research projects to address the issue. In 2002, it became clear that some new thin-film PV products that now represent a significant number of systems in operation were showing signs of wear. Industry representatives recognized that resolving any performance problems early in this market process would be crucial to rapid acceptance of the new technology, and they asked the Solar Program to work with them to head off problems.

Following the successful pattern of assembling national teams, the PV Subprogram responded to the industry by sponsoring a new Thin-Film Module Reliability National Team to address module design and reliability issues. Cosponsored by the Thin Film PV Partnership and the Systems and Module Reliability projects, the new national team brings together more than 60 scientific representatives from NREL, Sandia, FSEC, industry, universities, and module-packaging experts. The first meeting, held in 2002, began the process of recommending activities.

One of the first issues discussed by the Thin-Film Module Reliability National Team was research that had been conducted at NREL in conjunction with BP Solar on the delamination of tin oxide on glass in thin-film modules. The activities to resolve this issue provided a model for the national team effort: identify a problem in the field; analyze and understand it in the laboratory; replicate the result in lab-scale, accelerated tests; design alternative manufacturable solutions; and test solutions using the lab-scale accelerated tests.

The second and third meetings of the new national team also drew more than 60 people and have set out a detailed research agenda for FY 2004 and beyond.

Solar Program Offers Integrated Test Beds

The NCPV and Sun♦Lab virtual laboratories offer specialized testing facilities for the solar research and development community. From atomic-level measurements and analysis to systems-level performance and reliability measurements, the Solar Program makes these tools available to industry through cooperative agreements and joint research projects. Test beds are located at NREL, Sandia, Oak Ridge, Brookhaven, FSEC, SWTDI, at the centers of excellence at Georgia Tech and the University of Delaware Institute of Energy Conversion, and at research universities that work with the Solar Program. Technical details on testing is available at the Web sites of each organization.

PV Technology Development

DOE does not commercialize solar technologies nor sell them in the marketplace. That is the private sector's responsibility. When technology reaches the application and market end of the development framework, the federal research program collects information and feedback from the private sector to help guide early stages of new technology development. An important way the program gets this feedback is through partnering with industry and with other government organizations such as within the states or other parts of the federal government. Partnerships among industry, government, and others integrate all elements of the PV Subprogram through the systems-driven approach to improve performance and reliability of PV systems and to help introduce PV to domestic and foreign markets.

Systems Engineering and Reliability

Systems engineering and reliability research of the PV Subprogram aims to reduce the lifetime costs of the entire PV system, improve the reliability of systems and components, and verify and improve the performance of systems in the field.

An important component of the systems engineering activity is the collection of data on the field performance of PV systems, including operation and maintenance (O&M) costs. Now that PV is being considered for distributed energy generation, it is more important than ever to record maintenance experience and identify lifecycle costs and/or levelized energy costs for fielded systems. Understanding these costs and their sources is critical to the systems-driven approach in managing continued R&D on PV because this information can identify areas for system or component improvements.

The reliability database being developed at Sandia is one of the few repositories of O&M information for fielded PV systems. In FY 2003, data were analyzed from Arizona Public Service Company for PV systems on homes not connected to the utility grid. For these homes, annual O&M costs were between 4% and 5% of the initial capital cost of the PV system. An analysis of water pumping systems in the Northwest Rural Public Power District showed annual O&M costs of about 4% of the initial capital cost of the PV system. In FY 2004, cooperative efforts with Tucson Electric Power and Arizona Public Service will assemble data for grid-tied PV systems in both residential and utility-scale applications. Additional partners in industry and government, such as the Department of Agriculture/Rural Utilities Service, will also provide experience data from fielded systems to guide future R&D in the PV Subprogram.

Inverter R&D: New initiative, valuable tests, enhanced facilities

PV modules work with other components to make up the system that delivers electricity to the end use, or load. An important component of most PV systems is the inverter that converts dc electricity from PV to ac electricity necessary for most appliances and for connecting to the utility grid. System engineers can get valuable information about inverters from the unique laboratories of the NCPV. For example, inverter test facilities at Sandia can provide surge testing and accelerated life testing. In one set of accelerated lifetime tests conducted during 2003 at Sandia, more than 20 possible problem areas were located and communicated to the manufacturer for consideration. The company also got the good news that its approach to transferring heat away from critical components was shown to be very effective by thermal imaging conducted during tests.

In the past, PV systems designers had to use inverters developed for other industries that often did not perform reliably when subjected to the special demands of PV systems. In 2002, the DOE Office of Energy Efficiency and Renewable Energy launched the High-Reliability Inverter Initiative to fund cost-shared work with three companies to design and commercialize inverters specifically for use with PV, energy storage, and other distributed energy resource (DER) technologies. By the close of 2003, three subcontractors, General Electric Global Research Center, Xantrex Technology, Inc., and SatCon Applied Technology, had completed engineering designs and proposed work to build prototype high-reliability inverters in FY 2004.

Arizona Public Service (APS) has installed 2 MW of utility-scale PV generation at the Prescott, Arizona, airport. Sandia is collaborating with APS to assess the field performance, operations and maintenance experience, and cost of these systems.

System Design and Evaluation: New techniques and standards

Before a PV module is incorporated into a system and installed in the field, it is important to know if it is operating up to specifications. Testing modules is important, and tools that make the process easier and more effective are in great demand. Responding to this need, engineers at Sandia worked with PowerLight Corporation to develop a low-cost procedure, called "dark I-V" testing. This procedure uses a power supply to flow current through the PV module and generate electrical parameters. Comparison of actual parameters with the expected performance of the module thus identifies any rejects. The procedure also quickly identifies problems such as reversed wiring cables from the junction box; any problems with bypass diodes, including polarity; and short-circuited or open-circuited modules. PowerLight and its module suppliers are using the testing procedure to verify the electrical integrity of modules before costly system integration and installation in the field.

Tucson Electric Power/PIX133328

As part of its GreenWatts program, Tucson Electric Power partners with local builders to install PV systems such as this one at an Arizona home.

In the world market for PV systems, buyers rely on international standards to assure minimum performance and safety of PV systems. Now, thanks to years of work by the NCPV and others, U.S. PV manufacturers can submit their systems to the same set of testing standards in the United States and abroad for stand-alone applications not connected to the electric grid. A new recommended practice approved in 2003 by the Institute of Electrical and Electronics Engineers (IEEE) IEEE-SA Standards Board Review Committee will be used in the United States. It will also serve as the basis for international standard, *IEC 62124, Photovoltaic Stand-Alone Systems—Design Qualification and Type Approval*. The new *IEEE P1526, Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems*, contains procedures for independent testing laboratories to evaluate the performance of stand-alone PV systems. FSEC is authorized to provide certification testing for PV systems and will use the procedures in P1526. Test results from NREL, Sandia, SWTDI, and FSEC over the past five years provided the data necessary to validate this recommended practice.

Sandia/PIX13333

This Distributed Energy Test Laboratory at Sandia was used in 2003 to study the effects of PV and PV hybrid systems and inverters on electrical utility operation.

Before standards or tests apply, designers rely on system-analysis tools to model the features of PV. One such tool, called HOMER, developed in part with PV Subprogram support, can model a wide variety of renewable energy systems including grid-connected systems. By the close of FY 2003, the HOMER database contained more than 300 users in 145 countries. HOMER is a key component of the NCPV's international technical assistance programs in renewable energy in many countries, including Brazil, China, India, Mexico, Philippines, the Maldives, and Senegal.

Partnerships for Technology Introduction

To meet the challenges of increased market demand posed by the *U.S. PV Industry Roadmap*, the PV Subprogram conducts analyses and distributes information about PV. These analysis and outreach activities raise the awareness of PV in numerous promising market sectors, including rural America and international markets.

Warren Gtrez/PIX12884

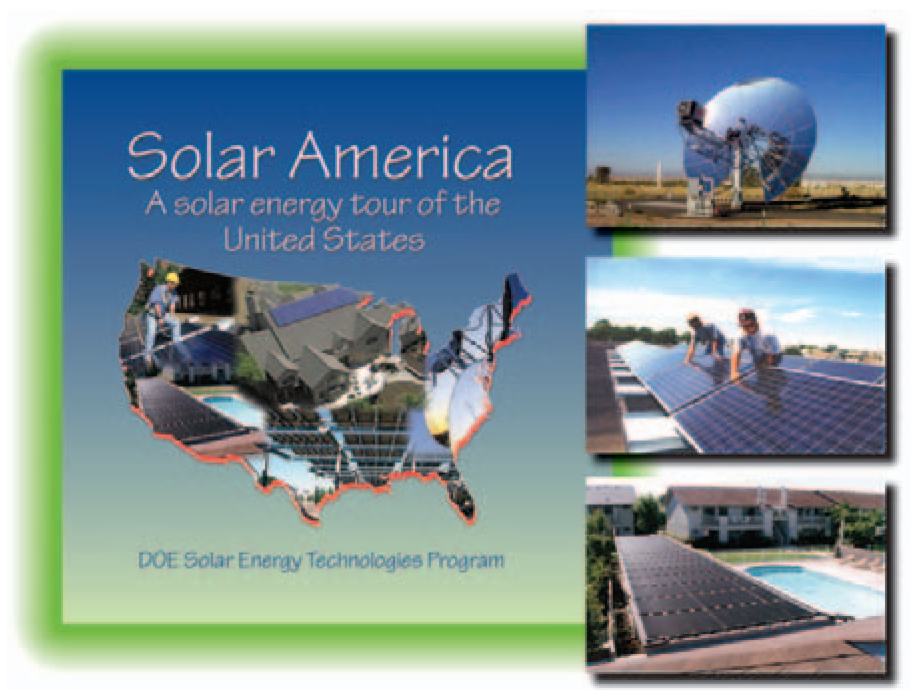
This traveling exhibit is used to educate students, teachers, and the community. Curriculum includes major renewable energy and efficiency themes researched and developed at NREL and BP America, which sponsored the exhibit. The bus is a teacher resource center, outfitted with electronics, displays, and workstations, whereas the trailer displays actual technology and renewable power generation.

Spreading the Word at Home

A huge potential market exists for PV systems owned by or financed by the federal government and other government entities. However, obstacles to wider use of PV in this market include overly complex procedures for procuring equipment and the need to be on approved lists of materials. To get PV systems onto such lists, experts at Sandia and FSEC are working through an interagency agreement with the U.S. Department of Agriculture Rural Utility Service (RUS). Applying their recent experience in developing the Florida PV Buildings Program, PV Subprogram engineers helped develop acceptance criteria and review procedures to get complete PV systems onto the RUS list of materials. Having PV systems on this list should greatly simplify the process for rural utilities to buy and install this equipment. In FY 2004, the RUS list of materials for the first time will include grid-tied residential and off-grid water-pumping PV systems. Work continues to get all PV applications on the RUS list of materials. This will also facilitate the purchase of renewable energy systems by other federal agencies and programs such as the Bureau of Land Management, National Park Service, and Farm Bill. Installed systems will provide performance and reliability data to the systems-reliability databases of the Solar Program.

Making consumers aware of the short- and long-term value of PV is a goal of the Solar Market, Policy, and Value Analysis activity. The NCPV's Value Matrix tool highlights the best areas of the United States for cost-effective PV installations. Available on CD, regulators are using this and other tools developed by researchers to implement portfolio standards, a very powerful incentive that is encouraging construction of PV generating systems in several states. Continuous updates to this useful tool are planned for FY 2004 and beyond.

Inspiring confidence among potential buyers of PV systems, an important goal of the Solar Program, will be served by the National Voluntary Practitioner Certification Program. With help from experts at the NCPV, this program to certify installers of PV systems got under way in FY 2003 by developing handbooks, study guides, and application forms. In FY 2004, the first installers will apply for certification, take tests, and receive



The Solar Program has many outreach activities to increase public awareness of renewable energy options. One award-winning effort in 2002 and 2003 was the Solar America CD, which features nearly 500 photos of solar energy installations in each of the 50 United States, Puerto Rico, and the U.S. Virgin Islands.

certificates from the North American Board of Certified Energy Practitioners.

Specialists in the Solar Program often participate in events that educate potential buyers of renewable energy systems. One such event that gathers farmers, ranchers, and residents of rural America each year is the National Western Stock Show in Denver, Colorado, which, in 2003, drew more than 640,000 people. For the eighth year, in January 2003, NREL volunteers staffed a booth on renewable energy at this event. Providing even greater depth on the subject, volunteers from the NCPV staffed three workshops on solar energy attended by 360 people.

A large potential market, the Navajo Tribal Utility Authority (NTUA) had several hundred PV systems in place at remote Navajo residences in Arizona, New Mexico, and Utah by the close of 2003. Engineers from Sandia have provided technical expertise over the years with technical training and community forums to make NTUA the nation's largest off-grid residential PV program. To take full advantage of PV in these homes, a dc refrigerator developed by a former NASA engineer is being tested at a remote home on the Navajo Reservation. This new refrigerator uses about 150 watt-hours of energy per day, compared with a conventional refrigerator's 1000 to 2000 watt-hours. To make the benefits of PV more widely known to native communities, Sandia published a book in 2002, *The Solar Way: Photovoltaics on Indian Lands*, that showcases uses of PV on tribal lands throughout the United States.

Peter McNutt/PIX13313

The electricity from five thin-film PV arrays is being used to power room lights, ceiling fans, computers, water coolers, air conditioners, and data acquisition systems at the Solar Energy Centre in New Delhi, India.

Solar Electricity Worldwide

To build stronger markets for U.S. PV products, the DOE Solar Program, the Organization of American States, and the U.S. Agency for International Development sponsored a one-day workshop, PV in the Americas, in conjunction with the PV Specialists Conference of the IEEE in 2002. More than 70 people from 10 countries participated in this forum for suppliers, installers, and researchers to discuss approaches to increasing consumer acceptance of PV technologies in the hemisphere. They discussed establishing component and system laboratories for testing and certification, demonstrating innovative applications such as hybrid PV-diesel systems for rural power, publicizing the success of small-scale business uses in Mexico, and targeting several national rural electrification programs.

Introducing U.S. technologies in major markets outside our hemisphere can provide important benefits to U.S. companies. DOE and NREL, in collaboration with the Solar Energy Centre in New Delhi, India, have installed 21 kW of thin-film PV modules made of amorphous silicon, CIS, and CdTe. The systems, supplied by U.S. companies, are undergoing tests and data are being collected on all aspects of system operation. The Chinese State Development and Planning Commission is working with DOE to help design a $240-million rural electrification program to provide electricity to 1,061 townships using only renewable energy technologies (including 20 MW of PV).

Sandia/PIX13331

In 2003, the Navajo Tribal Utility Authority installed 44 small wind/PV hybrid power systems in Arizona, New Mexico, and Utah under the Navajo Electrification Demonstration Program.

Solar Program Supports Deployment

The Million Solar Roofs (MSR) Initiative, announced in June 1997, seeks to install solar energy on one million U.S. homes and buildings by 2010. By the close of 2003, more than 300,000 solar roof installations had been made, thanks in large part to partnerships in states and communities across the nation. As part of the MSR initiative, the federal government is committed to installing solar electric and solar thermal energy systems on 20,000 federal buildings by 2010.

The technical and analysis staff of the NCPV and the solar water heating activity of the Solar Thermal Subprogram are contributing to many of these projects. They are testing equipment, reviewing designs, and collecting performance data. Some installations feature prototype or early commercial versions of products from the R&D programs.

The use of renewable and energy efficiency technologies in detecting, preventing, mitigating, and recovering from both natural and human-caused disasters is a growing market. The Solar Program provides technical assistance to the Federal Emergency Management Administration and the insurance industry about the advantages of renewable energy technologies in the face of disasters. Accomplishments and plans have been featured on NREL's Web site, Surviving Diaster with Renewable Energy (www.nrel.gov/surviving_disaster), since FY 2002. By the close of FY 2003, this site was listed in the Intermediaries and Reinsurance Underwriters Association Database of Storm and Weather Catastrophe Web Sites.

John Masson/PIX11040

PV provides high-reliability power for a communications tower in Dinosaur National Monument, Utah/Colorado. Communications facilities can be powered by solar technologies, even in remote, rugged terrain. Also, if a natural or human-caused disaster disables the utility grid, solar technologies can maintain power to critical operations.

ELECTRICITY AND HEAT FROM SOLAR THERMAL

The Solar Thermal Subprogram complements the PV Subprogram with similar goals of product development, improved manufacturing, and reduced cost. Two key applications are being addressed: Concentrating Solar Power (CSP) and Solar Heating and Lighting (SH&L). The near-term CSP goal is to help industry bring commercially proven technologies (trough, dish, and power towers) to power markets in the United States and to export CSP technologies to other countries. The long-term goal for CSP is to provide a significant fraction of U.S. power-generation capacity. For SH&L, the near-term goals are to cut solar water heating system costs in half and to perfect solar hybrid lighting prototypes for transfer to the lighting industry. The long-term SH&L goals are to develop solar space heating, cooling, and lighting systems that are economically competitive with conventional technologies.

FRANK WILKINS, TEAM LEADER, SOLAR THERMAL SUBPROGRAM

The mission of the Solar Thermal Subprogram is to get solar technologies into the marketplace. To do this, we believe it is important to work closely with industry. Our collaborations between DOE researchers and industry engineers feed into the systems-driven approach to planning and have resulted in major progress toward our programmatic milestones. We set these milestones based on discussions with industry about top research priorities and the necessary collaborative activities to reach our objectives.

In FYs 2002 and 2003, we made significant progress. For example, we launched the next generation of parabolic trough collector developed by Solargenix Energy. We worked closely with Stirling Energy Systems to improve the reliability of its 25-kW dish/engine system. We worked with two industry teams, Fafco and Davis Energy/SunEarth, to develop a new low-cost solar water heater. And, to bring sunlight indoors, in collaboration with the University of Nevada, we began tests of a prototype hybrid solar lighting concept.

During this same period, the CSP activity underwent intense evaluation—first by Sargent & Lundy, an engineering company in Chicago, and then by the National Academy. The objective was to get an independent assessment of the potential for achieving trough and power tower cost goals. The report issued by Sargent & Lundy in 2003 estimated trough costs could be reduced to between 4.3 and 6.2 cents/kWh and towers to between 3.5 and 5.5 cents/kWh. To achieve these cost goals, however, required a combination of R&D and deployment. The National Academy verified these results, although it expressed doubts that sufficient deployment would take place. To address the need for deployment, we formed the *1000 MW CSP Project Team*, which has since discussed the benefits of CSP with several states in the Southwest. These discussions have created interest in deploying CSP technology and will continue in FY 2004. These accomplishments, along with continued R&D in the years ahead, will help launch the commercial solar products that will enrich our nation's energy portfolio.

Craig Christensen/PIX12944

CONCENTRATING THE SUN'S ENERGY

CSP technologies use mirrors to concentrate the sun's energy up to 10,000 times. This concentrated energy powers conventional turbines, heat engines, or other devices, such as PV cells, to supply electricity. These attributes, along with world-record solar-to-electric conversion efficiencies and costs that are projected to decline rapidly when large numbers of systems are deployed, make CSP an attractive renewable energy option.

The Solar Thermal Subprogram is working with industry to position several CSP technologies for wider commercial development. CSP technologies, including parabolic troughs, power towers, and dish/engines, can range in size from 10 kW to 10 MW for distributed power, village power, and grid-connected applications. Systems supplying up to several hundred MW can be used for utility power generation. Some systems use thermal storage during cloudy periods or at night. Others can be combined with natural gas, and the resulting hybrid power plants provide high-value, dispatchable power that can be fed to the utility grid when it is most needed.

1,000 MW CSP PROJECT TEAM

R&D has reduced the cost of CSP technology by a factor of three since 1985. Future R&D will continue this trend. However, an in-depth study of the technology by Sargent & Lundy in 2003 indicated that more than R&D is required if cost goals are to be met. Deployment—the building of projects—is also necessary. Deployment contributes to cost reduction in two ways. It enables industry to take advantage of mass production and enables the building of larger, more-efficient solar power plants. To address this need for deployment, the Solar Thermal Subprogram

Sun◆Lab

A key component of the CSP research effort is the Sun◆Lab virtual laboratory. The expertise of the Sun◆Lab technical staff covers every scientific and engineering field needed to develop, operate, test, and evaluate complex solar systems and facilitate their use. The staff has received two recent R&D 100 Awards for work in CSP research as well as numerous awards for papers and technical accomplishments. An important feature that makes Sun◆Lab effective is the excellent working relationship between researchers at the national laboratories and test facilities and their counterparts in the solar industry.

assembled a *1,000 MW CSP Project Team* to make contacts in the states and to develop appropriate information about the benefits and characteristics of CSP projects. The team, which includes members from industry, Sandia, NREL, and DOE, has made presentations to the Western Governors Association, Western Interstate Energy Board, and Governors' offices in Arizona, Nevada, New Mexico, and California. Governor Bill Richardson (NM) subsequently announced the formation of a solar task force that is to plan a concentrating solar plant in New Mexico. Members of our *CSP Project Team* are on that task force. Other southwestern states have also expressed an interest in CSP plants, and activities are planned for FY 2004 that we hope will lead to 1000 MW of new CSP capacity in the Southwest.

Sandia/PIX13332

Established in 1976, the National Solar Thermal Test Facility covers 110 acres of land and includes four distinct test areas: the Central Receiver Test Facility with a central tower and 222 heliostats; the Trough Rotating Platform Facility; the Engine Test Facility; and the Distributed Receiver Test Facility with two 25-kW parabolic dishes.

Concentrating Trough Component R&D

One type of CSP system is the parabolic trough. These systems, some of which have been operating for as long as 18 years, are the most commercially mature of all CSP technologies. By the close of 2003, more than two million square meters of collectors totaling 354 MW were operating in the United States. Trough systems use parabolic trough-shaped mirrors to focus sunlight on thermally efficient receiver tubes containing heat-transfer oil. The hot oil is pumped through a series of heat exchangers, producing superheated steam that powers a conventional turbine generator to produce eletricity. The DOE CSP research program is working to improve each component of trough systems to reduce costs and improve performance.

The CSP R&D effort is working in partnership with industry to develop a U.S. supply of parabolic trough collector technology. During 2002 and 2003, Solargenix Energy (formerly Duke Solar) developed a new parabolic trough concentrator under contract to NREL and tested a prototype at the NSTTF at Sandia. This next-generation concentrator uses an aluminum collector structure made up of accurately manufactured hubs and low-cost struts. The new aluminum design is stronger and stiffer than previous steel structures, which leads to improved optical performance and the possibility to make larger systems. It should also have relatively lower shipping costs because it is lighter and more compact than previous designs. The NSTTF tests in FY 2003 validated the optical accuracy and expected thermal performance of the prototype.

Sandia/PIX13335

This new parabolic trough concentrator developed under contract to NREL was tested on a rotating platform at the National Solar Thermal Test Facility in Albuquerque, New Mexico.

In FY 2004, full-scale field tests of the new collector will be conducted, and the first commercial installations are expected by late in the year. Arizona Public Service will have Solargenix build a 1-MW_e Organic Rankine cycle plant. Solargenix will use this collector design for a 50-MW_e commercial plant in Nevada planned for 2005.

Improving Thermal Energy Storage

One long-term development project has been the power tower CSP concept, pioneered at Solar One in Barstow, California, in the 1980s. A power tower plant has a field of heliostats (large mirrors) that track the sun to reflect solar energy onto a receiver mounted on top of a tower in the center of the field. Today's receivers use molten salt as the working fluid and heat exchangers to produce steam. The steam powers a conventional steam turbine-generator power block. The molten salt doubles as thermal storage so that power towers can generate power on demand to the utility grid up to 24 hours a day. The DOE CSP Subprogram provides technical assistance to manufacturers, who are marketing these systems in the United States, Spain, and South Africa.

CSP researchers are also exploring thermocline systems for reducing the cost of thermal energy storage for power towers and troughs. A thermocline system uses a low-cost filler material as the primary thermal storage medium and molten nitrate salts as the direct heat-transfer fluid. The filler materials displace the bulk of the more expensive molten salt. To test candidate filler materials, a series of isothermal and thermal cycling experiments were conducted at the NSTTF. The thermal cycling test ran for 14 months (10,000 cycles) at 287° to 450°C, simulating a 30-year plant life. Final chemical analyses will be completed in 2004, but preliminary results indicate that the quartzite rock and silica sand tested are compatible with the molten salt environment.

Concentrating Dish System R&D

Promising dish/engine systems use a tracking parabolic dish to focus sunlight onto a thermal receiver. Thermal receivers absorb and transfer the solar energy to a heat engine-generator where electrical power is generated. The dish-engine systems use kinematic Stirling engines. Improving the performance and reliability of these systems is a goal of the DOE CSP research effort.

The CSP Subprogram has been working with industry to develop several prototype dish concentrator systems for commercial applications. About two dozen dish-engine units have been built and tested over the last 10 years. The Advanced Dish Development System (ADDS) 10-kW prototypes were designed and developed under contract to the CSP R&D effort by WG Associates. The ADDS system is intended for remote power applications. Mod 1 and Mod 2 ADDS prototypes were installed at the NSTFF and operated successfully in an unattended mode. For example, in 2002, the Mod 1 ADDS produced 17,133 kWh of electricity (net) and had 91.4% availability. In 2003, a second Mod 2 system was erected and converted to grid-connected, unattended operation.

The ADDS technology was purchased by Stirling Energy Systems (SES) in 2003 to augment its 25-kW dish/Stirling design. SES plans to bring a dish/Stirling design to market as soon as possible. Using ADDS technology, the company improved the control system of the 25-kW system. When deployed at the NSTTF, the modified 25-kW design demonstrated closed-loop tracking and unattended automated operation. Based on the success of this cooperation with the CSP team at Sandia, SES will deploy six new units at the test facility in 2004 and 2005. In a unique cost-sharing arrangement, SES will support its engineering staff working at the NSTTF and supply the hardware. DOE program funds will be used to support SES with in-kind engineering and operational support, facilities upgrades, foundations, and computing resources. This partnership should help reach the Solar Program's goal of commercial deployment of dish/electric technology.

Sandia/PIX13336

This 10-kW prototype of the Advanced Dish Development System provided valuable test data at the National Solar Thermal Test Facility in Albuquerque, New Mexico.

Advanced Materials R&D

To improve the efficiency and durability of CSP systems, the R&D effort is developing and testing advanced reflector materials. Materials must resist corrosion, delamination, and deformation because these events reduce the effective concentration of sunlight on the receiver. The Optical Materials Team collected data on the performance of commercially available thin-glass mirrors, quantified the impact of defects, and proposed degradation mechanisms accounting for these defects. After surveying standard mirror painting practices, they devised a large matrix of sample combinations of paints and adhesives so that a contractor could screen for the 84 most promising constructions. This information will be passed on to the industry to help companies improve concentrator performance.

CSP Subprogram Investigates Concentrating PV

All of the components of CSP dish systems have been under development for many years within the DOE Solar Program. The same holds true for high-efficiency PV systems. What hadn't been done was to take a close look at how advanced CSP and PV technologies might be used in the same system.

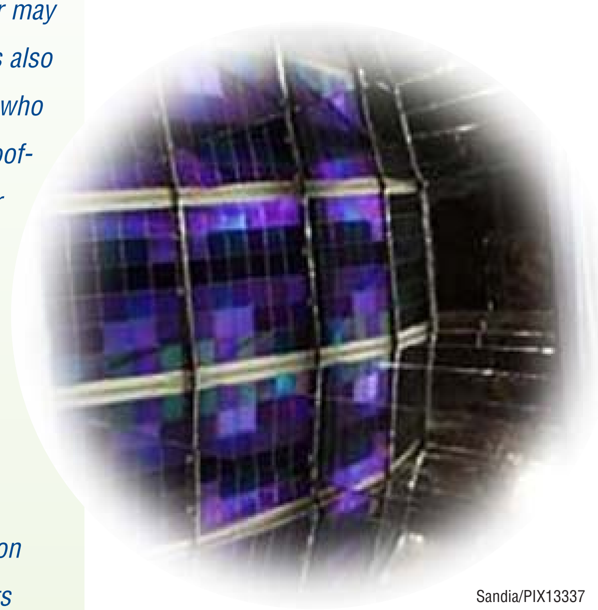
In the next decade, dish concentrators that use a Stirling engine as the receiver may be commercial if reliability can be improved. PV, which has no moving parts, is also attractive as a receiver because of its high reliability. So, in FY 2003 engineers who work on projects in the CSP and PV Subprograms joined forces to conduct proof-of-concept demonstrations of high-concentration components for PV and solar thermal systems.

One of the first steps was to fine-tune analytical tools and experimental facilities to support this work. The High-Flux Solar Furnace at NREL was adapted to conduct preliminary tests of dense-packed arrays of PV cells from Amonix and Spectrolab. Amonix uses lenses in its commercial PV systems, but wanted to test a dense array designed for use with mirror-based systems. Tests of the Spectrolab dense arrays showed efficiencies slightly greater than 30% (based on cell area and incident flux at the module plane). This is very close to test results achieved at ideal indoor laboratory conditions for a single cell. The modified High-Flux Solar Furnace now serves as a test bed for the solar concentrator industry.

Another step toward developing a prototype concentrating PV system was to modify the dish concentrator for a PV receiver (the dense-packed array). The dish developed by Science Applications International Corporation for Stirling engine receivers was upgraded to provide uniform flux to the focal point. NREL supported this upgrade with optical characterizations using the SolTrace modeling software in conjunction with the Video Scanning Hartmann Optical Test, a system designed to measure optical performance of focusing optics. Dozens of fixed-focal-length mirror facets were tested for use with the PV receiver array.

After working together in this effort, Spectrolab and Solar Systems, Ltd., will work with NREL in FY 2004 to integrate III-V high-performance PV cells into Solar Systems' concentrator systems that currently use silicon PV cells. Spectrolab's goal is to surpass 40% cell efficiency and achieve system solar-to-electric efficiencies approaching 33%.

As part of the advanced materials effort of the CSP Subprogram, NREL and ReflecTech are developing a low-cost reflector material for high-volume production. Early, small scale samples of the material tested well for reflectance and durability. During 2002, ReflecTech delivered 16-in.-wide by 30-ft-long rolls of several improved reflective films



Sandia/PIX13337

This densely packed array of PV cells is seen through the secondary concentrator during a test at the NREL High-Flux Solar Furnace in Golden, Colorado. These tests were part of a Solar Thermal Subprogram activity to develop a concentrating PV system.

to NREL for measurement and testing. At the close of 2003, after two years of testing outdoors, the material showed no significant loss of reflectance. Other accelerated weathering tests simulating eight years of exposure also showed no significant loss in solar-weighted reflectance. The CSP Subprogram goal of 10-year durability for this low-cost material seems achievable as tests continue.

In other work on reflector materials, DOE has been working with Science Applications International Corporation (SAIC) in McLean, Virginia, to combine the best of thin-glass and silvered-polymer reflectors. The ultra-thin glass reflector being developed has a

Warren Gretz/PIX11548

The 10-kilowatt High-Flux Solar Furnace, which began operation late in 1989, uses a tracking heliostat and 25 hexagonal mirrors to concentrate solar radiation. The furnace can nominally provide flux at 2,000 suns but, when required, can use specialized secondary optics to generate concentrations greater than 20,000 suns. In addition to testing solar energy systems, this installation is used for applied R&D in advanced materials and processes and research on destruction of environmental contaminants.

polymer or metal-foil substrate coated with a copper layer, followed by a layer of silver, and topped by an optically transparent protective alumina coating. The goal is to achieve a cost of $10.76/m^2 at deposition rates above 40 nanometers per second (nm/s). During 2002, deposition rates for samples were increased to 20 nm/s, and preliminary durability tests in 2003 were promising.

Using the Sun for Heat and Light

Solar Water Heating

Using the sun to heat water is a relatively simple concept that, if perfected in a low-cost system, could significantly reduce consumption of non-renewable energy supplies in the United States. In 2003, solar heating of swimming pools was a strong commercial market, with eight million square feet of collector being installed each year in the United States, equivalent to 300 megawatts thermal (MW_t) in rated capacity. Solar water heating systems are being included with some new homes; however, sales have lagged since the federal tax credits expired in the late 1980s. Reducing the costs of these systems is a major goal of the Solar Thermal Subprogram.

Low-Cost Solar Water Heating Systems

Cost seems to be one of the biggest obstacles to wider use of solar water heating. In fact, analysts have projected that lowering the first cost of installed solar hot water systems to $1,000 could significantly expand the current market. Much of the expense of today's solar water heaters is the cost of key components made of glass, copper, and aluminum. As a result, finding and testing alternative materials is a major goal of the R&D effort.

Low-cost polymer-based materials for solar water heaters have the potential to reduce costs by 50% because of lower material, manufacturing, and installation costs. The Solar Thermal Subprogram has explored and tested promising new materials and is working with two industry teams to develop low-cost, passive systems with polymer components. The same polymer-based technology being developed for low-cost water heaters can also be used eventually to provide space heating, thus reducing consumption of fossil fuels for heating homes and businesses.

Using these new materials, FAFCO, Inc., and Davis Energy Group/SunEarth, in partnership with NREL and the DOE Solar Program, are developing unpressurized integral collector storage (ICS) system designs. In these systems, fresh water moves through the system whenever hot water is drawn. The water is heated in a heat exchanger while it sits in the ICS system. These simple systems use no pumps or motors and are being developed initially for use in freeze-free regions of the country.

Sun Systems/PIX05978

This prototype roof-integrated thermosiphon system has a very low profile, comparable to a skylight. This less obtrusive orientation does not significantly reduce energy production. This prototype is testing the performance of new low-cost materials that resist corrosion caused by various groundwater conditions.

Finding the Answers

The analysis, testing, and engineering resources of the Solar Thermal Subprogram help answer the inevitable questions that arise with evolving technology. For example, the Civano sustainable community in Tucson, Arizona, incorporates active and passive solar energy, including PV, daylighting, and solar water heating, on about 300 homes. These homes, which consume far less energy than conventional homes in other subdivisions, have solar water heating systems that use integrated collector storage designs from several manufacturers. Each system holds about 40 gallons of water. About a dozen collectors eventually developed pinholes in the copper tubing and began leaking. Engineers from Sandia were called in to find out why and to assess the potential for more problems. Their tests showed that, while all collectors had some pitting, only a small group of systems were vulnerable to leaking. These were thin-walled systems that operated at higher temperatures. The analysis concluded that corrosive elements in the water that attacked copper were responsible for the holes, rather than manufacturing defects. Fortunately, the Solar Thermal Subprogram, through Sandia, had been working with the Salt River Project (SRP) utility and a manufacturer, Energy Laboratories, Inc. (ELI), to develop a solar water heating system that could operate with the potentially corrosive well water common in the region. The new design is called the roof-integrated thermosiphon system and uses stainless steel, instead of copper, on all components exposed to water. Using stainless steel to protect against corrosive water demanded a new manufacturing method for the collectors. With help from Sandia and SRP, ELI devised a manufacturing approach and produced prototype systems that were installed on homes in 2001 and 2002. Data from these prototypes were used to improve the systems. ELI began manufacturing this new product early in 2004.

In FY 2003, about a dozen second-generation ICS polymer solar water heaters were installed in the field. This controlled field-testing is designed to stress the systems until weaknesses appear. They are carefully monitored and operate under extreme conditions at laboratory and university settings in Arizona, California, Florida, and Hawaii. Monitoring data show efficiencies as high as 40%, which is higher than predicted.

The passive solar water heating systems nearing commercial readiness are appropriate for areas that do not experience hard freezes. In FY 2004, work begins to identify promising concepts for cold-climate applications.

Testing Materials for Durability

Supporting efforts to replace costly materials with polymer substitutes, the University of Minnesota Department of Mechanical Engineering tested and identified promising polymers for use as heat exchangers in FY 2003. Their recommendations will form a starting point for the cold-climate solar water heating effort that begins in FY 2004.

In 2003, additional tests at DOE's accelerated weathering testing facility in Golden, Colorado, showed that Korad, a promising ultraviolet screen coating for low-cost polymer glazings, began to exhibit signs of degradation at about 13 years of equivalent ultraviolet exposure for a 2-mil-thick coating. However, thicker 4- and 6-mil coatings of the same material now being tested look more promising. If these coatings prove durable, the polymer glazing underneath should reach the 20-year life necessary for commercial success. Testing also showed that neither wet nor dry stagnation should cause structural problems for the polymer absorber materials.

Hybrid Solar Lighting

Good lighting is essential to health and productivity in our schools, offices, factories, and stores. Electric lighting also represents 30% to 35% of the electricity consumed in a typical school, office building, or retail store. Roughly 10% of the electricity consumption in the United States is used to light commercial buildings. Therefore, increases in the energy efficiency of lighting these spaces could have a significant impact on national energy consumption. In addition, some research has credited sunlit indoor spaces with improvements in human health and performance versus spaces illuminated with electric lights. Sunlight indoors has also been shown to increase product sales in retail stores. Hybrid solar lighting, which combines natural sunlight with electric light, is a relatively new concept with the potential to reduce energy consumption and improve the indoor environment.

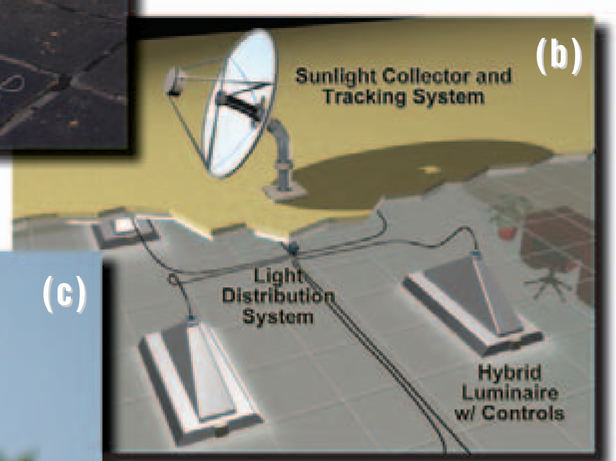
Hybrid solar lighting now has a greater potential to deliver natural light to interior spaces thanks to new low-cost, flexible optical fibers. Hybrid solar lighting systems use small, tracking parabolic solar concentrators that focus sunlight onto flexible optical fibers. These optical fibers "route" the sunlight inside the building and connect to modified electric light fixtures that distribute the sunlight and provide back-up light when needed. Control systems using dimmable ballasts adjust the level of electric light from fluorescent fixtures to compensate for variations in sunlight and maintain a constant illumination level. Hybrid solar lighting can deliver the benefits of sunlight without some of the disadvantages of conventional daylighting from skylights and windows such as glare, variability, heat gain, and costly architectural design requirements.

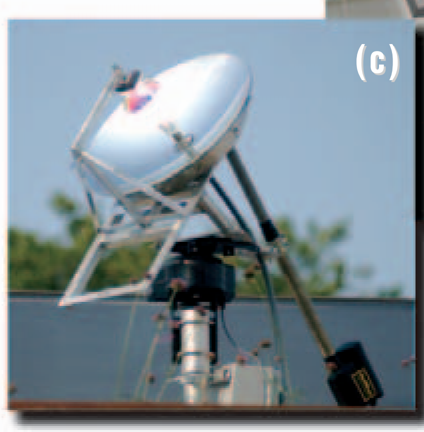
After three years of development, the Solar Program's first hybrid solar lighting system began testing in FY 2003 at Oak Ridge National Laboratory. Laboratory experience suggested several improvements. For example, in FY 2004, a second-generation collector and light distribution design will be tested that uses a new type of fiber optic bundle developed by Advanced Lighting Systems, Inc. The new design will eventually be used in a stand-alone hybrid lighting system that can be integrated with several different electric lamps of differing lumen outputs and used in direct, indirect, task, and general illumination applications. The system is expected to be complete in 2004 or 2005 and meet a cost goal of $0.12/kWh (levelized cost of energy).

Key technical challenges for hybrid solar lighting include reducing system complexity while improving efficiency. Collectors/concentrators must be easy to assemble, align, calibrate, and maintain. The mirror and fiber-mounting arrangements must be straightforward for installers, and components (mirrors, motors, and mounts) must be low cost, lightweight, and easy to manufacture. The spectral characteristics of the sunlight delivered indoors must be well matched to the backup electric lamps. And the clarity and robustness of fiber optic materials must continue to improve while costs continue to fall. The above challenges form the nucleus of a national R&D agenda that is being systematically addressed by members of the Hybrid Lighting Partnership and other organizations. As part of the systems-driven approach, data will be collected at demonstration installations planned for Alabama, California, and Tennessee in FY 2004 and used to determine future R&D activities.

Oak Ridge

Hybrid solar lighting (HSL) systems use parabolic solar collectors, flexible optical fibers, and modified electric light fixtures to "route" sunlight into buildings: (a) the first prototype HSL system, which was installed on the National Transportation Research Center at Oak Ridge National Laboratory in Tennessee; (b) the basic HSL system design; and (c) the University of Virginia's Solar Decathlon house, which boasted the world's first domestic-scale HSL system.

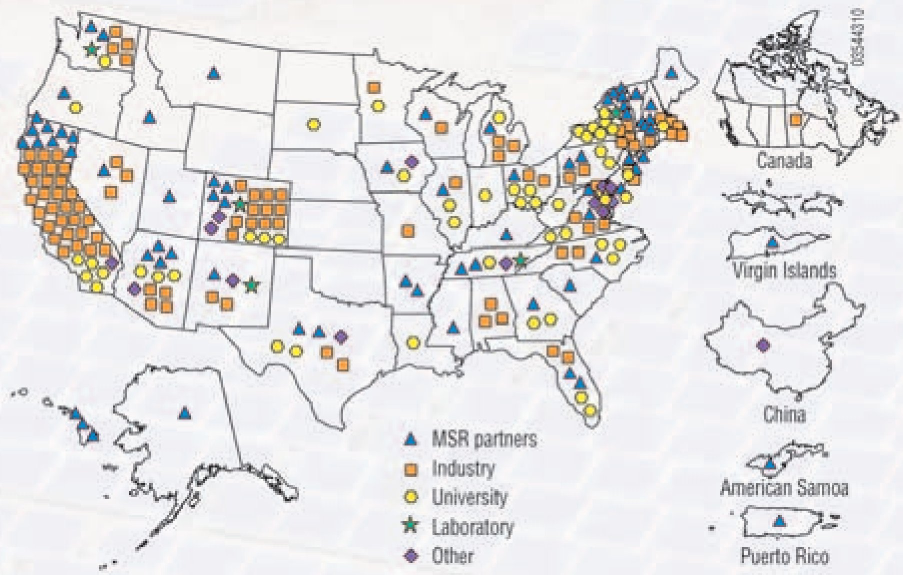




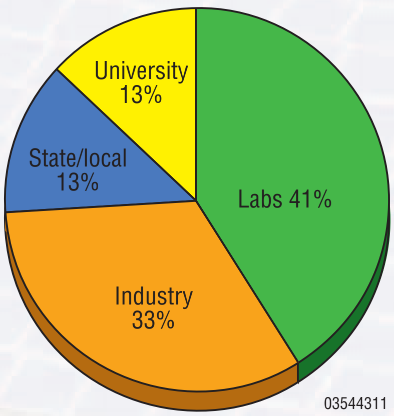
Chris Gun/PIX12174

Resources of the Solar Energy Technologies Program

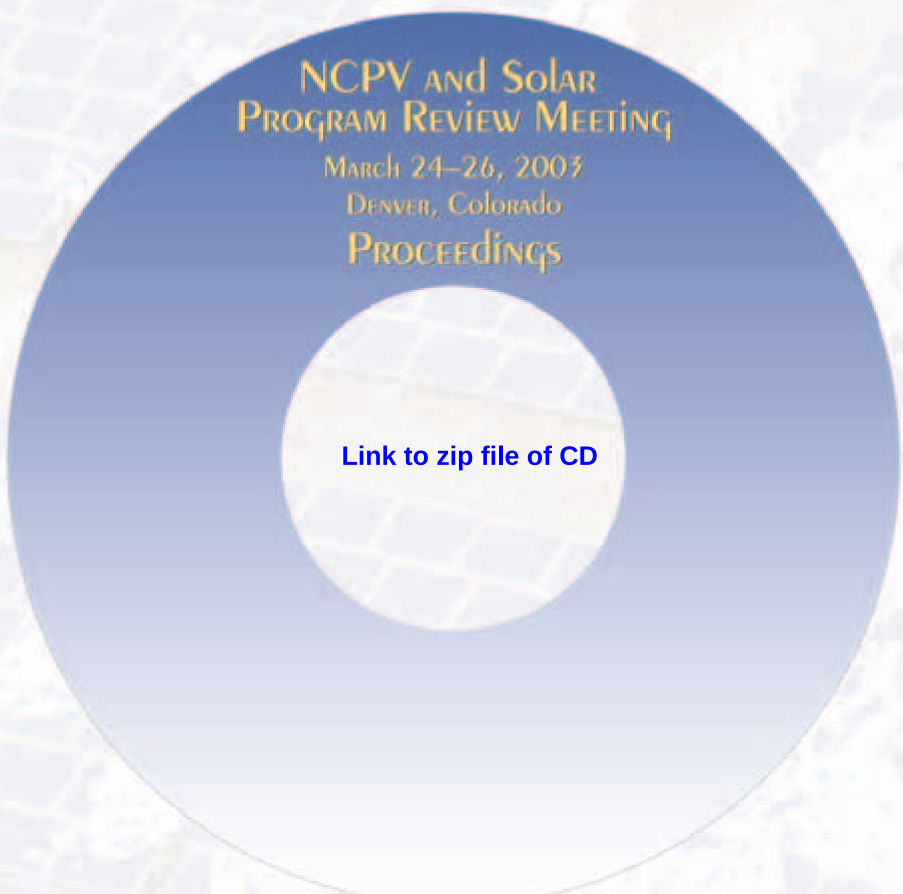
The Solar Energy Technologies Program uses partnerships to shorten the time of project completion and to ensure rapid transfer of the technology from the research laboratory to the factory floor. Through competitive procurements and multi-year funding strategies, the Solar Program works closely with the national laboratories, industry, state and local agencies, and universities to leverage their expertise and resources.



The Solar Program's support spans partners from industry, universities, and national laboratories across the United States.

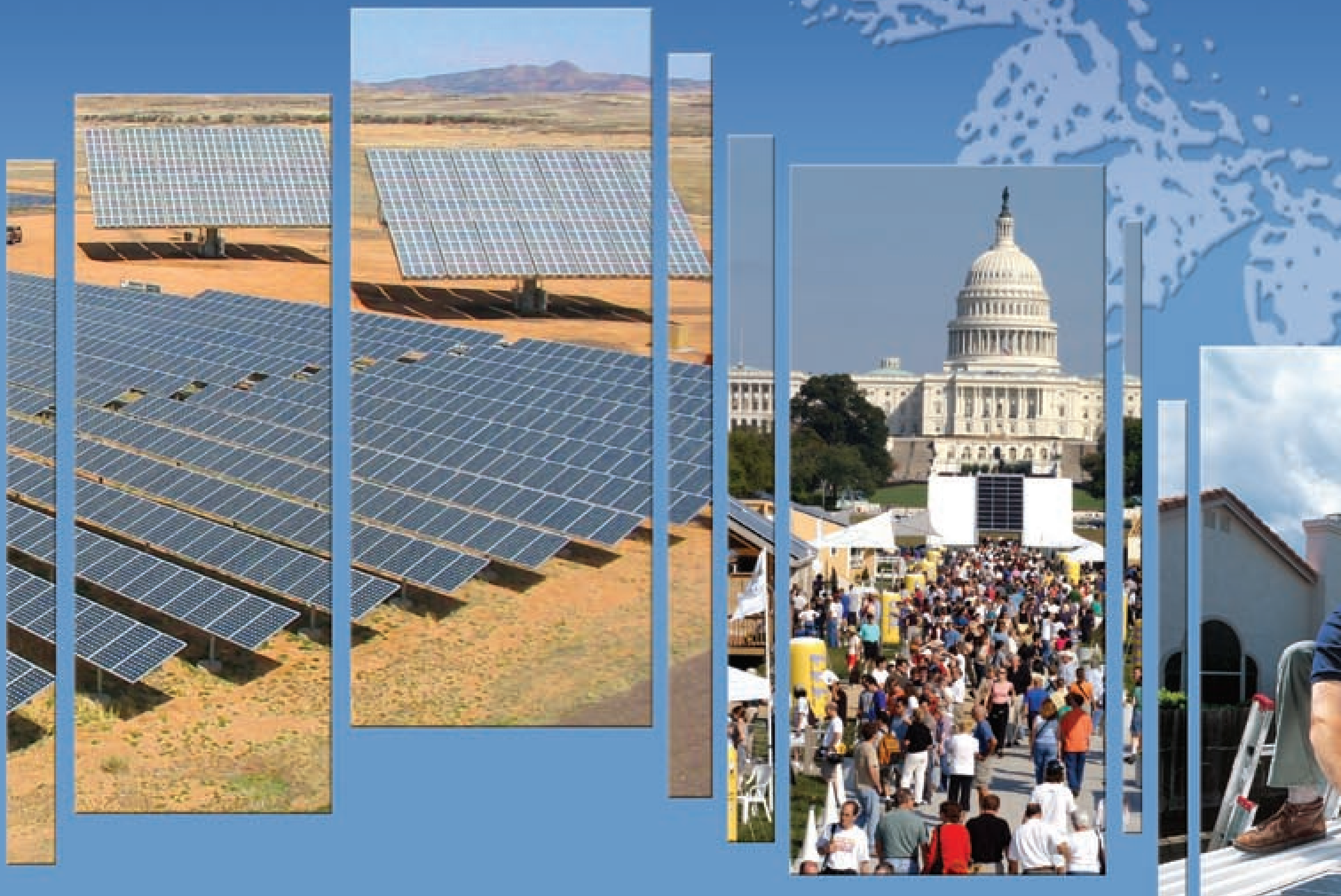


This pie chart shows the Solar Program's research performers and their share of total funding.



Solar Program Web Site

www.eere.energy.gov/solar



A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

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