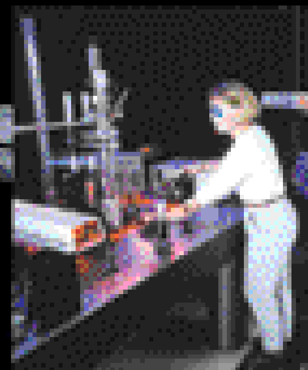
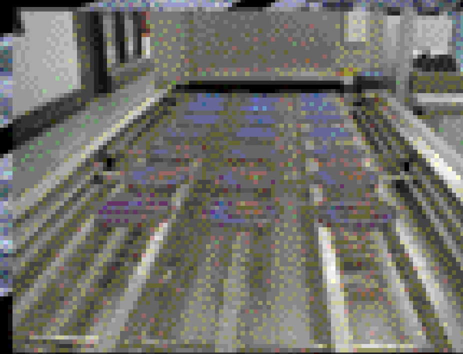
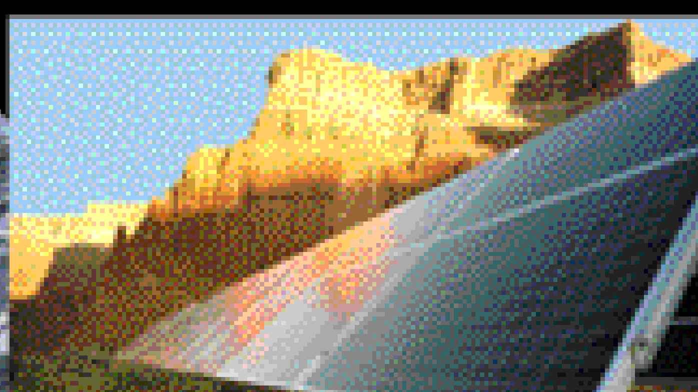
U.S. Department of Energy

Photovoltaic Energy Program Overview

Fiscal Year 1999







Program Highlights

Research and Development . . . . Page 2

- Developed, jointly with Spectrolab, a record-breaking GaInP/GaAs/Ge concentrator cell that is 32.3% efficient (at 50 suns).
- Fabricated world-record, 18.8%-efficient CIGS cell by applying improvements developed over several years. Received patents for the three-stage process and issued four licenses to U.S. industry.
- Provided Web-based "virtual laboratory" transfer of test data to more than 50 different research groups.
- Shared R&D 100 award with Siemens Solar Industries and the California Energy Commission for development and deployment of commercial CIS thin-film modules.
- Tied world record with a 15.8%-efficient CdTe device using innovations that offer potential for additional increases in efficiency and ease of manufacture.
- Supported new model of a-Si degradation using pulsed illumination experiments. This model could lead to designing a-Si cells that are more stable.
- Supported industrial partner United Solar in development of a 10.4%-efficient (stabilized) triple-junction a-Si module.
- Sponsored the 9th Workshop on Crystalline Silicon Materials to promote exchange of research results.
- Developed novel method for fast deposition of thin silicon layers on low-cost glass substrates.
- Made *PVScan* and *PV Optics* analysis tools available to the research community.
- Continued experiments with plasma processing of silicon PV devices to increase light absorption.
- Achieved record 18.0%- and 15.2%-efficient large-area, back-contact silicon cells using evaporated and low-cost screen-printed metals, respectively.
- Awarded 18 new subcontracts to universities for exploratory research into future-generation PV technologies.
- Promoted education of new researchers through the Renewable Energy Academic Partnership and Sunrayce solar car race.

Technology Development . . . . Page 9

- Supported the efforts of the PV Industry Roadmap Workshop.
- Reduced module-manufacturing costs by more than 30% and increased manufacturing capacity fivefold since 1992 within the Photovoltaic Manufacturing Technology project.
- Made optimization of PV system design easier by introducing a computer model that predicts module performance under varying conditions.
- Identified solder bond abnormalities through destructive tests of weathered modules.
- Promoted the increase of mean time between failures for inverters from 3.4 years in 1996 to 13 years in 1998.
- Conducted surge testing of inverters to identify potential risks of islanding and to identify design solutions for inverter manufacturers.

Systems Engineering and Applications . . . . Page 14

- Provided technical assistance to federal agencies, the City of Chicago, the Nevada Test Site, and others to promote use of PV.
- Wrote an end-of-millennium review for the prestigious journal, *Progress in Photovoltaics*, which identified topics of great concern for PV's future.
- Supported development of consensus standards by performing intercomparison of small-system tests to validate test methods; validating module energy ratings procedure to within 5% of actual annual production; supporting PowerMark Corporation to certify the first modules from two U.S. manufacturers.
- Provided technical assistance to Million Solar Roofs Initiative by conducting workshops for communities, presenting public information exhibits, supporting projects for the utility industry such as Utility PhotoVoltaic Group, educating the insurance industry about benefits of PV, and working with state and local programs.
- Commissioned a study that demonstrated the benefits of distributed generation on a feeder line in Washington State.
- Worked with the State of Florida and the Florida Solar Energy Center to develop a model buildings program, which will serve to ensure widespread PV system success among other agencies.
- Worked with organizations in China to promote installation of more than 600 PV systems.
- Honored by U.S. Agency for International Development for the PV component of the Mexico Renewable Energy Program.

Message from the Director

We made major advances toward the promise of competitive electricity from photovoltaic (PV) solar cells in this pivotal year—with more record efficiencies and a burgeoning industry. As the accomplishments of the U.S. Department of Energy (DOE) National PV Program described in this document testify, we turned a corner this year. Now we see even greater possibilities ahead. The last 20 years of research and development (R&D) have built a firm foundation for continued advances in performance and cost-effectiveness in the coming years.

Generating electricity with PV offers many potential benefits to the United States and the world. PV is a distributed electrical generation technology that is less susceptible to large-scale outages than centralized power supplies. PV is an emission-free technology that provides an insurance policy against the risk of global warming. PV mitigates our dependence on foreign energy supplies, while providing distinct benefits to the domestic economy. PV is an open-ended technology in which there is much to discover and much to reap.

We know this; industry knows this. To help make sure the world comes to know of the great potential of PV, the U.S. PV industry completed a roadmapping exercise in 1999 that is similar to the one used by the U.S. semiconductor industry to meet foreign competition. The *PV Industry Roadmap Workshop Report* sets ambitious goals for annual installed production capacity and cost to the end user.

What do these industry goals mean to the PV research and manufacturing community? In 1999, PV systems in the United States generated about 150 megawatts of electrical power, and over the past several years, sales have grown by 15% to 20%. The PV Industry Roadmap goal of 3.2 gigawatts of power installed in the United States in 2020 demands consistent growth in sales of 25% annually.

What do these goals mean to the National PV Program and the National Center for Photovoltaics (NCPV)? The aggressive but achievable roadmap pathway challenges all aspects of the government program to continue doing what it does best. R&D will bring improved materials and devices suited for low-cost mass production. Technology development will incorporate laboratory performance into products. Systems engineering will accelerate the availability of high-performance, long-lived, low-cost systems in diverse applications. We at the National PV Program have taken the industry's challenge to heart.

The new National Photovoltaics Program Plan that will guide the Program's efforts from 2000 to 2004 details the R&D accomplishments needed to make the journey charted out in the PV Industry Roadmap. Together, the PV community will realize the full potential of PV with the concomitant cleaning up of the environment, creating of domestic jobs, and securing of an onshore energy supply.

James E. Rannels

James E. Rannels, Director
Office of Solar Energy Technologies
U.S. Department of Energy
Washington, D.C.

U.S. Photovoltaic Industry Roadmap 2000–2020

To meet growing market demand, confront increasing foreign competition, and retain and build their leadership position, U.S. PV companies worked over a two-year period to devise a unified industry roadmap with long-term strategies and goals and an overarching vision. Highlights from the *PV Industry Roadmap Workshop Report* follow.

Strategies

- Maintain the U.S. industry's worldwide technological leadership
- Achieve economic competitiveness with conventional technologies
- Maintain a sustained market and PV production growth rate
- Make the PV industry profitable and attractive to investors.

Goals

- Maintain a 25% annual production growth rate
- During 2020, ship 6 gigawatts of PV power for installation worldwide, with more than half of that total used in domestic installations
- Drop costs to the end user (including operation and maintenance costs) to $3.00 per watt AC by 2010 and to about $1.50 per watt AC by 2020.

The Vision

...to provide the electrical-energy consumer with competitive and environmentally friendly energy products and services from a thriving United States-based solar-electric power industry.

Research and Development

Developing new materials and processes to improve PV devices

Developing PV products that can compete with other forms of electric generation begins in the laboratories of our research scientists. These researchers explore the basic science of materials and apply newly gained understanding to devices that will eventually become components of complete PV systems with higher performance.

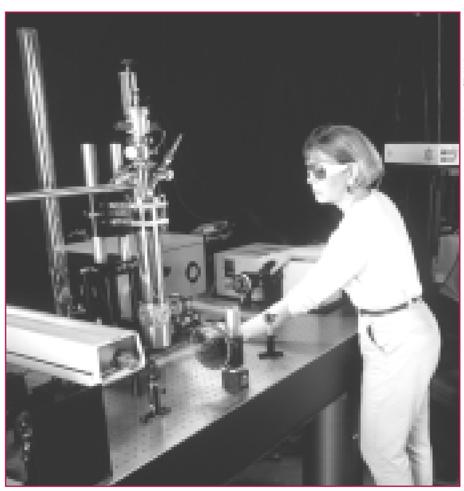
One important aspect of PV performance is efficiency—the percentage of energy from sunlight falling on a PV device that is converted to electricity. We use efficiency as one measure of our progress with materials and devices. Over the years, efficiencies of PV devices have increased from 1% or 2% to more than 32% for the most advanced materials. Eventually, we expect to have materials and devices that are more than 40% efficient.

Other measures of progress look at how easily the improved material or device can be produced outside of the laboratory. We expect the highest efficiencies from materials and devices made within the laboratory, where we have the very latest equipment and highly trained personnel who control every step of every process. Once a record laboratory efficiency is achieved, industry must be able to adapt the laboratory process for large-scale production.

Measuring our progress

For the PV Program to make the greatest advances toward high-efficiency materials and devices, the Program's Measurements and Characterization teams must provide timely data and interpretation on samples from our laboratories and from industry. Our basic research with university and industrial partners relies heavily on the specialized testing and measurement capabilities at our national laboratories—the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (Sandia), and Brookhaven National Laboratory. In 1999 alone, NCPV laboratories provided characterization expertise to more than 150 PV-related organizations. The Program's laboratories analyzed more than 18,000 samples for in-house, university, and industrial researchers.

In 1999, our Web-based "virtual laboratory" allowed collaborators from universities and industry to view real-time data collection from their samples while sitting at their own computers. These characterizations can reveal incremental improvements in materials. For example, two tools for analyzing the surface of materials (Auger electron and X-ray photoelectron spectroscopy systems) provided information on the composition of materials used by the PV community. In 1999, more than 50 different research groups participated in this Web-based data transfer approach.



Yost/PIX07100

NREL uses energy-resolved photoluminescence spectroscopy to measure material quality, determine bandgaps of solid-state materials and devices, identify defects and impurities, and analyze recombination mechanisms.

Thin-Film PV: higher efficiencies, new processes, new structures

Making PV devices by applying thin layers of semiconductor material to a substrate holds great promise for reaching our long-term goal of cost-competitive electricity from PV. This approach is promising because the components of these thin-film PV devices could potentially cost very little in terms of materials, equipment, and labor.

The NCPV and the Thin Film PV Partnership's sustained research effort, in collaboration with universities and industry, has steadily driven up the efficiency of thin-film devices. In 1999, the best copper indium gallium diselenide (CIGS) cells rose from 17.7% to 18.8% efficient. This is the world's highest efficiency for any thin-film cell on a glass substrate. In addition, the best cadmium telluride (CdTe) cells are 15.8% efficient; and the best amorphous silicon (a-Si) cells are more than 12.1% efficient. Module efficiencies are also rising. In 1999, the Program's research efforts achieved CIS-based modules with 12.1% efficiency; CdTe modules with 9% efficiency; and a-Si modules with 10.4% efficiency. With continued research, we expect commercial thin-film modules from these three technologies with efficiencies in the 10%–15% range.

These accomplishments in efficiency for CIS, CdTe, and a-Si are only part of the NCPV thin-films research story. The PV Program is also exploring less mature options such as thin-layer silicon on low-cost substrates, and multijunction combinations of different thin-film materials.

An NCPV partner that complements the work of NREL and Sandia is the University of Delaware's Institute of Energy Conversion (IEC). IEC has been conducting research in thin-film PV for nearly 28 years, working simultaneously with CIS, CdTe, and Si materials. Much of this work has been conducted through alliances with industry, government laboratories, and other universities worldwide. IEC also participates in the team activities of the Thin Film PV Partnership.

Research on copper indium diselenide (CIS, CIGS)

In 1999, an NCPV research team achieved a new world record—an 18.8%-efficient CIGS cell—by improving the absorber layer and the transparent-conducting oxide (TCO) layer. These improvements were made possible by years of research within the PV Program. For example, the absorber-layer improvements were made by changing the precursor layers and controlling the conditions during their deposition. This was accomplished thanks to new insights into the role of sodium and the development of growth models that predict material behavior as conditions change. The TCO improvements resulted from several years of incremental changes that increase the photocurrent of the device.

After breaking this efficiency record, NCPV researchers went on to systematically apply these improvements to different configurations of cells, resulting in new efficiency records in four other types of CIS-based devices. First, devices were made without a cadmium sulfide (CdS) buffer layer and they reached 15% efficiency. Second, devices deposited by electrodeposition, a potentially very low-cost production alternative, reached 15.4% efficiency. Third, flexible cells grown on stainless steel, a promising new product, achieved 17.4% efficiency. And finally, larger area devices made in the conventional configuration retained efficiencies of 18.2%.

NREL has been granted patents for the three-stage process for fabricating CIS and has awarded four licenses for these patents to U.S. industry. In addition to breaking records, the NCPV helped previous laboratory advances to make their way into commercial products. One of these products won an award from *R&D Magazine* as one of 1999's 100 most significant technological innovations. The magazine's panel selected Siemens Solar Industries (SSI) of Camarillo, CA, the California Energy Commission, and NREL for their collaborative development and deployment of the first commercial CIS thin-film modules. Marketing these modules, which average 11.5% efficiency, required overcoming technical barriers to cell and module performance and answering challenges of manufacturing, such as the requirement to repeatedly produce uniform layers of material over a large area while maintaining a high yield of product during processing.

One of the modules sent to NREL for testing set a world record for the highest efficiency thin-film module of any kind—12.1%. Throughout the


Kroposki, NREL/PIX09031

The laboratory research promise of CIS thin-film cells is proving true. This 1-kW array, comprising 28 CIS modules from Siemens Solar Industries, is the highest efficiency thin-film array to date (averaging 11.5% efficiency at Standard Test Conditions). The modules, winners of an R&D 100 Award in 1999, are being monitored at NREL for long-term performance and reliability.

Intellectual Property: the role of patents and licenses in commercial development

The primary purpose of patents and copyrights on items such as software is to facilitate the commercial development of NCPV-developed technology. The NCPV seeks to protect and maximize the value to U.S. industry of investments conducted on behalf of the U.S. Department of Energy in PV technology research and development. Intellectual property rights promote commercial development in the following ways.

First, good documentation and speedy application for patent protection assures ownership of intellectual property by the scientists and organizations involved.

Second, once ownership is protected, procedures for licensing can be initiated to expand the application of the new idea, process, or software within U.S. industry.

Third, when patented technology is licensed, the licensee receives individual assistance from NCPV staff to help ensure the successful implementation of the approach.

development of their CIS product, SSI has received support from the NCPV Thin Film PV Partnership and has collaborated in the National CIS R&D Team.

Research on cadmium telluride (CdTe)

In 1999, using several patented innovations to a process that is relatively simple (and therefore, transferrable to industry), a research team at NREL fabricated a CdTe device that is 15.8% efficient. This efficiency is equal to the world record achieved at the University of South Florida in 1992. One of the innovations included a new TCO, cadmium stannate used with a zinc stannate resistive layer, which yields higher electrical conductivity within the cell, higher optical transmittance, a smoother surface, and lower shunt-path losses. These innovations offer potential for additional increases in efficiency and promising new approaches to manufacturing.

Two companies that make CdTe PV modules made arrangements this year to expand their collaborations with the National CdTe R&D Team and move the NREL-developed processes into their production systems. BP Solarex, of Fairfield, CA, is fabricating modules in its newly built factory designed to produce up to 7 megawatts (MW) of CdTe PV modules per year. Early production modules are undergoing tests at NCPV laboratories, with real-time data returned to BP Solarex. First Solar, of Toledo, OH, is building a plant designed to produce as much as 100 MW annually of CdTe-coated plates, using its ultrahigh-rate vapor transport deposition method. The company is also working closely with NREL researchers and the rest of the National CdTe R&D Team on important issues, including contact-degradation mechanisms.

Research on amorphous silicon (a-Si)

Today, about 10% of worldwide PV production uses a-Si technology. To make this technology even more competitive, researchers are challenged to eliminate or reduce the up to 30% loss of efficiency in a-Si modules that takes place during initial exposure to light. In the past, success has been limited because the degradation process was poorly understood.

A new model of hydrogen collisions that seems to explain the photodegradation process was introduced by the NCPV in 1998. In 1999, experiments using pulsed illumination supported the model by showing the degradation mechanism occurring on a slower timescale than other models predict. This new insight could lead to designing a-Si cells that are more stable.

In the meantime, industrial partner United Solar Systems Corporation, Troy, MI, continues to break efficiency records with its triple-junction a-Si modules. In 1999, one of its modules tested at 10.4% efficiency (stabilized). The company uses the same technology in its roof-shingle product, which won two prestigious awards in 1998. In 1999, United Solar made a 300-watt module on a flexible, stainless steel substrate for use on flat roofs. Progress in the triple-junction technology was supported by the Thin Film PV Partnership in collaboration with the National Amorphous Silicon R&D Team. The company has also received support from the PV Manufacturing Technology and PV: Building Opportunities in the United States projects.

Addressing environment, safety, and health (ES&H) issues

The NCPV's team approach to research is exemplified by the National ES&H Team, which includes all major thin-film manufacturers and is cochaired by scientists from NREL and Brookhaven National Laboratory. The team has studied manufacturing issues of dust and gas toxicity (silane, germane, arsine, cadmium), and recycling methods of stripping thin films from glass and metals. In addition, the team has explored infrastructure and cost issues of an approach to recycling that uses materials from retired modules to make new ones. The ES&H Team has also studied regulatory issues using techniques such as the U.S. Environmental Protection Agency's Toxicity

Kroposki, NREL/PIX09032

This building-integrated array of 36 amorphous silicon modules from BP Solarex will shade the building and produce 2,250 kWh per year for use in the Outdoor Test Facility at NREL and for delivery to the local utility grid. The system was installed as part of a Cooperative Research and Development Agreement with BP Solarex to study the long-term performance and reliability of the system.

Leaching Procedure to clarify the toxicity and applicable regulations for thin-film technologies.

A major success of the ES&H Team has been to resolve most of the toxicity issues surrounding production, use, disposal, and recycling of products using cadmium telluride, clearing the way for large-scale manufacturing. Another success has been to work with crystalline-silicon manufacturers to reduce or eliminate lead from cell-interconnect solders and grid pastes.

CRYSTALLINE SILICON: IMPROVED MATERIALS, REFINED PROCESSES, AND NOVEL DEVICES

Companies that sell PV products made with crystalline silicon control 90% of the world market. Yet, there is still room for technological advancement to improve performance and reduce costs. The PV Program funds research to improve both silicon materials and fabrication processes and devices.

Facilitating cooperation among researchers is an important role for the NCPV. For example, in 1999, the Program sponsored the 9th Workshop on Crystalline Silicon Materials and Processes, in which more than 100 researchers from around the world reported on their efforts to achieve the full potential of silicon.

Researching silicon PV materials

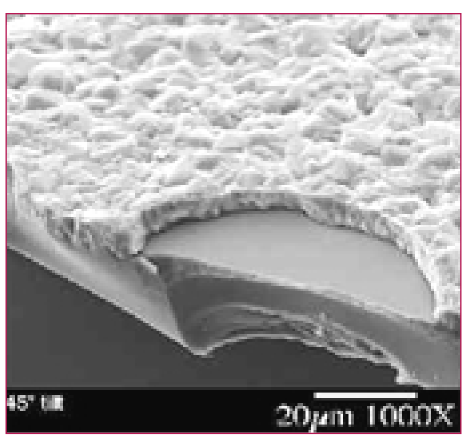
Thin-layer silicon is seen by many as the next logical step in solar cell development. First there was single-crystal technology, followed by cast silicon, and then came various sheet-growth methods. Now the challenge is to produce a very thin, active silicon layer at a fast deposition rate on a low-cost substrate. In 1999, a research team at NREL developed a novel method that produces continuous silicon layers 5–20 microns thick with 5–10-micron grain size on glass at a rate of 1–10 microns per minute. The team has applied for a patent while it continues to prepare this method and material for eventual use by the U.S. PV industry.

The NCPV develops specialized analysis tools for those working on PV materials and devices. In 1999, for example, a new characterization tool developed by NREL, *PVScan*, produced defect maps of crystalline-silicon materials. After several requests to build systems for others, *PVScan* has now been documented so that it can be built at a job shop and operated more effectively by new users.

An upgraded version of another popular analysis tool, *PV Optics*, was released this year to 80 licensees. The new version models the emissivity of silicon and allows calculation of the temperature of a Si wafer during optical processing. The new version also reduces the calculation time for analysis of multijunction cells.

Researching processes and devices for silicon PV

Improving the way solar cells are made can significantly reduce cost and increase performance. For example, single-crystal silicon wafers can be textured to increase light absorption and electricity generation in PV systems. To increase the light absorption of lower cost multicrystalline silicon cells, researchers at Sandia are experimenting with plasma processing to form a highly transmissive surface on the material. In 1999, using a plasma process known as reactive-ion etching, they achieved a 39% relative increase in the absorption by the cell. Work continues to optimize the process so that such texturing can be incorporated into cell fabrication by manufacturers of multicrystalline PV products.



NREL

A thin layer of silicon on glass produced by a novel method developed by NCPV researchers at NREL is shown in this scanning electron microscopy image.

Another way to reduce costs in cell fabrication is to combine steps and move toward continuous processing rather than treating cells in batches. To this end, the Program commissioned the design of a plasma-processing machine to replace the standard antireflective coating machine used in industry today. The conceptual design incorporates automatic loading and unloading of wafers, a belt transfer system, and an air-to-vacuum transfer compartment that allows continuous processing. Because of continuous processing, the machine can incorporate reactive-ion etching of the surface prior to deposition to decrease the reflectivity of the surface. Then, after depositing silicon nitride by plasma-enhanced chemical vapor deposition, the system achieves plasma hydrogenation along with the nitride layer. The machine should be able to process as many as 1,000 cells per hour and meet cost constraints specified by industry.

Developing new cell designs is another way the PV Program supports research leading to commercial products. One of these new cell designs has both of the electrical collection grids on the back of the cell. This cell structure avoids the shading from the front gridline structure that collects charge in conventional silicon solar cells. Back-contact cells also hold the promise of easier assembly because the contacts could be interconnected using higher-throughput techniques. In 1999, NCPV researchers at Sandia achieved a new record efficiency of 18.0% for a large-area, back-contact silicon cell using evaporated metals. More importantly, this research team achieved an efficiency of 15.2% for a large-area, back-contact cell using low-cost, screen-printed metals.

Research at the Georgia Institute of Technology PV Center complements the research activities at NREL and Sandia. Georgia Tech holds a Sandia subcontract to emphasize fundamental understanding appropriate for education and advanced degrees, while still performing industry-relevant research that could lead to low-cost, high-efficiency silicon solar cells.

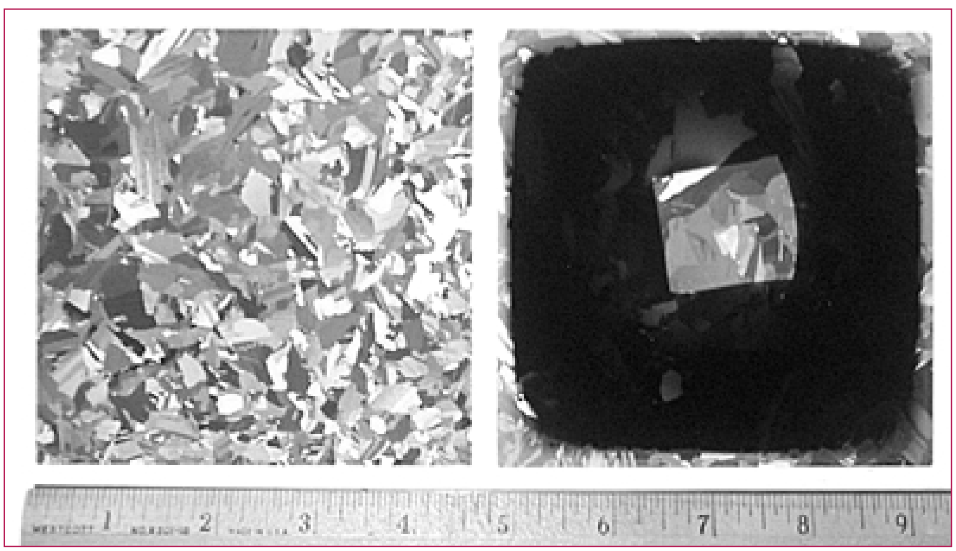
Georgia Tech is trying to fabricate high-efficiency cells on low-cost thin-silicon materials by developing and integrating rapid and cost-effective technologies. Rapid thermal processing (RTP) uses banks of tungsten halogen lamps to radiatively heat the sample in a cold-wall system. The radiation spectrum of RTP contains high-energy visible and ultraviolet (UV) photons, which can accelerate semiconductor processes, such as oxidation and diffusion, to reduce the cell processing time.

Georgia Tech has done pioneering work in this field by developing RTP technology for each part of the solar cell fabrication process while maintaining high efficiency. University researchers have fabricated record-high-efficiency (19.5%) RTP cells and continue to raise the efficiency, while making RTP more manufacturable and adaptable to advanced cell-design concepts.

> *"Multijunction solar cells have made a major impact on the cost-effectiveness and revenue-generating capabilities of high-power space satellites over the last five years, and we expect them to have a similar impact on the \$1 billion terrestrial (PV) industry."*
>
> David Lillington, Vice President for Solid-State Products, Spectrolab.

HIGH-EFFICIENCY CONCEPTS: NEW RECORDS, LICENSES TO INDUSTRY

Another world-record efficiency—32.3% at 50 suns—was achieved in 1999 by Spectrolab, a unit of Hughes Electronics Corporation, and NREL. Spectrolab's concentrator cell is a triple-junction device: gallium indium phosphide (GaInP) on gallium arsenide on germanium. Cells such as this could double the power output of terrestrial PV applications in operation today.



The sample on the right is plasma-treated multicrystalline-silicon material that appears almost black to the eye. Unlike the untreated sample on the left, the etched sample will absorb almost 98% of the usable portion of the solar spectrum without the need for an antireflection coating. PV Program researchers used specialized plasma-processing facilities at Sandia National Laboratories to conduct these experiments.

In other work on high-efficiency PV, NREL's patents covering the GaInP/GaAs high-efficiency tandem solar cell have been licensed by TECSTAR and Spectrolab for production and sales in markets for space satellite power systems. Commercial runs produce cells in large quantity that are about 25% efficient. The best cells coming off the line have tested at 27% efficiency.

EXPLORATORY AND FUNDAMENTAL RESEARCH: NEW APPLICATIONS, NEW INITIATIVE, NEW SCIENTISTS

The fundamental research of the PV Program has fueled the steady improvement of PV materials and devices for the terrestrial PV electricity market. In addition, the nation has benefited from the application of our research to other venues. For example, our successful long-term work with GaAs PV cells, begun in the mid-1980s, has made satellite power systems more efficient and more resistant to damage from radiation in space.

New materials are being discovered all the time, in part because our ever more powerful analytic and modeling tools are allowing scientists to predict structures and outcomes before experiments are conducted. These new discoveries hold great potential for increasing efficiency in PV devices and lowering their cost.

For example, researchers are exploring semiconductor nanocrystals. This novel class of semiconductor material, called quantum dots, lies between the single-atom and solid-state forms of matter. Their small size produces many interesting effects in semiconductors and allows the tuning of material properties simply by controlling particle size.

Another team of researchers is working on the dye-sensitized solar cell. In this simple and potentially inexpensive cell, titanium dioxide (TiO_2) converts the UV portion of sunlight to electricity. Dyes make TiO_2 sensitive to the rest of the solar spectrum. Recent research in Switzerland showed that making dye cells with nanosize TiO_2 particles can produce cell efficiencies as high as 12%. At NREL, research is under way to increase efficiency and improve stability.

In 1999, work began on 18 subcontracts to universities under the Future-Generation PV Technologies competitive solicitation. Using information from a conference on PV Technologies for the 21st Century, a Workshop on Basic Research Opportunities in Photovoltaics, and the results of the solicitation, a research plan was developed to fund exploratory research into future generations of PV technologies. Supporting a large number of highly competent researchers, even with fairly low project budgets, greatly increases the probability for successful research results from these fundamental and exploratory research efforts.

1999 Awards to Universities

Arizona State University, Tempe
Test Standards for Future-Generation PV Technologies.

University of California, San Diego
GaInNAs Structures Grown by MBE for High-Efficiency Solar Cells.

University of California, Santa Barbara, in collaboration with **Harvard University**, Cambridge
Growth and Characterization of GaInNAs for High-Efficiency Solar Cells.

University of California, Berkeley
Photovoltaic Devices Based on New Nanocrystal Composites.

California Institute of Technology, Pasadena
Low-Temperature, High-Throughput Process for Thin, Large-Grained Poly-Silicon.

Cornell University, Ithaca
Elastic Properties of Thin-Film Silicon.

University of Illinois, Urbana
Medium-Range Order and Stability in Amorphous Silicon.

University of Minnesota, Minneapolis
Experimental Studies of Light-Induced Changes in Long-Range Disorder in Amorphous Silicon.

Northwestern University, Evanston
Improved Transparent Conducting Oxides for Photovoltaics.

North Carolina State University, Raleigh
Novel Growth Methods for GaInNAs for High-Efficiency Solar Cells.

University of Oregon, Eugene, in collaboration with **Reed College**, Portland
Novel Capacitance Measurements in Copper Indium Gallium Diselenide Alloys.

Pennsylvania State University, University Park
Real-Time Optics for the Growth of Textured Silicon-Film Solar Cells, and

Chemical-Reaction Modeling for Encapsulants in Photovoltaic Modules.

University of Rochester
Porous Polycrystalline Silicon Thin-Film Solar Cells.

State University of New York at Buffalo
Synchrotron Radiation Studies of Photovoltaic Materials and Devices.

Vanderbilt University, Nashville
Biomimetic Photovoltaics Employing Semiconducting Nanocrystal Multicomposites.

Washington State University, Pullman
Novel Characterization Methods for Microcrystalline Silicon.

West Virginia University, Morgantown
Nanostructure Arrays for Multijunction Solar Cells.

Encouraging students

A good supply of new scientists coming in to the field of PV research is basic to our continued progress. One of several projects to promote undergraduate and graduate education is the Renewable Energy Academic Partnership (REAP), begun in 1995. REAP is designed to advance knowledge of PV for students in Historically Black Colleges and Universities (HBCUs). This year, the PV Program funded eight HBCUs to develop research projects in PV involving undergraduate students. A REAP Conference to review the progress of these projects brought students and professors together to learn from each other and from other experts in the field. Hosted by Southern University and A&M College in Baton Rouge, LA, the meeting featured presentations on exciting research projects and outreach activities by students in their communities and in developing countries.

Stafford, NREL/PIX08953

Student teams combine technical design, project management, public relations, and fund-raising skills to bring their solar-powered cars to the Sunrayce biennial competition. "Innovation and imagination drives these students," according to Energy Secretary Bill Richardson. Sponsored by DOE, General Motors, and Electronic Data Systems, NCPV staff have helped organize the competition since its inception in 1990.

FY 1999 Additional Achievements in Cooperative Research and Development

Organization achieving result	What was accomplished	Why it was important
NREL	Gained patent for ethylene vinyl acetate formulations for PV module encapsulation.	Wider availability of formulas through licensing agreements should improve the performance reliability of PV modules.
NREL	Achieved high-rate a-Si deposition indicating feasibility of industrial deposition rates up to 100 times greater than those seen today.	Increasing throughput of equipment is a key way to reduce production cost and increase production growth rates.
Sandia	Performed detailed thermochemical calculations on purification of silicon melts.	Development of new silicon purification techniques is important to expand supplies of silicon feedstock for industry.
Sandia	Published "Circuit Modelling of the Emitter-Wrap-Through Solar Cell" in a special issue of *IEEE Transactions on Electron Devices*, October 1999.	Modelling led to improved device physics for an important cell design option, helping to achieve new records for back-contact cell efficiencies.
DOE Office of Science-Basic Energy Sciences, Office of Renewable Energy and Energy Efficiency	Identified a new III-V alloy material (GaInAsN) that shows exciting optoelectronic properties; work under way to optimize the material for use in multijunction solar cells potentially approaching 40% efficiency.	Investigating the physics of this innovative technology enhances the fundamental understanding of an important class of solar cell materials.
BP Solarex	Increased deposition rate 100% (from 1 to 2 angstrom/second), reduced use of germane by 50% in production of a-Si products.	Reduced production costs of a-Si modules.
EBARA Solar, NREL	Improved the success rate of EBARA's ribbon starts by a factor of 2.3; eliminated surface tension instabilities; and thermally isolated growth and feeding zones.	Improved crystal growth in EBARA Solar's production process.
United Solar Systems Corporation, Colorado School of Mines, NREL	Found that infrared absorption provides a rapid, simple technique for identifying hydrogenated a-Si with enhanced medium-range ordering.	Improvement over X-ray line width or H-evolution temperature measurements to characterize improved material ordering.
Georgia Institute of Technology	Using rapid thermal processing to make 19.6%-efficiency cell; Built belt furnace prototype, used intense light to allow lower temperatures, faster processing (2 hours or less) with screen-printed contacts.	Belt furnace could substantially increase the throughput and performance of silicon PV cells.
Institute of Energy Conversion and Global Solar Energy	Fabricated an 11.5%-efficient CIGS cell on a flexible stainless-steel substrate; device structure ZnO/CdS/CiIGS/Mo/SS.	Progress toward the goal of a 13%-efficient prototype module.
Institute of Energy Conversion and Unisun	Developing a new particle-based technology to deposit CIS materials using IEC's fabrication and analysis facilities to evaluate the materials.	Allows start-up company to concentrate on developing materials rather than also on fabrication and evaluation.

Technology Development

Improving manufacturing processes and component performance

To reach the goals that the U.S. PV industry set in its PV Industry Roadmap Workshop—40% of the world PV market and annual domestic sales of 3.2 billion watts by 2020—domestic manufacturing capacity must increase by nearly a hundredfold. This calls for applying R&D advances in materials, devices, and processes to the manufacture of lower cost, highly reliable products. The PV Program and industry must cooperate closely to leverage expertise, facilities, and funds and to gain maximum technological and market advances over the next 20 years.

The PV Program's work in manufacturing research has reduced average direct manufacturing cost among our industrial partners by more than 30% since 1992. In addition, manufacturing capacity has increased fivefold during this period. This year's work, stemming from manufacturing R&D subcontract awards, continues to reduce costs and increase capacity for U.S. module manufacturers and for the companies that produce balance-of-system (BOS) components.

The technology path to reach goals identified in the PV Roadmap Workshop requires continued effort in three key areas of manufacturing R&D. First, processes must operate more quickly and reliably. This requires intelligent processing and in situ diagnostics, just beginning to be explored by industry. Improving processes will increase yield—the number of usable cells and modules that come out the end of the production line—and throughput—the rate at which these products are produced. Second, the PV systems produced must incorporate the higher efficiencies that are being demonstrated in research laboratories. And third, processes must be adapted for large-scale manufacturing lines.

Manufacturing Research and Development Partnerships: faster production, higher efficiencies, lower costs

Industrial partners of the PV Manufacturing Technology (PVMaT) project continued to improve manufacturing processes, reduce manufacturing costs of modules and components, improve the performance and reliability of their products, and present investment opportunities to increase manufacturing plant capacities in 1999. Companies working under cost-shared contracts in the most recent PVMaT solicitation are addressing a broad range of manufacturing problems, including issues with materials, modules, BOS components, and systems.

In addition to PVMaT contracts, many of the industrial partners participate in other aspects of the PV Program and apply the benefits of this participation to their manufacturing efforts. Here are highlights from the 1999 accomplishments of our industrial partners in manufacturing R&D.

Ascension Technology, Inc., is working on the manufacture of its sequel to the SunSine™ 300 AC module, the SunSine™ 325. The company's recent work has reduced the inverter's size by 40%; this and other improvements have contributed to a 42% reduction in manufacturing costs. In addition to cost improvements, the company expects to raise inverter efficiency to 91% or greater at full power. More than 240 AC modules were shipped for grid-connected applications by the end of FY 1999.

ASE Americas, Inc., grows crystalline-silicon material in the shape of thin octagonal tubes. The material is then cut into wafers for manufacture into PV

ASE Americas/PIX09036

ASE Americas/PIX09037

Under a PVMaT contract, ASE Americas designed, constructed, and tested a 50-cm-diameter crystal growth system for producing silicon wafers. This new system produces the PV material in a cylinder (rather than the octagon shape currently used), which allows a thinner wafer to be grown—down to 100 microns of wall thickness versus 275 for the current system. Cylinders as long as 1.2 meters have been grown.

cells and modules. In 1999, the company improved its manufacturing processes, which resulted in increasing the efficiency of its cells to more than 14%. The company changed the width and firing temperature of grid fingers, the belt speed and firing temperature for front metallization, and the temperature profiles of antireflection coating and diffusion processes. In addition to cell production, the company is working to speed up production of its silicon material by growing large cylinders and improving laser-cutting technology.

AstroPower, Inc., is improving the continuous processing of its Silicon-Film™ PV material in collaboration with NCPV laboratory personnel. In 1999, NREL developed and applied three techniques to help AstroPower qualify feedstock material. These include a system to measure ultrahigh-frequency photoconductive decay, a spectroscope to measure deep-level transients, and a spectroscope to measure Fourier transform irradiance. These tools have substantially improved AstroPower's knowledge of its material and processes, bringing the company closer to the goal of having a reliable in-line monitoring system in the factory to produce 900-cm^2 silicon PV cells that are 12% efficient.

BP Solarex made progress in two areas of research: silicon feedstock production and module manufacturing. The company is increasing the yield of its manufacturing line while reducing labor costs by improving the way materials and products are handled. For example, units for casting silicon ingots were converted to new PC-based controllers. Wire saws for cutting ingots into wafers were converted from 180-micron wire to thinner 160-micron wire to reduce waste during cutting. Solarex used the waste from its cutting process in several experimental casting runs, with no apparent degradation in wafer yield or quality.

Also in 1999, BP Solarex worked with subcontractors Viridian Technology and SiNaF to design and estimate the cost of a pilot line to produce silicon feedstock from commercial grade H_2SiF_6 material. The 100-metric-ton pilot line is scheduled for development in 2000.

BP Solarex/PIX08178

PV cell manufacturing is coming of age as PVMaT partner BP Solarex demonstrated this year. The company developed a fully automated cell-processing system. By automating the cell-contact process, throughput has been increased as well as efficiency of the finished product.

Crystal Systems, Inc., is working to free the PV industry from reliance on the rejects and scraps from the semiconductor industry for its supply of silicon feedstock material. Using metallurgical-grade silicon, the company approached the purity level of scrap silicon by modifying its refining techniques and reducing metallic impurities to less than 1 ppma (parts per million atoms) and boron and phosphorus content to less than 10 ppma for a 50-kg charge. The new thermochemical refining process uses a modified heat-exchanger-method furnace that incorporates gas blowing, vaporizing, slagging, and sampling. In addition to producing solar-grade silicon feedstock with fewer impurities, the process is expected to result in higher throughput rates and reduced labor costs. The company's goal is to reduce the cost for silicon feedstock to less than $20/kg.

Energy Conversion Devices, Inc., is monitoring and controlling temperature more effectively to improve production of high-efficiency, triple-junction, a-Si solar cells. The company has developed a set of in-line, real-time, monitoring systems to evaluate material quality. The company is also demonstrating the use of zinc metal sputtering targets to prepare zinc oxide layers for high-performance back reflectors. The internal hardware for a-Si intrinsic-layer deposition chambers is also being redesigned.

Evergreen Solar, Inc., incorporated a new string material into its production process for String-Ribbon silicon PV modules. The company found a commercially available material for the string that has a coefficient of thermal expansion close to that of the silicon. This resulted in production runs of string ribbon four times longer than the prior record. This innovation, along with others, should reduce labor and materials costs by 20% and result in a 5% (relative) increase in cell efficiency.

First Solar, L.L.C. (formerly Solar Cells, Inc.) is working on a CdTe module production line. The company is designing, developing, and implementing an improved ethylene vinyl acetate (EVA) lamination process. In addition, a new potting procedure and scribing technique have contributed to a lamination process that requires only 2 minutes per module (down from 3.3 minutes) and has reduced capital and labor costs by 90% each. The improved production line can coat 1,080 ft^2/hr (100.34 m^2) of module material.

Meanwhile, the modules produced have successfully completed qualification tests and demonstrated reliability over several years of outdoor testing. The company markets these production lines to the PV industry to manufacture CdS/CdTe modules.

Global Solar Energy, L.L.C., is refining its processes to make CIGS-based thin-film modules. The company is using multiple-beam lasers for high-speed scribing of the CIGS layers in the modules. In addition, a new process uses ink-jet printing to deposit insulating material on scribed areas. This process works as well as screen printing, but could be much faster and less expensive. The company is also integrating a new CIGS deposition process to move flexible substrate onto the manufacturing line.

Omnion Power Engineering Corporation is enhancing the design of its 2-kW inverters, which will be easily manufactured and be suitable for use in residential applications. Omnion has finalized the topology, selecting a transformerless configuration that allows an input of 100 to 400 volts DC with an output of 120 volts AC. Omnion Power was purchased in 1999 by S&C Electric Company.

PowerLight Corporation markets fully engineered PV systems for rooftop applications. The crystalline-silicon or thin-film modules are mounted on a 3-inch-thick styrofoam board coated with a proprietary cementlike coating. A new manufacturing plant in California for this PowerGuard® product is being automated. Thus far, installed system costs have been reduced by $1/W for large systems and production capacity has been increased from 5 to 20 MW per year.

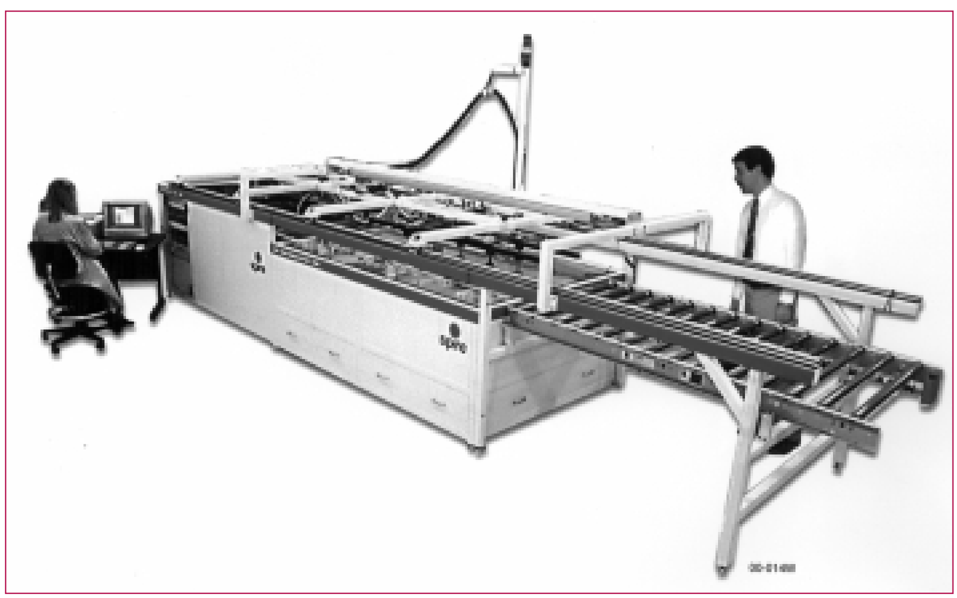
Siemens Solar Industries is developing and integrating new fabrication processes for its 17%-efficient, 125-micron-thick silicon cells. The company is also setting up production for its larger, 200-mm-diameter prototype cells and for prototype modules.

Spire Corporation builds equipment for automated assembly of PV modules. The company is working on several improved systems for the PV industry that can be used to assemble modules made with either silicon solar cells or thin-film materials. In 1999, Spire developed an automated buffer storage system that holds modules between steps along a continuous-processing conveyor line. The company also debuted a test system for finished modules that combines high-voltage isolation testing and module performance testing in a SPI-Module QA™ 350. Work is under way on an automatic system to trim, seal, and attach framing to the edges of PV modules. Another planned system will automate the installation of junction boxes on modules.

Utility Power Group (UPG), with its lower-tier subcontractor Trace Technologies, is working on a rooftop PV system that includes a PV array, consisting of modules, a frame and roof-top mounting, an optional battery storage unit, and a Power Unit with a continuous power rating of 12 kW and a peak power rating of 19.2 kW. UPG and Trace selected this power rating to meet large household requirements and to manage motor starts such as air conditioners. In 1999, Trace Technologies tested the prototype Power Unit and reports the continuous, full-power measured efficiency is 95.7%, exceeding the goal of 94%. The high-frequency Power Unit switching at 30 kHz makes this a quiet unit, well suited for its planned application as a residential system.

Frank, ITFT/PIX06416

In a PVMaT contract completed this year, Iowa Thin Film Technologies' new roll-based lamination process (shown above), in combination with other automation improvements, provides a factor-of-ten increase in throughput.



Spire/PIX09038

In June of 1999, Spire Corporation completed and began marketing the SPI-MODULE QA™ 350, an automated module-testing system that was developed under a PVMaT contract. This new piece of equipment gives PV manufacturers a leg up in their quest to fully automate all functions of PV module production and quality control.

System Components: increased performance and reliability

In 1999, the unique equipment and expertise of the NCPV were brought to bear on some of the thorniest industrial problems—such as long-term durability of modules and the effects of power surges on electronic control equipment.

Module performance testing and modeling

Reducing uncertainty about how a PV system will perform in a given environment is important for expanding the use of PV systems. The NCPV facilities for outdoor testing, accelerated testing, and laboratory simulations are available to industry—to guide redesign efforts and to evaluate commercial products.

For example, after nine months of outdoor exposure at the NREL Outdoor Test Facility, the 1-kW CIGS array from Siemens Solar Industries showed stable performance, 11.4% efficiency, and no degradation. Other detailed performance information such as average operating temperature and normalized DC power output will be forwarded to Siemens Solar over the two-year test period. In other work directed toward reducing uncertainty, the PV Program made a new computer model available in 1999 to predict module performance characteristics under varying weather conditions on a daily or even annual basis. This model, developed at Sandia, is based on four years of painstaking outdoor module testing and analysis.

Now, PV system designers can access these test data in a format that makes system optimization easier. The user selects modules by manufacturer and model number. Performance parameters for more than 50 commercial modules are in the model. Then, adjusting for seven variables ranging from ambient air temperature to solar angle-of-incidence, the user generates graphs of current-voltage at specified operating conditions.

This model has been combined with design software by a commercial software company (Maui Solar Energy Software Corporation, HI) for use by PV system designers. Designers can select and configure modules whose performance, in terms of either power or energy, best matches the application and climatic conditions. Two other software companies plan to incorporate the NCPV model into their design tools. The result should be systems that are better matched to their locations. Data for new modules coming on the market, such as thin-film and concentrator modules, will be added to the model each year.

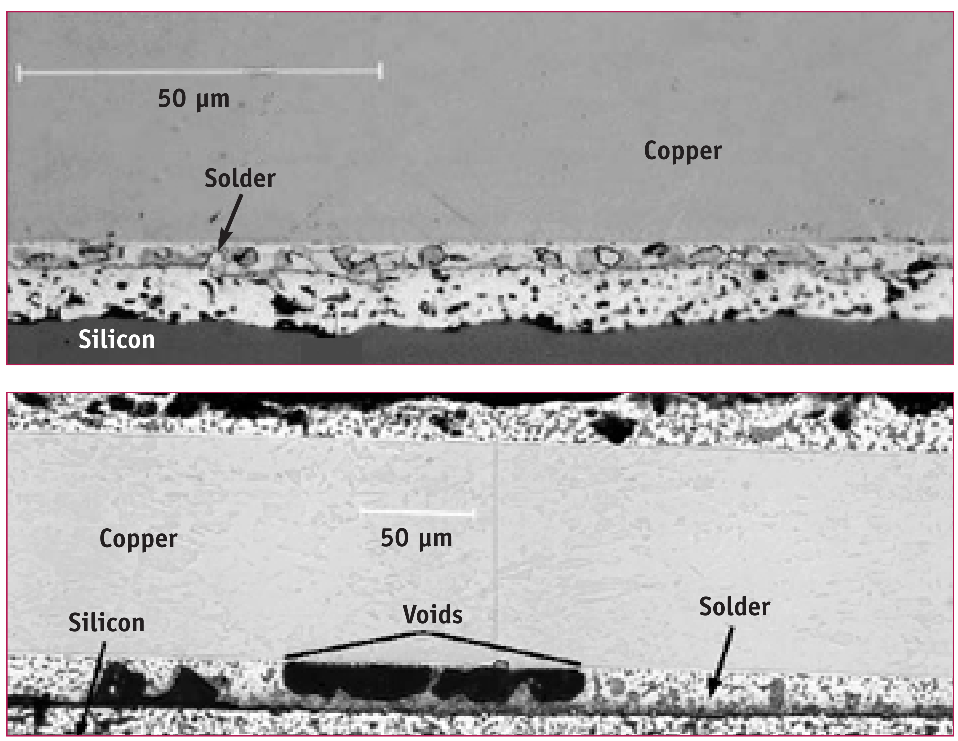
The model will be further enhanced and validated by incorporating the results of ongoing array testing conducted by both Sandia and NREL.

Long-term exposure studies

To identify and solve specific durability issues that result from long-term operation, the NCPV coordinates the Module Durability Research Cooperative (MDRC), a collaboration with U.S. industry.

One of the issues identified by the MDRC for research is the quality and longevity of solder bonds in PV modules. When solder bonds fail, series resistance goes up, performance goes down, and hot spots develop on the module. Temperatures of some spots can get so high that laminate materials melt, causing catastrophic failure.

The key to solder-bond durability is good manufacturing technique—applying the solder to compatible materials, maintaining rigid process controls, and controlling the geometry of the resultant bond. Today's module manufacturers use three or four different soldering processes to make the interconnects necessary to produce modules with a variety of power ratings. To test the success of their manufacturing techniques, companies use a "peel strength" test. This test does not represent



Sandia

Researchers examining solder bonds look for characteristics such as solder volume, geometry, contact angle, intermetallic formation, and wetting to characterize joints that will stand up well over time (micrograph on the top). Solder joints that are more prone to failure will exhibit characteristics such as voids, coarsening, irregular geometry, and cracks (micrograph on bottom).

the actual stresses a bond sees in the field, which are largely shear stresses caused by differential thermal expansion. Researchers at Sandia are working to develop new, nondestructive test methods that can be used in the factory to control the quality of solder joints on modules coming off the manufacturing line.

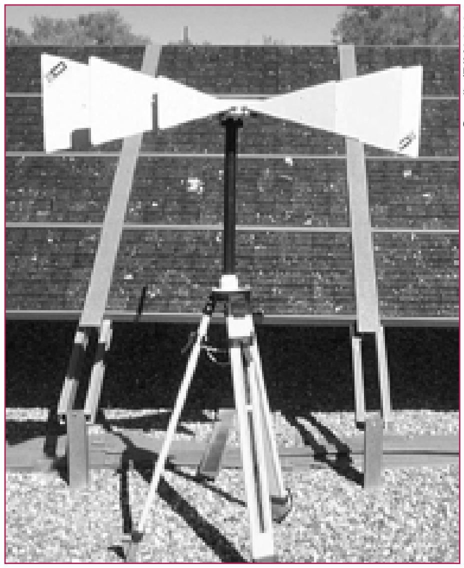
Balance-of-systems (BOS) studies

Under programs such as the BOS development program, PVMaT, and PV:BONUS, the PV Program issues contracts for hardware development and industrial quality control. Components other than the PV modules themselves represent about half the initial cost of a PV system today and account for most of the maintenance costs during operation. The NCPV's work to reduce the costs and improve the reliability and performance of BOS components will have a significant impact on the cost of electricity from a PV system over its lifetime.

A key PV BOS component is the inverter that converts the DC electricity produced by the PV array to the AC power necessary for many uses, including grid-connected applications. The Sandia BOS program works with inverter manufacturers to improve the reliability and performance of these electrical devices with PV systems. As a result of

Omnion/PIX07800

Development of sophisticated power conversion equipment, such as this series 3300 by Omnion, has been supported by the PV Program for several years. As a result, increased efficiencies and reliable operation are being enjoyed by consumers of PV systems.



Sandia/PIX09027

Part of the specialized equipment to test BOS components, this device measures unwanted electronic "noise" from power conditioning systems.

these efforts, a 1999 study showed that the mean time between failures of inverters for one manufacturer increased from 3.4 years in 1996 to 13 years in 1998.

Another way the Program advances inverter technology is by testing new hardware designs under normal and worst-case operating conditions. In 1999, nine inverters were operated using PV arrays to generate the input power and real loads (such as batteries, the local utility grid, and motors) to test performance. All relevant operating parameters were carefully monitored and supplied to the manufacturer. In most cases, the manufacturer used this information to optimize its design for PV.

One of the key requirements for inverters is that they will not operate as an "island" within the utility system under any condition. Islanding results when a dispersed generation source (such as PV) and a portion of the utility system operate while isolated from the remainder of the system. Utilities fear islanding because line workers could be exposed to electricity in a line that should be de-energized with the rest of the system. There is also potential for damage to utility and customer equipment from uncontrolled voltage and frequency swings within the island. For example, the PV inverter will probably be destroyed if the utility reconnects while the inverter is still operating. Because most manufacturers do not have the equipment to test inverters for this kind of behavior, the NCPV's inverter test facility at Sandia subjects inverters to conditions likely to produce islanding.

Nearby lightning and capacitor switching can result in surges on AC and DC inverter power wiring and diagnostic cables that have the potential to shorten inverter lifetime. In addition, the potential for such surges to disable the anti-islanding technology of the inverter is of concern to utilities. For these reasons, Sandia has initiated a surge testing program. The Institute of Electrical and Electronics Engineers (IEEE) C62.41-1991 (category B) and C62.45-1992 define the pulses that are applied to the hardware. Initial testing has been limited to PV inverters. Criteria for successful completion of a test are: (1) no failures at agreed-to open-circuit surge generator voltages, and (2) no impairment of anti-islanding circuitry. Note that this is a design evaluation test and that the stress to the inverter is not necessarily limited, as it would be in a screening or qualification test. In tests done specifically to determine compliance with a utility requirement, the voltage will be limited to the utility requirement.

This anti-islanding test and analysis work is providing information to modify the IEEE 929 standard used by utilities to define a grid-tied inverter that is acceptable for installation on their systems. The standard must be modified to define inverters that will not island when exposed to surges.

Systems Engineering and Applications

Reducing barriers to expanding markets

What really matters to customers is that PV systems perform reliably, as expected, for many years. Satisfied customers are an important element of any strategy to meet the ambitious market goals outlined during the PV Industry Roadmap Workshop. Industry must continually address technical and institutional barriers to expanded applications of PV systems. The NCPV works with industry to ensure the continued competitiveness of U.S. PV products.

Engineering Systems: targeted technical assistance and support for standards development

Some important performance issues must be addressed by looking at the entire PV generating system. System-engineering activities within the NCPV collected field data and provided technical assistance to improve the performance of PV systems installed in diverse applications around the world.

In addition to addressing technical barriers, Program personnel organized training and information activities to remove institutional barriers. Addressing both technical and institutional barriers, the Program played a crucial role with industry in developing qualification protocols, energy production models, and accepted standards for interconnection to the utility grid.

Technical assistance and field engineering

The NCPV offers technical assistance in the design and assessment of PV systems. These activities range from public information to hands-on field engineering for government agencies wishing to install PV for the first time. Many former first-time users are now consulting to others within their agencies thanks to recently completed NCPV projects with the National Park Service, the Bureau of Land Management, the U.S. Forest Service, and the Department of Defense. In 1999, an assessment performed by an NCPV team found several good opportunities for PV at a new park facility in Katmai National Park, Alaska.

Thornton, NREL/PIX06249

This 15-kW grid-connected PV system at the Pentagon in Washington, D.C., began operation in June 1999. The SunSine™ AC modules developed by Ascension Technology under several arms of the PV Program require no separate power-conditioning unit to deliver electricity to the utility. The phased installation will eventually result in a 75-kW system funded entirely by the U.S. Department of Defense.

In additional work this year, NCPV personnel worked with the City of Chicago to convert abandoned industrial land to a PV manufacturing district. Our experts are also advising on the installation of PV at the Yucca Mountain/Nevada Test Site to power monitoring equipment at the nuclear waste storage facility.

During 1999, NCPV personnel in the PV Systems Assistance Center at Sandia responded to more than 250 requests for field-engineering assistance from utilities, local, state, and federal agencies, and from companies putting PV systems in new applications. An integral part of our technical assistance is documenting what works best and providing that information to guide future efforts.

Much of this information was made available to the public in 1999 with award-winning Internet Web pages maintained at NREL and Sandia for the NCPV. These popular sites feature everything from downloadable technical reports to basic information for the homeowner. In addition, printed reports and brochures about PV applications remain as popular as ever and were distributed widely in response to requests.

NCPV experts were also called on in 1999 to write papers and conduct workshops. In the Washington, D.C., area, workshops for consumers at the

Smithsonian Institution and for government employees at DOE Headquarters had standing room only. The publication authored by NCPV experts of an invited paper, "Photovoltaic Systems: An End-of-Millennium Review," in the international journal *Progress in Photovoltaics* was the first review paper on PV systems ever published in the journal. In addition, *IEEE Spectrum*, the general interest journal of the Institute of Electrical and Electronics Engineers, published a cover story on PV in September 1999 that was authored by NCPV scientists.

Supporting standards development and certification

From technical reports to test procedures to recommended practice, the work of NCPV test engineers contributed this year to several key standards activities. The initial draft of IEEE P1526, "Recommended Practice for Testing the Performance of Stand-Alone PV Systems," was supported by detailed intercomparison of small system tests. The tests validated the interim test methods developed by the standards committee. These methods will be used by the PV Global Approval Program (PVGAP) until International Electrotechnical Commission standards are published.

In other work to support standards development, a study validated a module energy ratings procedure developed at the NCPV. PV performance measurements were made at NREL's Outdoor Test Facility and used to compare modeled and measured maximum power values for several modules representing different technologies. Modeled values compared within 5% of measured values on an annual basis. The detailed test procedure will be incorporated into IEEE P1479 "Recommended Practice for the Evaluation of Photovoltaic Module Energy Production."

NREL and Sandia researchers worked with industry and utility representatives to develop a qualification standard for PV concentrator modules (IEEE P1513, Recommended Practice for Qualification of Photovoltaic Concentrator Modules). Patterned after the Program's successful facilitation of crystalline-silicon and thin-film module standards, the intent of the proposed qualification testing procedure is to identify design, material, or component flaws before modules enter the marketplace. The activity began in 1997 and working group members have developed and reviewed seven drafts. They plan to complete the standard next year.

The effort to assure consumers of the performance of PV modules moved forward in 1999. PowerMark Corporation certified modules from two U.S. manufacturers, BP Solarex and United Solar Systems Corp. This kind of third-party certification provides evidence to consumers that modules meet PV performance and quality consensus standards. The PV Program was instrumental in establishing the PowerMark Corporation, which accredits laboratories to certify PV modules in the United States.

Developing Applications: expanding domestic and international markets for U.S. products

Installing PV systems through efforts of the NCPV provides feedback to the technical research program and helps address institutional and economic barriers to the rapid expansion of the U.S. industry. Monitored installations supply a benchmark database for analysis of lifetime, initial costs, safety, interconnections performance, and recurring operating and maintenance costs. These carefully designed projects demonstrate the advantages of PV as an energy supply and pave the way for future installations.

PV applications in the United States

In 1999, the NCPV worked in partnership with government, utility, grass-roots, and industry groups to promote the installation of well-designed PV

Kroposki, NREL/PIX09028

This testbed at NREL's Outdoor Test Facility can be configured in many combinations to power up to six different stand-alone systems on the front rack and one grid-connected system on the roof. The testbed was being used in 1999 to validate performance test procedures for stand-alone PV systems that could become part of the IEEE standard.

systems in the United States. We are moving toward the goal of the Million Solar Roofs Initiative, announced by President Clinton in 1997, to place one-million solar energy systems on buildings and homes across the nation by 2010. Work is also guided by the *PV Industry Roadmap Workshop Report*, which sets a goal of supplying 40% of the world PV market and achieving annual domestic sales of 3.2 billion watts by 2020.

Domestic Applications

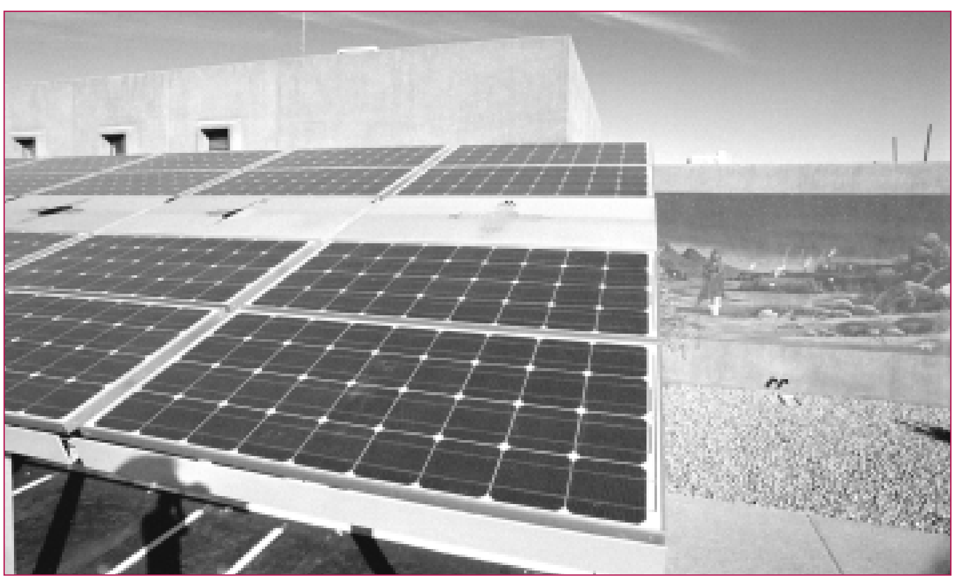
To foster widespread acceptance of PV in markets where PV has not been widely used, NCPV staff work in partnership with federal, state, and local groups to raise public awareness and develop projects. Promising but barely tapped market sectors include insurance and disaster-mitigation industries, residential and commercial buildings, the agricultural and ranching sector, electric utilities, and state and federal agencies.

PV:BONUS

Beginning in 1993, the PV: BONUS (PV: Building Opportunities in the United States) program has helped teams from the PV and building industry develop prototype PV products that could replace conventional windows, skylights, and walls while generating electricity. In 1998, seven of the building-integrated PV projects were selected for continued funding in a product and business development phase.

The Appeal of Distributed Generation

One consequence of the restructuring of the utility industry is a growing interest in small (10-MW or less), cost-effective, distributed natural-gas turbines to meet new demands for power. It is easier than ever before to add more small generating units, such as PV. Pursuing this promising application for PV, a study was commissioned by the NCPV. The study found that, for an overloaded feeder line in Washington State, a combination of distributed resources—energy efficiency improvements, PV, and cogeneration of heat and electricity with propane—could save the utility $1.4 million versus upgrading the distribution line from the central power station.



Sandia/PIX08978

At the Indian Pueblo Cultural Center in Albuquerque, NM, this PV carport stands ready to impress more than 400,000 visitors each year. The system delivers about 23 megawatt hours of clean electricity annually to the local utility grid, making it the largest commercial PV system in New Mexico. NCPV engineers from Sandia were responsible for the project's electrical design review.

In one project, PowerLight Corporation is evaluating two ways to incorporate solar-thermal improvements into PV roofing products that reduce solar heat build-up in summer and block radiant heat losses in winter. One approach is to incorporate coatings to increase the insulation value of the product. Another is to add a thermal absorber system. Both improvements will increase the value of the PV roofing tiles to the commercial building sector.

UPVG

Created in 1992, the Utility PhotoVoltaic Group (UPVG) has been promoting economic applications of PV systems for the benefit of electric utilities and their customers. By the end of 1999, membership increased to 110 utilities and related organizations. With $52 million in private funds and $15 million from DOE, a total of 36 ventures with more than 130 partners in 30 states installed more than 2,300 PV systems, for a total of 7.5 MW. Performance data on some of these installations are available on the UPVG Web site (*www.upvg.org*).

Insurance Industry

Disasters cost the insurance industry billions of dollars every year. These losses could be reduced if basic energy supplies were more resistant to disaster. PV and other renewable energy and distributed technologies are disaster-resistant because they do not rely on large networks and they can be repaired quickly. The widespread use of these systems could help reduce future insurance losses by preventing, mitigating, and recovering more quickly from disasters.

In 1999, NCPV staff continued to present case studies and analyses losses to CEOs, planners, and economists from the insurance sector that show how PV can help reduce losses. These studies imply that incentive programs, such as premium discounts for installation of PV systems, could be cost effective to the insurance industry. A PV-oriented Web page on disasters was also made available (*www.nrel.gov/surviving_disaster*).

State and Local Programs

The NCPV worked with states in 1999 to promote the kind of regulatory and financial framework that leads to high-quality, high-value installations of PV systems. A good example of the kind of teamwork necessary to reach our ambitious goals for 2010 or 2020 occurred this year in the state of Florida.

The Florida PV Building Program was initiated in 1999, with a detailed implementation plan written by the Florida State Energy Office, the Florida Solar Energy Center (FSEC), and Sandia. The plan outlined the steps necessary to expand the use of PV in public and private partnerships, which include nine end-user groups.

For each type of application experiment, the state issues requests for proposals (RFPs). These RFPs describe the types of rebates and green pricing that will apply, and they provide technical specifications developed with help from FSEC and Sandia. Site surveys are conducted and training programs are available to certify installers. Designs are reviewed and installations are approved after acceptance testing and rating of the modules. After acceptance, the systems are connected to the grid and performance monitoring begins. Reliability information accumulating in a Sandia database will help to examine how to reduce costs for grid-connected systems.

In early FY 2000, a Workshop on Implementing a State or Community PV Buildings Program will be held to share information among Program participants and with representatives from other states interested in meeting the Million Solar Roofs objective. To track progress toward this objective, check the Web site at *www.MillionSolarRoofs.org*

International applications of PV systems

The competition is fierce to supply reliable power to the 40% of the world's population without access to electricity. Because many people currently without electricity need only small amounts of power for indoor lighting, water pumping, communications, or refrigeration, electricity generated by PV is often the least expensive and most reliable power choice. And although each system is small (200 W to 4 kW), the potential cumulative economic and environmental impact of this market is enormous.

Taylor, NREL/PIX09029

This water purification system for the Nigerian town of Kuje uses a-Si solar panels manufactured by United Solar Systems Corp. to power a UV light disinfection unit manufactured by Waterhealth International, Inc. Capitalizing on the near-Equatorial Africa location, the PV panels are in a flat orientation to capture the sun's direct rays. On each sunny day, the system provides about 1,500 gallons of clean drinking water from a hand-dug well. DOE provided the system in 1999 to promote broad application of similar water-purification systems in Nigeria.

PowerLight/PIX07400

In a PV:BONUS project, PowerLight Corporation is evaluating two ways to incorporate solar-thermal improvements into its PV roofing products, such as this rooftop power system installed recently on the Mauna Lani Bay golf clubhouse in Hawaii. Such improvements will further increase the value of the PV roofing tiles to the commercial-building sector.

To help U.S. industry compete with foreign companies who have direct government support through direct subsidies and close industry-government interactions, the PV Program sponsors carefully designed demonstration programs using U.S. hardware to remove local institutional barriers to PV installations, to train local distributors, and to develop ways to finance continued beneficial use of U.S. PV products around the world.

The PV Program's support for demonstration projects in Brazil, China, Ghana, India, Indonesia, Kenya, Mexico, Morocco, Nigeria, Pakistan, the Philippines, Russia, South Africa, and Venezuela have helped increase the U.S. share of the growing world PV market.

More Systems Planned for China

Five years of work with political and economic organizations in China led to the installation of more than 600 U.S. PV systems by 1999 and more than 110 wind/PV hybrid systems. The PV Program promoted these installations with combinations of cost sharing, public information, design assistance, and training workshops. As a result, at least one Chinese county developed a plan for installing 4,000 more systems over the next five years. As an important added benefit, the operational characteristics of these systems are being monitored and the results relayed to the appropriate U.S. companies so they can benefit from any lessons to be learned from the demonstrations.

In recognition of his dedicated work for U.S.-China relations, Bill Wallace, an NREL staff member, was appointed senior technical advisor to the United Nations Development Programme and placed on a one-year assignment in Beijing.

DOE Key to PV in Mexico

Honored as one of the most successful renewable energy programs of the U.S. Agency for International Development, the Mexico Renewable Energy Program promotes the use of renewable energy systems as tools to enhance economic and social development. This program, which will now serve as a model for increasing the use of renewables in other parts of the world, has been so successful because it works with local organizations in each geographic and political area to purchase, finance, install, and maintain the initial systems.

Especially successful has been the effort, managed by NCPV engineers from Sandia, to install U.S.-manufactured PV systems. For example, all 345 systems installed under the program were done in partnership with U.S. industry, and all are being maintained today by local suppliers, who have greatly increased their capabilities.

These installations have led to the purchase and installation of many other PV systems by consumers, with improved confidence in the technology. Thanks to these innovative efforts to strengthen the local supply, finance, and maintenance infrastructures, the end users are benefitting from easier access to U.S.-supplied PV systems.

The PV and wind installations of the Mexico Renewable Energy Program have benefited more than 100,000 people in Mexico. In addition, U.S. PV suppliers also report dramatically increased sales in Mexico. And finally, DOE engineers and U.S. PV manufacturers are collecting valuable technical data from monitoring the systems installed by the PV Program.

Sandia/PIX09030

Despite flooding that left part of this 11.4-kW PV system under two feet of water at the Chajul Biological Research Station in Chiapas, Mexico, local personnel got the system back on line soon after the water receded. This quick response resulted from the hands-on training and spare parts that are an integral part of the Mexico Renewable Energy Program. The system was installed as a pilot project for Conservation International under supervision of NCPV engineers from Sandia.

PROGRAM RESOURCES

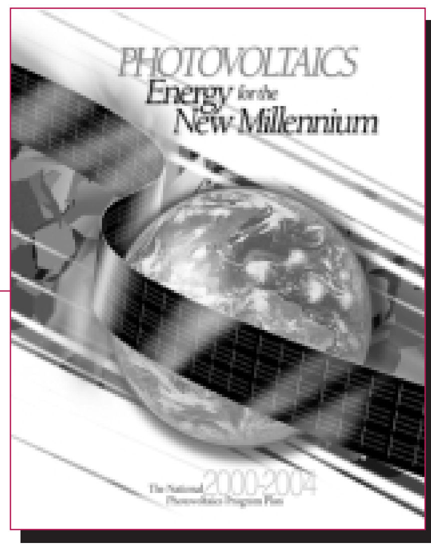
The National Center for Photovoltaics (NCPV), an alliance of organizations working to help the U.S. PV industry maintain its global leadership position, is proving to be an effective structure for planning and implementing the DOE National PV Program. The R&D goals and strategies are carried out by its governing board, which develops an all-encompassing operating plan each year, with specific performance goals for participants. Program review meetings presented by key members in government, industry, and universities contribute to the implementation of the Program and the strategic planning for coming years.

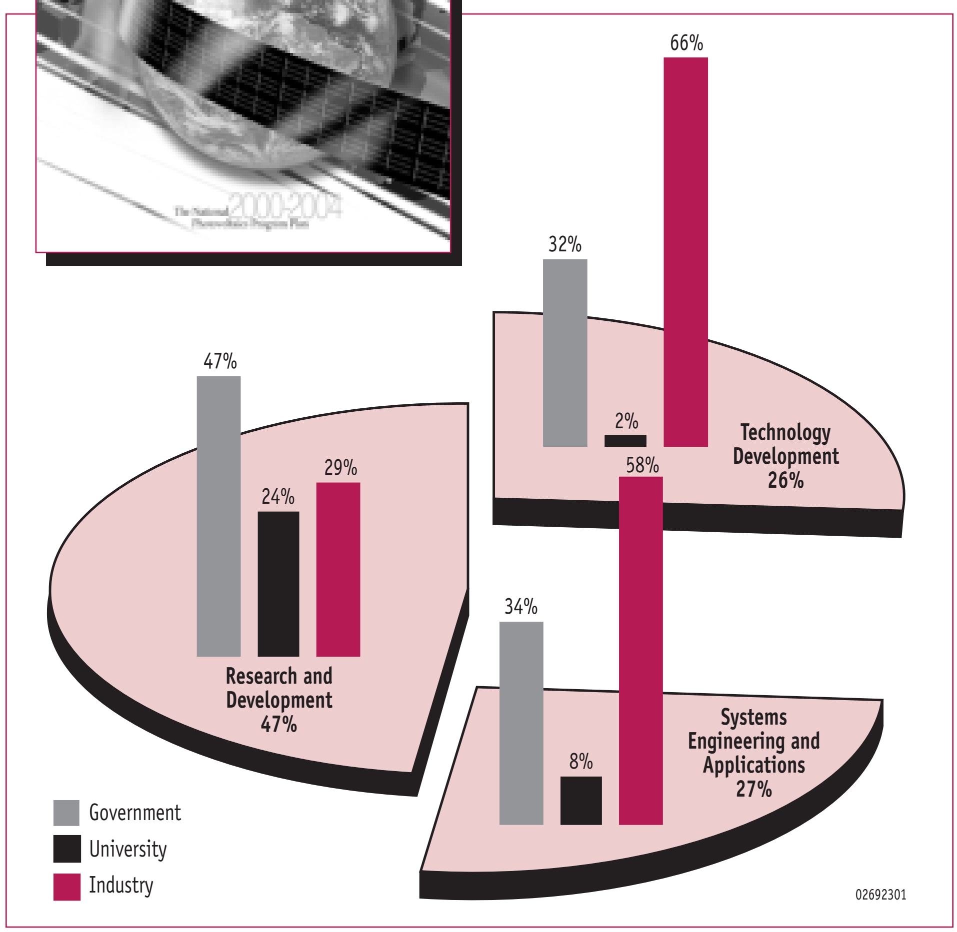
At the end of FY 1999, a new *National PV Program Plan 2000–2004* was in press. Its title is "Photovoltaics—Energy for the New Millennium." The first section of the document points out that photovoltaic technologies promise great things for our nation's energy supply, economy, environment, and overall future. The PV Program works with the nation's PV community to build strong leadership in this valuable technology by coordinating these efforts through its policies, organization, strategies, and funding.

The second section of the Five-Year Plan describes the direction of the Program within Research and Development, Technology Development, and Systems Engineering and Applications. Specific goals are highlighted in a five-year milestone chart.

To reach the milestones listed in the Five-Year Plan and in the Annual Operating Plan of the NCPV, the PV Program relies on the core expertise of the National Renewable Energy Laboratory and Sandia National Laboratories to create, develop, and deploy PV and related technologies. Other national PV resources that the NCPV draws on are Brookhaven National Laboratory, two Regional Experiment Stations (the Florida Solar Energy Center and the Southwest Technology Development Institute), and DOE's Centers of Excellence in PV at the Georgia Institute of Technology and the University of Delaware (the Institute of Energy Conversion). In addition, more than 100 university and industry research partners across the country are linked together to function in a unified way.

Communicating technical information—The PV Program distributes the information generated by its research and development activities in formats appropriate for researchers, regulators, government officials, and the general public. Through a combination of printed reports, award-winning Web sites, and conferences, the PV Program ensures





The NCPV awards most of its federal funds through competitive procurement to industry, universities, and other research centers around the country.

the widest possible distribution of key scientific and technical material relating to the development and use of PV systems.

Facilities available—Because most companies cannot afford large research facilities of their own, the National PV Program conducts long-term, high-risk, high-payoff research, development, and testing of PV components and systems in partnership with the PV industry. The world-class facilities of the national laboratories make this possible.

Directed basic research—Features solid-state spectroscopic analysis, experiments with photoelectrochemical processes, and applications of advanced theoretical and computational tools for predicting the behavior of PV materials such as a-Si, CIS alloys, CdTe, III-V materials, TCOs, and others.

Measurements and characterization—For analytical microscopy, electro-optical characterization, surface and interface analysis of materials, analysis of cell and device operation, computer modeling of system and component performance, and the development of special measurement techniques and instruments for U.S. firms.

Material, device, and system development— Includes user-accessible laboratories for fabricating and evaluating thin-film technologies (a-Si, CdTe, and CIS alloys), crystalline-silicon cells and modules, concentrator cells and PV arrays, and for developing and characterizing balance-of-systems components such as charge controllers and inverters.

Solar resource characterization—Measurement systems traceable to world standards are used to characterize solar resources. Electronic data sets, maps, and models are available to quantify or estimate the global distribution of solar radiation and the quantity and variability of the resource at specific locations. Researchers use satellite imagery, meteorological data, and models to estimate solar radiation in areas with limited data.

Performance and reliability testing—Prototype cells, modules, and systems are tested using outdoor testbeds, indoor laboratories, and field trials. Equipment can be tested under simulated, accelerated, and actual outdoor conditions, and under varying temperature, humidity, precipitation (including hail), voltage, and radiation levels.

Manufacturing and deployment—Cost-shared development programs with individual manufacturers evaluate and resolve technical issues in the production of PV components and systems. NCPV experts also work with large user groups such as utilities to address technical issues in deploying PV technologies in new applications.

Market development and outreach—Information and outreach activities of the staff include assisting those who buy systems, facilitating ways to finance PV installations, and analyzing technological, economic, and environmental impacts for specific applications.

Kroposki, NREL/PIX08952

AC PV modules that have a DC/AC inverter attached directly to the back side are being monitored for long-term performance and reliability by the PV Program on this new, specially designed testbed at NREL's Outdoor Test Facility. The four modules pictured are (from right to left) BP Solarex/Advanced Energy Systems 240 W, Evergreen Solar 90 W, and Ascension Technology 275 and 250 W.

The core expertise of the NCPV is provided by the National Renewable Energy Laboratory and Sandia National Laboratories. For more information about the structure and mission of the NCPV, see the Program Resources Section on page 19—or visit the NCPV Web site (*www.nrel.gov/ncpv*).

The cover photos demonstrate the progress of photovoltaic technologies as they move from the laboratory to the marketplace. The photos show, from top to bottom:

A spectroscopy device at one of NREL's research laboratories that analyzes the quality of solar cell materials. Yost/PIX07100.

A process used for grid-firing solar cells by Siemens Solar Industries, a partner in the PV Program's Photovoltaic Manufacturing Technology project. Siemens Solar/PIX07831.

A hybrid PV system, manufactured by Applied Power, at the Dangling Rope Marina in Glen Canyon National Recreation Area at Lake Powell, Utah. Gretz, NREL/PIX08011.

The starting line for a solar car race, called Sunrayce, that traversed a 1,425-mile route from Washington, D.C., to Orlando, Florida. University students on 29 teams honed their design and engineering skills, all the while promoting the environmental rewards of solar energy. Stafford, NREL/PIX08953.

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