# Photovoltaic Energy Program Overview

## Fiscal Year 2000

U.S. Department of Energy

# Program Highlights

## Research and Development

Page 3

■ Accomplished rapid deposition of amorphous silicon (a-Si) thin film with low defect densities and high efficiencies.

■ Fabricated many copper indium gallium diselenide (CIGS) thin-film devices with efficiencies between 18.1% and 18.8%.

■ Marked first copper indium diselenide (CIS)-based thin-film products entering market.

■ Validated partner BP Solar's production of 10.6%-efficient cadmium telluride (CdTe) modules.

■ Transferred *PVScan* system to industry.

■ Coordinated meeting of researchers exploring transparent conducting oxides (TCOs) to apply their work to PV.

■ Launched *High-Performance PV Initiative* research contracts to increase efficiency of multijunction thin-films and III-V cells for concentrators.

■ Demonstrated with Spectrolab a 32.3%-efficient GaInP/GaAs/Ge cell under 566 suns of concentration.

■ Sponsored 10th Workshop on Crystalline Silicon Solar Cell Materials and Processes to promote exchange of research results.

■ Issued four new research contracts exploring hydrogen passivation.

■ Marked Sandia's 12 years of contributions to research in crystalline silicon.

■ Published *World Photovoltaic Scale Recalibration* and *North American Solar Atlas*.

■ Issued *PV Technologies Beyond the Horizon* research solicitation.

## Technology Development

Page 11

■ Issued new solicitation, *PV Manufacturing R&D—In-line diagnostics and intelligent processing in scale-up manufacturing*.

■ Evaluated 7 grid-tied inverters and 9 inverters in off-grid configurations.

■ Held workshop with Brookhaven National Laboratory on use of lead-free solder in manufacturing.

■ Identified positive features of 20-year-old modules that have performed well.

■ Began testing modules from three manufacturers on the Performance and Energy Ratings Testbed.

■ Documented continued technology improvements under the PVMaT contracts that will be completed in FY 2001.

■ Compared module energy-rating methods in support of IEEE Module Energy Rating standard under development.

## Systems Engineering and Applications

Page 16

■ Gained approval from testing and standards organizations for "non-islanding inverter."

■ Continued support for standards development. Achieved procedure for testing small PV systems; passage of the first standard for interconnection of PV, *IEEE 929-2000 Recommended Practice for Utility Interface of PV Systems;* and balloting on *IEEE Recommended Practice for Qualification of Concentrator PV Receiver Sections and Modules*.

■ Supported development of Solar Load Controller to increase the value of PV to customers on time-of-use tariffs.

■ Supported TEAM-UP project to install 7.2 MW of solar electric systems in 40 states.

■ Worked with Native American tribes to encourage installation of solar electric systems.

■ Recorded accomplishments of partners in Mexico that obtained World Bank and Global Environmental Facility grants and loans based on successful projects with PV Program.

■ Initiated technology validation activities for thin-film PV technologies in India.

# Message from the Director

***...to offer the world a cost-effective, reliable technology that turns sunlight into electricity with no pollution, wherever it is needed.***

**Mission of the National Photovoltaics Program**

This year, concerns about rising fuel costs, energy security, statewide brownouts, and demand surges that exceeded electrical supply underlined the urgency of positioning solar electric systems to meet a greater share of our energy needs. In response to these problems, the PV Program is poised to take on an increased responsibility to meet the urgent challenges facing the nation. The market for solar electric systems is steadily increasing as improved products resulting from our research efforts in collaboration with industry are accepted. Customers in the restructured electricity market are seeking local sources of electricity that are clean, quiet, and reliable.

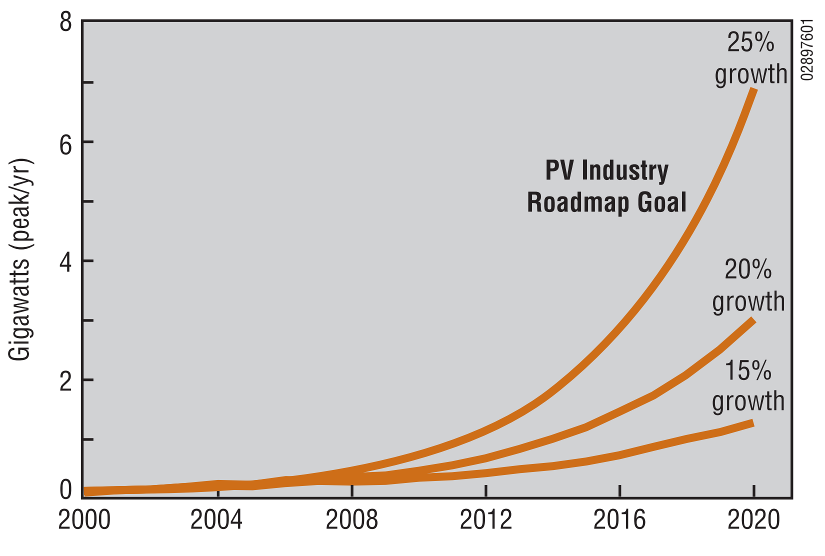
To meet the demands of a growing market, the solar electric industry has new systems both in the marketplace and on the drawing board that produce higher electrical output for lower cost. In fiscal year (FY) 2000, we saw the first commercial products made from copper indium diselenide, a thin-film material that we have been researching with industry for nearly 20 years. If we apply this development cycle to other promising technologies in our laboratories today, more new products will be introduced each year. To keep the pipeline from laboratory to marketplace filled with innovative approaches to supplying electricity from the sun, we began the process of issuing new contracts for fundamental research and development (R&D) in 2000.

We cannot overstress the importance of these new R&D efforts in conjunction with our manufacturing R&D and systems development and application activities. In FY 1999, we saw the solar electric industry develop a roadmap for market development over the next 20 years. Achieving industry's goals demands significant reductions in the cost of solar electric systems; cost reductions can only be achieved through aggressive work in fundamental research, manufacturing, and system applications. For our part, the National Photovoltaics Program continues to sponsor high risk, potentially high payoff research and development from which private enterprise can choose options for further development and application in competitive U.S. electrical energy markets.

Taking account of the industry roadmap goal, the National Photovoltaics (PV) Program issued its multiyear plan for 2000 to 2004 last year, complete with specific research goals necessary to support the industrial goals. Results are encouraging after the first year of the Program's 5-year plan. Although the data are not yet in for industry sales, we have met every R&D milestone of the Program Plan. As described in this report of our accomplishments for the year, the National PV Program is providing the R&D necessary to make solar electric systems an ever more significant contributor to our national energy supply.

*James E. Rannels*

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




*"The vision is to provide consumers with competitive and environmentally friendly electricity from a thriving United States-based solar electric power industry."*
PV Industry Roadmap Vision

# Introduction

***The purpose of the U.S. Department of Energy (DOE) Photovoltaics Program is twofold: to accelerate the development of PV as a national and global energy option, and to ensure U.S. technology and global market leadership.***

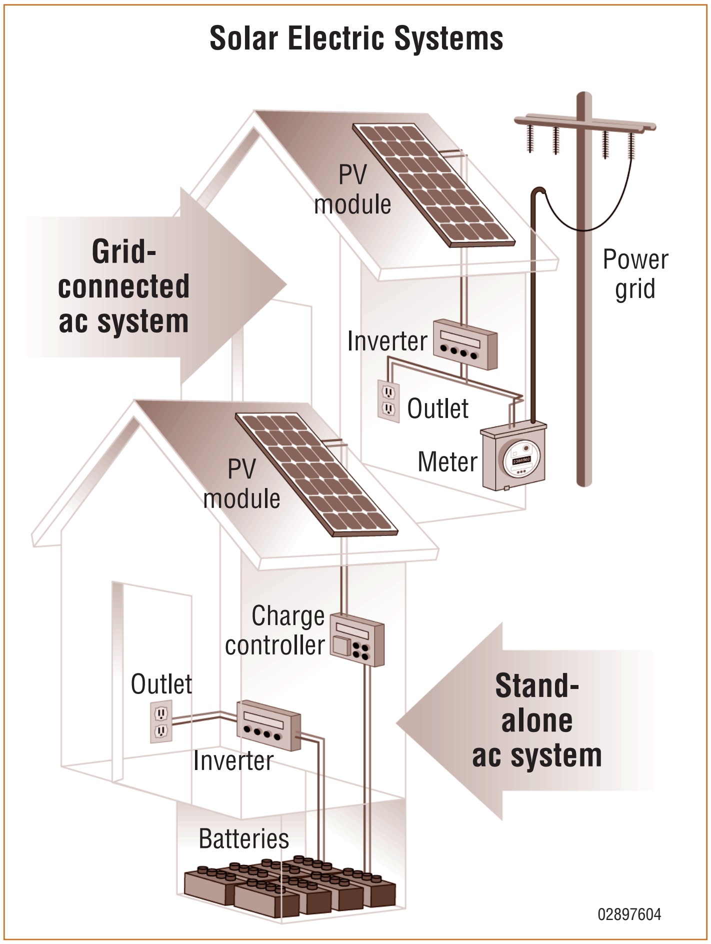
**The National Photovoltaics Program Plan**

In 1839, a French physicist found that certain materials would produce small amounts of electric current when exposed to light. The first PV device to actually generate electric power was made of silicon at Bell Laboratories in 1954. The proportion of sunlight energy that those early cells converted to electrical energy was between 1% and 2%. The efficiency of today's best solar electric cells is about 32%. Efficiency is an important benchmark for PV technology, and it is theoretically possible for solar cells to operate at greater than 40% efficiency.

Commercial use of solar electric cells began in 1958, when the Vanguard 1 satellite carried PV cells to power a 5-milliwatt backup transmitter. Today, virtually all satellites and spacecraft use solar cells to generate their electrical power. Interest in making PV technology affordable for terrestrial use was sparked by rising energy costs in the mid-1970s. Since then, the federal government, working with universities and industry partners, has conducted an aggressive research and development (R&D) program to further develop this promising technology.

Expanded use of solar electric systems depends on lowering the cost of systems and ultimately the cost of the energy they produce. System costs come down as we develop new, higher efficiency materials, as we improve manufacturing processes, and as we engineer greater reliability into all parts of the generating system.

The R&D activities of the National PV Program accelerate the development process, with fundamental research supporting development of materials and devices, manufacturing technology, systems engineering, and market information. The PV Program implements 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. The National Renewable Energy Laboratory (NREL) in Golden, Colorado, and Sandia National Laboratories (Sandia) in Albuquerque, New Mexico, are the key national laboratory participants in these efforts.




*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.*

# Research and Development

*R&D on thin films, high-performance devices, silicon materials, characterization techniques, and innovative concepts will deliver low-cost PV and fill the technology pipeline for future progress.*
**The National Photovoltaics Program Plan**

The National PV Program, through the National Center for Photovoltaics (NCPV), coordinates teams of in-house researchers, industrial partners, and university researchers, all working to increase our understanding of solar electric materials and devices. Including industrial partners in this work assures the speedy transfer of research results to industry for product development and manufacturing.

## Thin-Film PV Research

Using thin films of semiconductor material to make solar electric devices holds the promise of low-cost manufacturing capitalizing on techniques perfected in the glass industry. When evaluating our progress with new PV materials, important criteria are material deposition rate, solar cell efficiency, and power output. Power output is related to module size and efficiency. High power output in a single module is desirable because it reduces other system costs such as those associated with connectors. Achieving large module size is a manufacturing challenge because it requires both consistent material performance over a larger area and special handling techniques to assemble modules. Deposition rate is important because high rates reduce initial capital costs and lower manufacturing costs.

FY 2000 saw many firsts for thin-film PV technology. In addition to improvement in the performance of materials in the laboratory, the first commercial products using cadmium telluride and copper indium diselenide materials went on the market in the United States, and planned increases to manufacturing capacity are at an all-time high.

Since 1994, the Thin Film PV Partnership Program has coordinated research contracts with industry, universities, and government researchers in the NCPV to explore the most pressing scientific issues that limit the wider use of this technology. Over the years, several companies have explored using thin films as additional materials for solar electric devices. In the early years, the market was dominated by crystalline silicon products with some thin-film amorphous silicon in consumer products such as calculators. In 2000, nearly 10 MW of thin-film modules were produced in the United States. Manufacturing plants planned or under construction will boost U.S. capacity to produce thin-film modules of more than 140 MW per year.

National investment in exploring the fundamentals of PV has provided the foundation for this unprecedented expansion in the market. However, much remains to be done to reach the full potential of PV. In FY 2000, the Thin Film PV Partnership's national research teams explored solar electric materials and devices made from amorphous silicon, copper indium diselenide, and cadmium telluride. Each team is composed of about forty scientists from universities, NCPV, and industry who collaborate on shared research goals important to the future of their technologies. Continued work on fundamentals will provide the advances that improve device performance and manufacturing processes.

*Table 1. Best Large-Area, Thin-Film Modules (standard conditions, aperture area)*

| Power (W) | Company/Date | Device | Size (ft$^2$) | Efficiency (%) |
|---|---|---|---|---|
| 91.5 | BP Solar, 5/00 | CdS/CdTe | 9.5 | 10.6 |
| 70.8 | United Solar, 9/97 | a-Si/a-SiGe/ a-SiGe/SS | 10.2 | 7.6 (stabilized) |
| 61.3 | First Solar, 6/96 | CdTe/CdS | 7.8 | 9.1 |
| 59.0 | Matsushita, 6/00 | CdS/CdTe | 6.0 | 11.0 |
| 56.0 | BP Solar, 9/96 | a-Si/a-SiGe | 8.2 | 7.6 |
| 53.9 | BP Solar, 4/00 | CdS/CdTe | 5.4 | 10.8 |
| 44.3 | Siemens Solar, 3/99 | CdS/CIS-alloy | 4.0 | 12.1 |
| 38.0 (est.) | Kaneka, 9/00 | a-Si/c-Si/glass | 4.1 | 10.0 (est., stable) |
| 35.7 | United Solar, 6/97 | a-Si triple junction | 5.0 | 7.9 (stabilized) |
| 31.0 | Golden Photon, 4/97 | CdS/CdTe | 3.7 | 9.2 |

Consequently, one PV Program Plan milestone for FY 2001 will be the issuing of a new solicitation for the Thin Film PV Partnership.

## Amorphous Silicon (a-Si)

Amorphous silicon is a growing segment of the solar electric market, accounting for nearly 10% of PV sales worldwide in 2000. Compared to crystalline silicon, it can be manufactured at lower cost, is more responsive to indoor light, and has advantages such as flexible or low-cost glass substrates. As a result, the PV industry in the United States is investing in significant new plant capacity.

*Table 2. Technical Issues: a-Si Technology*

| Topic | Issue |
|---|---|
| Stability | Can we use improved understanding of Staebler-Wronski degradation mechanisms to minimize or eliminate the problem? |
| Deposition cost | Can we increase amorphous silicon deposition rates while maintaining efficiencies to reduce manufacturing costs? |
| Efficiency | Can we improve cell and module efficiencies through greater fundamental understanding of present limitation, and by development of improved component cells and interfaces? |
| Low-gap bottom cell | Can we improve the low-gap bottom cell for use with an amorphous silicon top cell, either by application of microcrystalline silicon or by improvement of a-SiGe:H alloys? |

One of the ways to reduce the cost of solar electricity is to decrease the time it takes to manufacture PV devices. Increasing deposition rates of PV materials during manufacturing can reduce industry's labor and material costs. To reduce costs of devices made from a-Si, deposition rates must be increased from the current 1–3 angstroms/sec levels achieved in manufacturing to the level of 6–10 angstroms/sec or higher. However, depositing the a-Si materials at higher rates can cause changes in the materials, such as increased defect densities, that adversely affect the performance of solar electric devices. Intense laboratory research is under way to develop materials and processes that produce high-performing solar electric devices in shorter time periods.

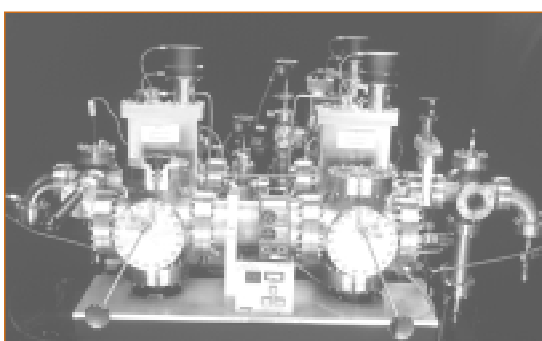
For example, in FY 2000, NCPV researchers at NREL achieved low defect density in hydrogenated amorphous silicon (a-Si:H) films that were grown at record deposition rates as high as 83 angstroms/sec. Normally, a-Si is deposited using plasma-enhanced chemical vapor deposition (PECVD). When PECVD rates are increased, the resulting materials have high defect densities, indicating that efficiencies of the resulting devices would be unacceptably low. The high-deposition-rate a-Si that researchers at NREL grew using the hot-wire chemical vapor deposition technique had much lower defect densities. Low defect densities are one indicator of potentially acceptable efficiency, but the performance of the material must still be demonstrated in PV devices. In FY 2001, the a-Si National Team will apply ultrahigh-deposition-rate materials to solar cells with a-Si:H layers grown in less than a minute.

Additionally, several subcontractors to the NCPV have achieved deposition rates higher than the industry norm, while still preserving acceptable efficiency levels. Energy Conversion Devices made an 8.8%-efficient cell from material deposited at 10 angstroms/sec, and United Solar made a 10%-efficient cell from material deposited at 4 angstroms/sec. These results were confirmed at NREL by the Measurements and Characterization group and mark a milestone identified by the National a-Si Team for FY 2000. In addition, BP Solar doubled the deposition rate, while maintaining the efficiencies of its multijunction a-Si modules. Higher throughput lowers manufacturing cost and is being applied in the BP Solar manufacturing plant.

## Copper Indium Diselenide (CIS)

Achieving world-record efficiency for a solar electric material or device is only the first of many steps along the way to industrial produc-

Jim Yost/PIX01812



*Using our patented high-speed, hot-wire deposition technique, NCPV scientists at NREL can accomplish in 2 minutes what now takes industry about 35 minutes to complete.*

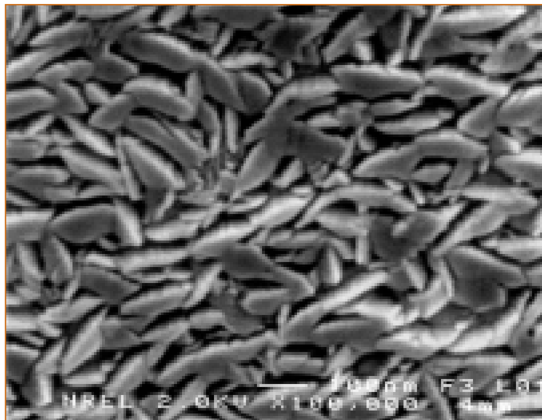
David Parsons/PIX06301

*United Solar plans to expand its production capacity from 5 MW per year to 25 MW per year, applying developments achieved through its participation in the National a-Si Research Team.*

tion. One of the very next steps after achieving a world record, as NCPV researchers at NREL did in FY 1999, is establishing a reproducible baseline process for achieving consistent efficiency results. In FY 2000, NCPV researchers at NREL demonstrated that its optimized substrate allowed repeated fabrication of CIS with added gallium (CIGS) devices with efficiencies between 18.1% and 18.8%. The special plasma vapor deposition (PVD) technique used to sputter molybdenum on the substrate used for CIGS deposition produced these consistent results for a set of 15 devices fabricated from seven CIGS samples.

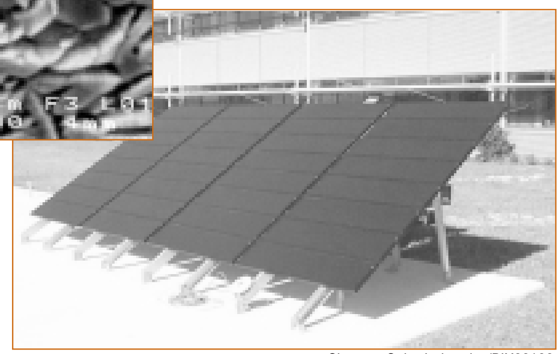
Industry is exploring a new processing system for large-area CIS deposition developed at the University of Delaware's Institute of Energy Conversion (IEC). Using the new system employing co-evaporation of $CdS/Cu(In,Ga)Se_2$, IEC produced solar cells that reached 14.9% efficiency. The cells were prepared in IEC's large-area, in-line deposition system designed to deposit CIGS-based semiconductors on a continuously moving substrate. The system is designed so that it could be adapted to use a web-type substrate (roll-to-roll deposition). IEC has also used *in situ* atomic absorption spectroscopy to control deposition rates. This means that IEC can work with industry in research efforts to produce larger sheets of CIGS materials for solar electric module production. Two companies planning to manufacture CIS-based solar electric modules are developing processes based on co-evaporation that are very similar to IEC's.

Meanwhile, Siemens Solar Industries gained Underwriters Laboratories (UL) listing for one of the first two commercial products introduced in 2000 using CIS-based thin-film materials. UL approval is an important step toward widespread use of a new solar electric product.



Siemens Solar Industries/PIX09742

*Secondary electron microscopy analysis shows this CIGS film (left) is composed of fairly large, aligned long grains that have an open structure and are less dense. These characteristics allow more sodium to diffuse into the CIGS absorber during the deposition and improves device performance.*



Siemens Solar Industries/PIX09100

*This CIS array from Siemens Solar Industries is being tested at the Florida Solar Energy Center.*

### *Table 3. Technical Issues: CIS Technology*

| Topic | Issue |
|---|---|
| CdS | Can chemical bath-deposited (CBD) CdS be replaced with alternate heterojunction partners without loss in performance? |
| Gallium | What is the optimum distribution of gallium in the absorber for best device performance? |
| Sulfur | Can S content be controlled at the interface to increase bandgap? |
| Sodium | What is the exact role of sodium, and how can we control it? |
| Substrates | Can high-efficiency devices be achieved on alternative substrates? (e.g., foils, polymer, or stainless steel) |
| Transients | Can transient effects in modules be eliminated or minimized? |
| Mfg. process | Can we develop a process that gives compositional uniformity, high efficiency, and high yields? |
| Moisture | Can the effect of moisture ingress be eliminated? |

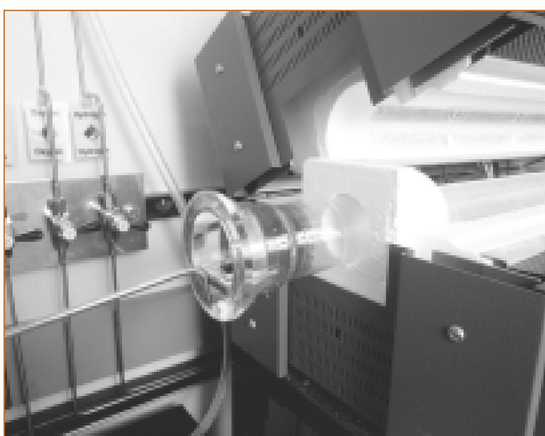
## Cadmium Telluride (CdTe)

Cadmium telluride has several features that make it a promising material for solar electricity generation. These include a bandgap well matched to the solar spectrum and a high absorption coefficient, meaning that even one micron of the absorber film is sufficient for solar cell fabrication. To date, more than 10 techniques have been used to grow CdTe layers, resulting in solar cells operating at 10% or greater efficiency. Three of these methods are currently used for module fabrication by industry. The NCPV works both to improve these methods and to develop alternative methods that may yield higher efficiencies or hold promise for low-cost manufacture.

In FY 2000, BP Solar, a participant in the National CdTe R&D Team, began production of a CdTe module with verified world-record aperture-area efficiency of 10.6% and power output of 91.5 W. These improvements to performance came from changes in the electro-deposition bath and reduction in the thickness of the CdS film. The BP Solar results demonstrate that high efficiency and good electrical properties (short-circuit current density, open-circuit voltage, and fill factor) can be achieved in a pilot line and eventually in large-scale manufacturing. These results further the Thin Film PV Partnership's progress toward an important PV Program Plan milestone for 2004—a 10%-efficient commercial thin-film CdTe module.

*Table 4. Technical Issues: CdTe Technology*

| Topic | Issue |
|---|---|
| Copper | What is the exact role of Cu? |
| Contacts | Can contacts be improved and stabilized, or alternative structures be developed? |
| $CdCl_2$ | What is the exact role of the $CdCl_2$ treatment? Can the wet process be replaced by a vapor process? |
| Interface | What is the role of interdiffusion at the CdS/CdTe interface? |
| Module design | Can large-area modules be as efficient as small cells? |
| Encapsulation | Are edge sealants required for stable modules? Can the effect of moisture ingress be eliminated? |
| Cd usage | Can Cd be used safely in the environment and workplace? Can modules be recycled at the end of their useful life? |



Warren Gretz/PIX04533

*NCPV research at NREL led to this annealing technique for heat treating CdTe solar cells to improve performance and manufacturing.*

First Solar/PIX08730

*This new manufacturing plant (right) in Toledo, Ohio, was built by First Solar to produce glass substrate PV plates coated with thin-film CdTe at the rate of 8 plates per minute. When fully operational, this plant can produce 100 MW per year of thin-film solar electric modules. First Solar has brought a technology to market that has been under development in cooperation with the DOE program for more than 10 years.*

## Transparent Conductors

Thin-film solar cells are composed of layers of materials that serve specific functions in the process of converting sunlight into usable electrical energy. An important layer in thin-film solar cells is the transparent conducting oxide (TCO) layer that serves as the top contact and collects electrical current. The structural, optical, and electrical properties of various TCO materials are the subject of active research within the Thin Film PV Partnership Program.

In FY 2000, researchers from the NCPV and DOE's Basic Sciences Center collaborated to develop new conducting oxides by chemical vapor deposition. The characteristics of this material could facilitate the use of cadmium stannate in commercial applications such as those of BP Solar and First Solar. The switch to cadmium stannate, if feasible in commercial production, could increase module efficiencies over those achieved today with tin oxide.

TCOs are a critical and frequently limiting component of advanced electronic devices, such as flat-panel displays, architectural coatings, and innovative lighting using light-emitting diodes. Pulling together researchers from the various industries working on TCOs could reduce research costs and speed progress in all of these applications, including solar electric modules. To keep PV applications visible to other researchers and to learn of their progress, NCPV researchers at NREL organized a workshop to attract researchers working in other applications of TCOs. This kind of coordination ensures that the PV industry benefits from the latest research being conducted for other purposes.

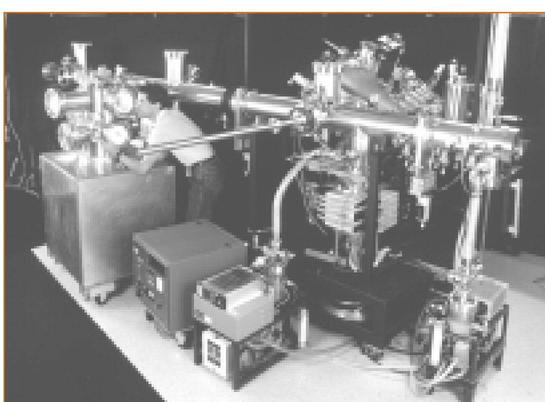
## High Performance and Concentrator Research

The attraction of high-performance solar cells is the possibility of using small, highly efficient cells with inexpensive concentrating lenses to produce large amounts of low-cost electricity. The NCPV and Spectrolab are working toward a goal of cells with 40% efficiency under concentrated sunlight.

In FY 2000, NCPV researchers collaborated with ENTECH Corporation to produce a 28%-efficient minimodule using NREL's triple-junction high-performance solar cell in ENTECH's linear Fresnel-lens (10 suns) concentrator system.

Meanwhile, work continues to develop materials that perform well at very high concentrations of sunlight. Such materials would produce electricity in commercial-sized systems by using a very small amount of highly efficient PV material operating under powerful lenses. In 1999, a special concentrator cell operated at 32.3% efficiency under 47-sun concentration. Efficiency fell off at higher concentration levels because of unexpected decreases in open-circuit voltage. In 2000, NCPV researchers at NREL and scientists at Spectrolab identified the cause of the problem and demonstrated an improved GaInP/GaAs/Ge cell that operated at 32.3% efficiency under 566 suns of concentration. Record efficiency at this level of concentration means that this cell is fully compatible with the high concentration levels expected in commercial applications. Work continues on achieving even higher efficiencies at concentrations up to 1000 suns.

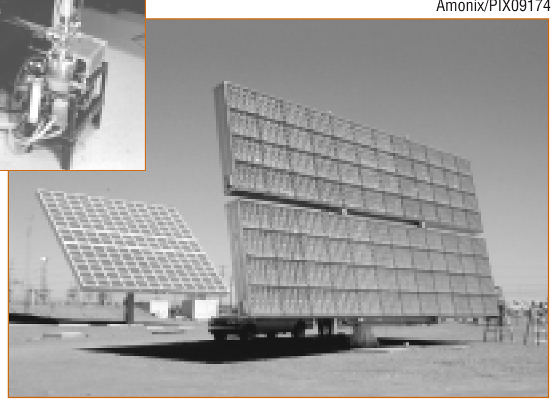
The National Photovoltaics Program Plan contains a 10-year program goal to double the efficiency of multijunction thin-film modules (to 20% efficiency). An additional goal is to demonstrate high-efficiency III-V cells in a precommercial concentrator module (to 33% efficiency). To help achieve this objective, the *High Performance PV Initiative* was launched in FY 2000. When contracts are awarded in 2001, university and industry contractors will begin work in two general areas—thin-film multijunction cells and high-efficiency III-V multijunction cells and concentrators. This solicitation complements work being planned by the NCPV for NREL in-house researchers. It also will begin identifying critical pathways to the 10-year efficiency goals.



Jim Yost/PIX01469

*High-performance solar cells produced with this kind of equipment could double the power output of terrestrial PV systems in operation today.*

Amonix/PIX09174



*Arizona Public Service is installing a large integrated high-concentration PV system from Amonix, Inc., totaling 300 kW.*

## Crystalline Silicon Research

Crystalline silicon was the first material used to make commercial solar electric devices, and it continues to be used in 90% of the PV systems being installed today. The NCPV strives to improve the performance of this durable material, while helping industry develop faster ways of manufacturing modules.

Among five research needs identified by industry participants in the 10th NREL Silicon Workshop, one was to replace the screen-print process used to apply contact metallizations in silicon solar cells. NCPV researchers at NREL had demonstrated nano-particle metallic inks that include metalorganic sources for delivering metal elements to "glue" the particles, resulting in conductivities comparable to electrodeposited metals. A cooperative research and development agreement (CRADA) has been established with Evergreen Solar to develop the new direct-writing approaches for contact metallizations in its silicon solar cells.

NCPV researchers also developed a technique for fast screening of single-crystal silicon wafers prior to solar-cell processing, using Fourier-transform infrared spectroscopy. This diagnostic technique could improve production yields and lower manufacturing costs.

Another industry-identified need at the workshop was a new understanding of hydrogen passivation of impurities and defects to better control their processes for high-efficiency crystalline silicon PV modules. NCPV researchers at Sandia and NREL have expanded understanding in this area. In FY 2000, four universities worked on these issues under contracts of the new *Hydrogen Passivation of Impurities and Defects in Silicon Solar Cells* solicitation. All five research needs identified by industry at the workshop will be topics in next year's solicitation for university research on crystalline silicon.

## A Dozen Years: Sandia's Contributions to Crystalline Silicon Research

Since 1988, researchers at Sandia have been conducting in-house research and supporting contracted research to advance the technology of crystalline silicon. They supported early research for dendritic web and silicon sheets that are now entering commercial production. They also supported development at Stanford University of ultrahigh-efficiency, one-sun silicon solar cells that have been incorporated into commercial products. Sandia helped found the University Center of Excellence in Photovoltaics program at the Georgia Institute of Technology. This work resulted in world-record efficiencies for cells made with novel processes and has contributed to the fundamental understanding of commercial processes. Sandia pioneered the teamed research approach within the DOE Program with the Crystalline-Silicon Research Cooperative, which includes industry, laboratory, and university researchers.

Sandia's in-house activities developed the first PC-based program for numerical simulation of PV devices (PC1D). Their new device-characterization techniques have become standards in the PV community. In-house researchers demonstrated a record 15.3%-efficient multicrystalline silicon module, explored plasma processing for solar-cell fabrication, investigated reactive ion etching for texturing crystalline-silicon substrates, and developed the Emitter Wrap-Through cell with back-contact cell design.

Sandia's PV Program has been restructured to emphasize PV system research, but will continue to provide some support to crystalline silicon PV research. In cooperation with industrial partners, NCPV researchers at Sandia will continue to investigate plasma-texturization of multicrystalline silicon cells. They will also continue to apply their years of experience to supporting contracted research and participating in the R&D cooperatives they were instrumental in founding.

## Measurements and Characterization

The Measurements and Characterization Division at the NCPV provides invaluable services to the research and industrial community in their detailed measurements from the atomic level to the systems level. For example, in FY 2000, researchers successfully analyzed CdTe and CIGS thin-film devices in cross section using atomic force microscopy. This technique provides, for the first time, three-dimensional information with a spatial resolution in the nanometer range.

In FY 1997, the NCPV developed *PVScan*, a specialized diagnostic tool to characterize crystalline silicon materials. In FY 2000, the PV Program met a planning goal by transferring this defect mapping system to industry. At AstroPower Corporation, it will be used to characterize the company's commercial product. The version delivered to AstroPower has a resolution of 50 microns and can scan at rates up to 10 cm/sec. A version of *PVScan* is also being used at the Georgia Institute of Technology to develop dislocation and grain-boundary maps, reflectance, and minority-carrier lifetime for PV devices up to 20 cm by 20 cm.

To serve collaborators in the NCPV's many partnership R&D efforts, the Measurements and Characterization Division uses the latest analytical tools to help solve important materials and device problems. In FY 2000, Web-based data delivery techniques were enhanced so that, for example, collaborators could receive real-time images of their materials from the NCPV's scanning electron microscope. These data are available to customers on their desktop computers anywhere in the world. This efficient delivery of data is one more way the NCPV works to accelerate development of technology for solar electric systems.

To provide the best measurement and characterization support to the U.S. PV industry for cells and modules, the NCPV strives to maintain leadership and compatibility of measurement with other laboratories around the world. In FY 2000, the *World Photovoltaic Scale Recalibration* project report was published, meeting a key milestone for the measurements program. This study, involving the leading measurement laboratories in the United States, Japan, France, Germany, China, and India, ensures that measurements conducted in any of these countries are comparable to those conducted by any of the other countries.

### Solar Resource Assessment

To help system engineers accurately assess the value and design of PV electric systems across North America, NCPV researchers at NREL completed the *North American Solar Atlas*. This atlas contains a new database that allows a wide range of users to determine monthly and annual solar resources for any spatial grid and for various solar electric module orientations. Reliable resource data allow increased confidence in power output projections. Installed systems designed according to accurate resource data result in systems that perform as advertised and that satisfy customers.

## Basic and University Research

Many researchers assert that science will be the force that moves solar electric systems from today's prices to those required to meet the PV Industry Roadmap goals. To tap into the latest ideas and provide support to develop promising creative approaches, the PV Program funded 18 proposals from the nation's universities to explore unconventional ideas in FY 1999.

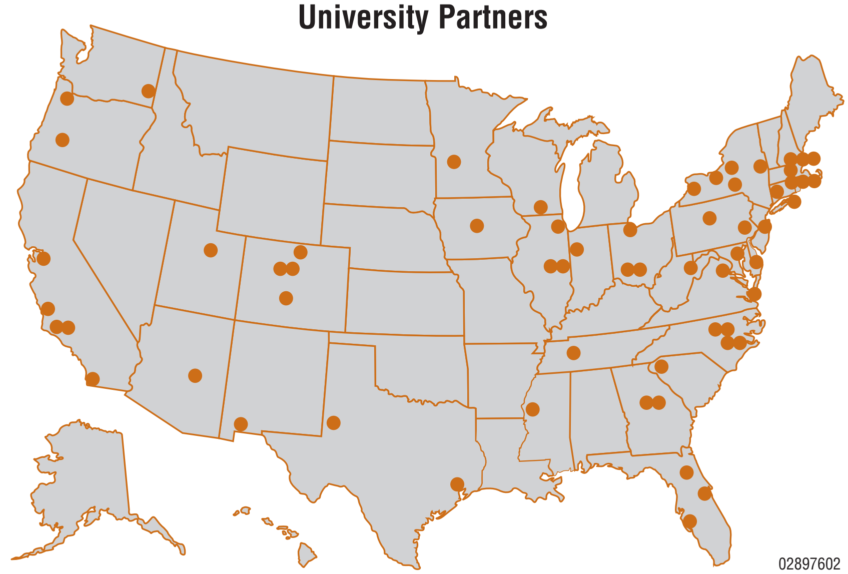
These Future Generation PV contracts have already yielded some interesting results. For example, crystalline silicon is known for its high efficiency and stability, but traditional silicon growth methods are expensive and can only produce substrates of limited size. Using a deposition technique similar to that used to produce a-Si, researchers at the California Institute of Technology are growing nonconventional silicon. This thin-layer silicon consists of large crystalline grains. So far, they have been able to grow 10–50 microns of silicon on glass. They are working to increase grain size and lower defect density, as well as to improve growth rates at low temperatures and to develop a surface with enhanced optical absorption.

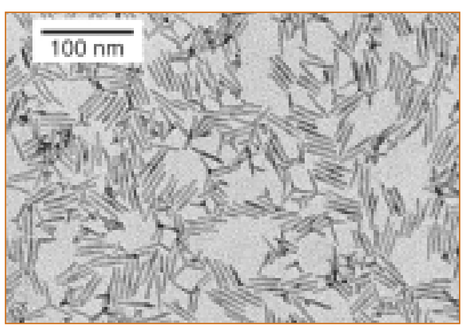
In other work to understand thin polycrystalline silicon films, Cornell University is using an elastic measuring technique to explore the molecular order in thin-film silicon. Yet another group, at Pennsylvania State University, is applying novel spectroscopic probes to study optical absorption in textured thin-silicon films.

While these Future Generation PV contracts were under way, another solicitation for proposals from universities, colleges, and U.S. companies was issued in 2000. The *Photovoltaic Technologies Beyond the Horizon* solicitation encourages basic research to explore nonconventional technologies that could lead to new options for generating inexpensive electricity from sunlight.

When awards are made in FY 2001, contractors will begin exploring technologies such as liquid crystal-organic solar cells, novel group IV solar cells, polymer solar cells, microcrystalline silicon cells, tandem organic cells, innovative Si substrates for III-V solar cells, low-temperature CIGS deposition, and nanoscale silicon theory. Scientists will also explore optical rectenna solar cells, nonvacuum CIGS processing, dye-sensitized solar cells, molecular array solar cells, ultrahigh-efficiency heterostructures, GaInNAs nanoscale characterization for high-efficiency cells, optical filter concentrators for multiple bandgap solar cells, and solid-state electrolytes for dye-sensitized solar cells.

**University Partners**




UC-Berkeley/PIX09746

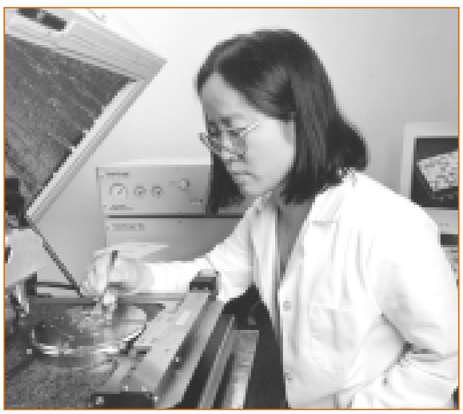
*In a totally new type of solar cell based on nanocrystal composites, University of California, Berkeley researchers discovered nanocrystal rods that may lead to improved photovoltaic performance compared with that of nanocrystal spheres dispersed in a polymer medium.*

In FY 2000, three researchers had their work sponsored by the PV Program published in the prestigious international journal *Nature*. Such honors ensure the widest possible application of our research results and indicate the groundbreaking nature of this work.

## Future Researchers

The purpose of the PV Research Program with Historically Black Colleges and Universities (HBCUs) is to advance undergraduate knowledge of PV through research investigations and to encourage a diverse group of students to learn about PV. In FY 2000, each of the eight participating universities had a subcontract with the NCPV to perform specific PV research. Each project has a principal investigator (professor) and several research associates (undergraduates) performing the work. Some of the associates have stayed with the project to the graduate level. Since 1995, about 30 college students have participated in the program for one or more years.

Ajeet Rohatgi/PIX08530



Institute of Energy Conversion/PIX08520

*In 1992, two universities were awarded "Centers of Excellence in Photovoltaic Research and Education" by the U.S. Department of Energy. The Georgia Institute of Technology (top) researches the fundamentals of crystalline silicon materials and the modeling and design of high-efficiency cells. Researchers have developed rapid thermal processing technologies and are working on fabricating low-cost, high-efficiency cells. Georgia Tech also provides high-quality research and education opportunities for student scientists. The University of Delaware's Institute of Energy Conversion (IEC) (bottom) researches thin-film PV cells. IEC works closely with the NCPV, PV manufacturers, and other government entities, thus allowing undergraduate and graduate students to obtain degrees while working with professionals in solar cell research.*

## *Additional Achievements in R&D*

| Organization | Achievement | Why it is important |
|---|---|---|
| Washington State University | Observed a change in the defect state of a-Si after light soaking with the help of positron annihilation spectroscopy. | A step toward understanding the Staebler-Wronski effect that could lead to eliminating its reduction of efficiency. |
| Siemens Solar Industries, Colorado State University, and NREL | Improved efficiency in CIS cell to 15% by applying a cyanide treatment to remove contaminants and binary impurity phases and by post annealing in air at 200°C for 2–10 minutes. | Measurements show reduced magnitude of transients. This points to further work to compare the transient effect in NREL devices and to analyze the compositional properties of the interface region. |
| University of California, San Diego | Improved electron mobility by a factor of two in GaInNAs material by using GaInAs/GaNAs superlattice structure. | This is a key 1-eV material needed for the structure of a 40%-efficient solar cell. |
| NREL | Reduced bias errors in outdoor solar radiometers by about one half. | Improve the accuracy of outdoor calibrations of PV cell technologies. |
| University of California, Berkeley | Discovered new nanoparticles and fabricated quantum rods instead of quantum dots, boosting the efficiency of nanoparticle solar cells. | Exploratory research that could lead to new high-efficiency, low-cost solar-cell technologies. |
| NREL | Researchers demonstrated >3 μm/min direct deposition of ~20 μm polycrystalline silicon layers on LGA-139 glass ceramic, mullite, glass, and tantalum at ~900°C by the atmospheric-pressure iodine vapor transport (IVT) process. | Progress at these high growth rates has stimulated commercial interest for further development of the IVT process. |
| Vanderbilt University | Fabricated a polymer nanocrystal composite solar cell with good open-circuit voltage. | Exploratory research that could lead to high-efficiency, low-cost solar cells. |
| NREL and PV industry | Conducted the PV Performance and Reliability Workshop. | Such workshops promote improved test methods, evaluation, and standards for PV modules and systems. |
| NREL | Secondary-ion mass spectroscopy (SIMS) measurements of CdS/CdTe samples revealed high concentrations of Cu located in the CdS layer far from the back contact. | Cu impurities resulting from deposition and processing conditions have been tied to device degradation issues. SIMS measurements can give clues for improving device stability. |
| Sandia | Patent application—metal catalyst process for reactive ion etch (RIE) texturing of multicrystalline silicon cells. | Patent protection will aid licensing for this approach that could improve efficiency and reduce cost. |
| Sandia | Patent award—self-aligned, selective emitter, plasma-etchback and passivation technique. | Allows further development and licensing to industry of this potentially beneficial cell design. |

# Technology Development

***The Program and industry work together to move technology from the laboratory to manufacturing, and to increase the reliability and performance of modules.***
**The National Photovoltaics Program Plan**

Annual increases in U.S. module production capacity of 15% to 20% and reductions in module production costs exceeding 35% can be largely attributed to the PV Program's cost-shared R&D projects with industry over the past ten years. During this decade, in addition to continuing fundamental research discussed earlier in this document, 40 subcontracts with industry have been awarded for high-risk manufacturing research and development. Twenty-five subcontracts improved module manufacturing. The other 15 addressed problems with components other than modules, such as power conditioning and system designs, as well as generic issues applicable to the entire industry. Twelve active subcontracts will be completed in FY 2001.

In 2000, the U.S. Photovoltaics Industry Roadmap Workshop set ambitious goals demanding a move to large-scale manufacturing in all technologies. Large-scale manufacturing for our most promising new technologies requires resolution of many issues due to the complexity of the processes involved. In addition, the required manufacturing equipment demands fundamental research and engineering work to ensure proper operation and reasonable costs.

In response to these realities, the PV Program issued a new solicitation in August 2000, *PV Manufacturing R&D—In-line diagnostics and intelligent processing in scale-up manufacturing*. This solicitation encourages teams to share the cost of high-risk research to develop intelligent processing for larger-scale manufacturing that will be the foundation for achieving the PV Industry Roadmap goals.

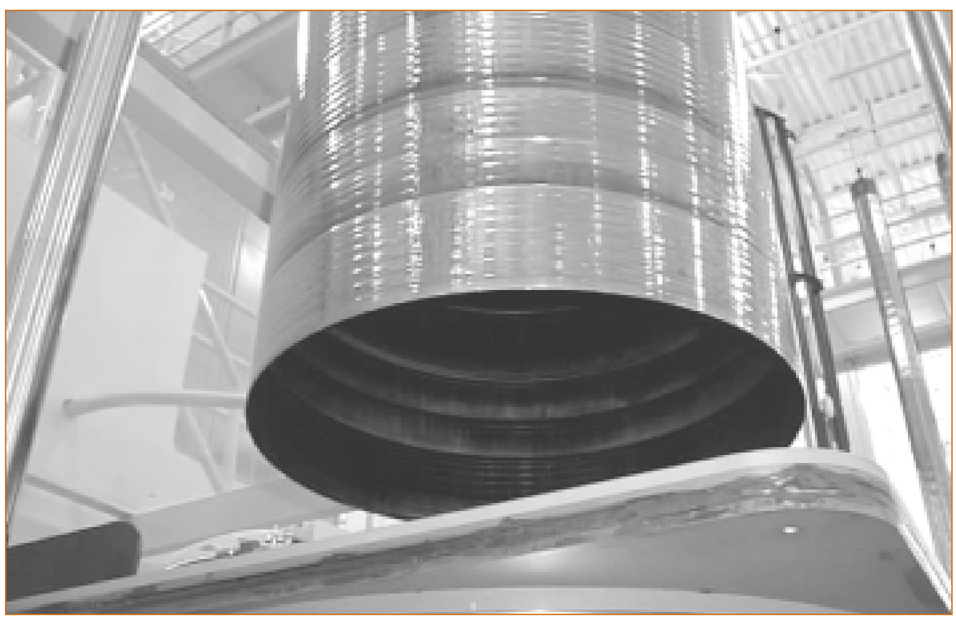
## Manufacturing Research and Development

Since Congressional funding began in 1991, the Photovoltaic Manufacturing Technology (PVMaT) Project has conducted manufacturing research and development in partnership with industry. The contracts have reduced costs of manufacturing PV modules, balance-of-systems components, and integrated systems and have improved the performance and reliability of commercial products. These activities have led to increased investment by industry for substantial scale-ups of U.S.-based PV manufacturing plant capacities.

### Module Manufacturing Processes

Each manufacturer of solar electric modules has a unique approach to producing high-performance, competitively priced products. Under PVMaT contracts, manufacturers perform high-risk research to improve their own processes and technologies.

**ASE Americas** cuts wafers from silicon material produced in the unique edge-defined, film-fed growth (EFG) system, which produces a thin-walled cylinder of crystalline silicon material that is cut into wafers for cell and module manufacture. In FY 2000, the company integrated lasers for high-speed wafer-cutting. Faster cutting can decrease labor costs by 75% and reduce the capital costs of production by 50%. The company also used Rapid Thermal Anneal processing developed at Georgia Tech for



ASE Americas, Inc./PIX08294

*This year, the ASE Americas EFG system produced larger, 50-cm-diameter, 1.2-meter-long cylinders with walls of crystalline silicon as thin as 100 microns. Growing larger cylinders with thin walls reduces material waste and increases the speed of silicon production.*

increasing EFG solar cell efficiency and used oxide formation, back-surface fields, silicon nitride, and gettering in their processing.

**AstroPower** produces solar cells from sheets of Silicon-Film™ material. This large-area sheet material is produced in a continuous manner that could be compatible with in-line processing. In FY 2000, the company continued its progress toward eliminating all batch process steps, from material growth to solar cell fabrication. The company fabricated cells processed with an in-line, water-based cleaning system. It evaluated a prototype in-line chemical etching system to prepare the silicon surface prior to the diffusion step and to remove post-diffusion oxides. AstroPower designed and purchased a prototype in-line diffusion-oxide etch system for processing Silicon-Film™ sheets. Continuous, in-line processing will increase production speed and reduce costs. In FY 2001, the company will demonstrate production of Silicon-Film™ sheets at 3.0 m/minute and will complete the design of a 50-MW/year Silicon-Film™ manufacturing line.

**BP Solar** is working to reduce the costs of producing its polycrystalline silicon PV modules and to increase the capacity of its manufacturing plant. In FY 2000, BP Solar completed a pilot facility to produce solar-grade silicon from $SiF_4$, an important step for reducing the costs of its silicon material. The company is using an optimized wire-saw process and has incorporated the recycling of SiC and oil. BP Solar has also begun environmental testing of the cells resulting from a new ultrasonic doper and a silicon-nitride deposition system. In FY 2000, the company studied methods for detecting cracks in wafers and finished cells, analyzed ways to reduce the cost of consumables, developed a prototype ultrasonic doper, selected a candidate method for in-line, nondestructive testing of cell interconnects, and selected two candidate fast-cure encapsulant formulations for environmental and outdoor testing. In FY 2001, BP Solar will continue incorporating the results of the research activities into its production line.

**Crystal Systems** has developed an effective and simple approach to removing impurities from inexpensive metallurgical-grade silicon to make it comparable to commercially available solar-grade silicon. In FY 2000, the company conducted refining experiments that produced charges of 150 kilogram. Hot loading procedures for adding feedstock to molten silicon were developed and demonstrated for charges up to 300 kg. With an appropriate crucible, charge sizes up to 500 kg can be refined using the current HEM™ (Heat Exchanger Method) furnace. Impurities have been removed to acceptable levels so that the approach is consistent with producing solar-grade silicon at a production cost of less than $20/kg. In FY 2001, the company will work on accelerating the removal of impurities to reduce refining times. Crystal Systems will also distribute its refined material to the photovoltaic industry for evaluation.

**Energy Conversion Devices** (ECD) works with United Solar Systems Corporation to improve the continuous manufacture of a-Si alloy PV modules in the United Solar manufacturing plant. ECD designed, fabricated, and installed a new substrate heating system in United Solar's 5-MW production facility, to decrease production downtime. Other ECD improvements include in-line diagnostic systems, a new process for depositing the back-reflector layer, improved cathode hardware, and new technology for changing substrate rolls. These improvements will be incorporated into equipment for United Solar's 25-MW production facility and should reduce module costs by 25% to 30% over 1997 levels and increase production capacity 60% over previous plans for this production line.

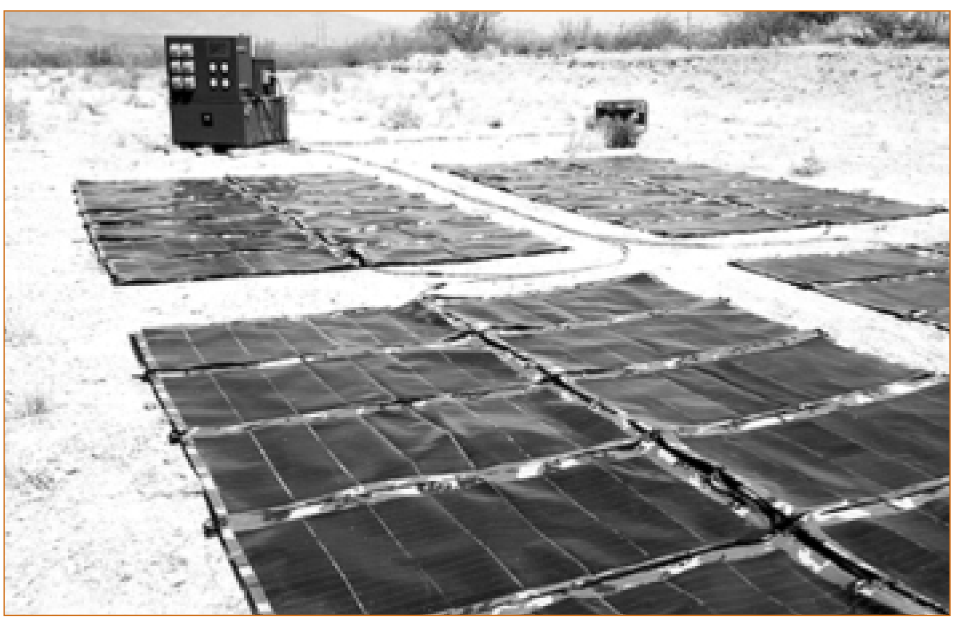
**Evergreen Solar** produces silicon material called string ribbon to make PV modules. In a continuous process, each machine grows a single ribbon 24 hours a day. For its 10-MW plant, Evergreen plans to install 120 of the new machines it developed in FY 2000. In FY 2000, Evergreen also began using an automated contact machine for soldering individual cells and for forming cell strings for modules. The company developed a new string material and edge meniscus control method and applied for patent protection of these innovations. These changes in manufacturing have increased run length by 200%, increased cell efficiency by 5%, improved factory yield by 20%, reduced costs of consumables by 60%, and reduced the cost of the new furnace by a projected 20%.

**First Solar** continued its work on its CdTe thin-film module manufacturing processes. The company adopted a new UL-listed mounting method and developed a new "cord-plate" contact termination method, replacing potted polyurethane termination "pigtails." Testing was completed for an improved module lamination process and for a high-throughput solar finishing line that will be used in the First Solar production line. Another production-line improvement is an automated, single-laser scribing system that is up to 10 times faster and shows a 15-fold improvement in registration of consecutive laser-scribe lines over existing systems. First Solar's improved modules passed UL 1703 qualification testing, and the company's Environmental, Health and Safety program continued work to ensure the safety of manufacturing its modules.

**Global Solar Energy** worked to increase the throughput of their manufacturing processes for CIGS thin-film PV modules. A new high-speed scribing process in its manufacturing equipment demonstrated robust and repeatable scribing. Engineers completed analyses and installed production equipment to integrate industrial ink-jet hardware and accomplish high CIS deposition rates. An alternative back-contact material and process for deposition on flexible polymer and stainless-steel substrates increased productivity without reducing product performance. In FY 2001, the company will incorporate these and other improvements into the manufacture of 27-W modules.

Most of the PV modules manufactured by **Siemens Solar Industries** are made with Czochralski crystalline silicon. The company is working to produce solar cells that are thinner and larger in surface area and that have back-surface field processes to increase efficiency. These changes should reduce module manufacturing costs by 30%. To produce the new 17%-efficient thin cells, the company has developed a pilot crystal-growth process for silicon ingots, which will be sliced into 150-micron-thick wafers and then processed into 125-micron-thick cells. Siemens has also developed a pilot process for fabricating the thin cells so that they have a back-surface field. In FY 2000, the company demonstrated prototype 125-micron-thick cells that were 16.5% efficient. To produce larger-area cells, Siemens grew a 200-mm-diameter ingot and developed a new process for fabricating these cells.

**Spire Corporation** sells production equipment for crystalline silicon or thin-film PV module manufacturers. It is developing automated systems that process the edge of modules, install junction boxes, test final modules, and store modules between processing steps. In FY 2000, Spire demonstrated the SPI-BUFFER™ 350, which stacks modules on a cart where they can be stored safely and moved to the next step on the production line. This buffer storage compensates for the batched steps of PV module manufacture. Spire also introduced the SPI-MODULE QA™ 350, a system for transporting, probing, and testing modules for electrical isolation, ground continuity, and performance in the form of current-voltage measurements. In FY 2001, two additional systems will be perfected: an edge trimmer for removing excess encapsulant and back-cover film from module edges after lamination, and an edge sealer and framer for trimmed modules. Development of automated processes for junction-box installation is planned.



Global Solar/PIX09747

*This 2.8-kW flexible solar array made of CIGS thin-film material was used in the U.S. Army's Operation Strong Angel training exercise in Hawaii. In FY 2000, Global Solar and Siemens Solar sold the first commercial products made from CIS-based thin-film materials.*

## System and Component Technology

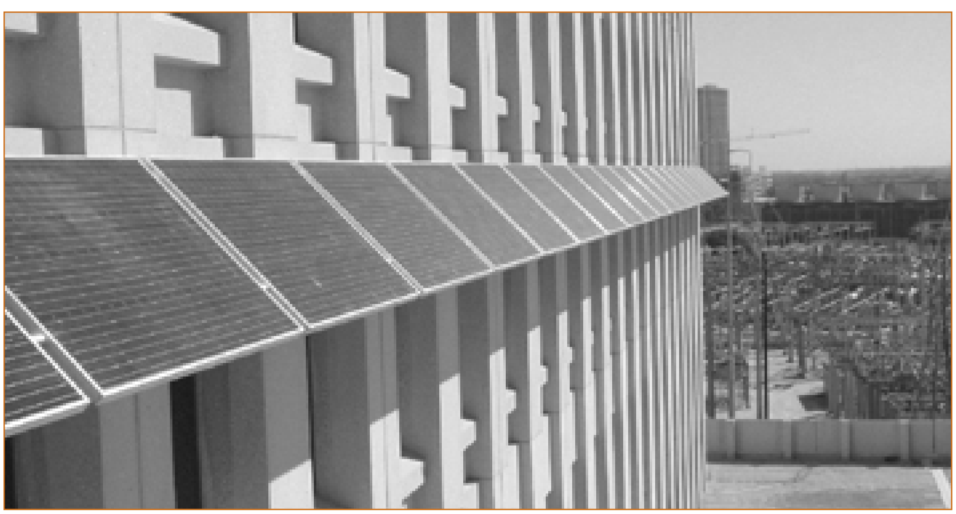
Research contracts to improve system and component technology address specific problems for manufacturing steps and include material development. Some of the research partnerships to improve manufacturing of the balance-of-system (BOS) components and complete design of solar electric systems began in 1995. Research aims to develop innovative, low-cost, high-return, high-impact PV products. The work addressed improvements to components such as inverters, efficient integration of components into the system, and improvement in the design of systems.

**Advanced Energy, Omnion Power Engineering** (a division of S&C Electric Company), and **Trace Engineering** worked to improve the inverters that convert the dc electricity from solar electric cells and modules into ac power for utility interconnection. The companies used advanced electronics, new approaches to power bridge design, and complex software to improve performance, reduce costs, and include monitoring and improved communications options in the inverters they supply to the PV systems industry.

**Applied Power Corporation** (formerly Ascension Technology) manufactures an ac solar electric module that makes PV truly modular and simplifies installation of systems that are fully compatible with ac appliances and with the utility grid. In FY 2000, the first prototype SunSine® ac module delivered to NREL for outdoor testing showed that inverter efficiency met the project target of 91%. Refining the product's design, the company designed and built prototypes, and began production of a die-cast aluminum enclosure. Applied Power filed two patent applications, one relating to the design of the die-cast enclosure, and the other relating to the power electronics design and a factory calibration procedure. Applied Power also improved the reliability of its ac modules by incorporating its proprietary Zero Voltage Switching soft-switching into the SunSine® inverter. The company reduced production costs by cutting the number of parts by 57%. To make components smaller, Applied Power reduced the footprint area of the inverter by 45%. The SunSine® AC 325 module passed FCC tests of electromagnetic emissions and underwent the PV Program's Highly Accel-erated Life Testing. Near the end of FY 2000, Applied Power began production of 110 units of this new version of its ac module. Of these, 28 were installed at the University of Texas, Houston Science Center.

**PowerLight Corporation** produces PowerGuard® tiles for rooftop solar electric systems. The company's process mounts PV modules (crystalline silicon or thin-film) on 3-inch-thick boards of extruded polystyrene foam covered with a cementlike coating. In FY 2000, PowerLight increased production from 200 to 400 tiles per day. The company improved handling and application of the cement coating by designing a new hopper that included pneumatic mixing, easy cleaning, and an electronic motion-control circuit, and it eliminated the need to handle laminates twice by integrating a spacer attachment process into the production line. Other improvements include incorporating electronic sensors to monitor and control steps in the process line, better edge trimmers, and a better hydraulic tool for moving finished tiles to pallets for shipment. In FY 2000, the company estimated an overall cost reduction per board foot of tile of nearly 60% compared with costs in 1999. PowerLight has increased production capacity from 5 MW to 20 MW per year.

**Utility Power Group** (UPG) is completing a factory-assembled PV array, and Trace Engineering is developing companion 12-kW power conversion and energy storage units. The power conversion unit can operate in a grid-tied or stand-alone configuration when coupled with the 13-kW/h capacity energy storage unit. This fully integrated residential PV system will incorporate advanced power management and storage. UPG's PV array design can accommodate PV modules from several different manufacturers, either framed or frameless. Its design uses bolts and a rail assembly to attach the factory-assembled panels to the roof. In a test for planned projects for the Sacramento Municipal Utility District, UPG reported a crew of two people installed a 1-kW PV system on a test roof in less than 1 hour. In FY 2001, UPG will complete field testing of the PV array, and Trace will complete development of the power unit's management control software and field test the system with storage.


University of Texas/PIX09436

*Applied Power Corporation's power modules serve as an awning for the University of Texas Houston Health Science Center. The ac modules will produce nearly 10,000 kWh of electricity each year.*

Work continues on improving the performance and reducing the cost of other BOS components, such as batteries, materials, and packaging. For example, tests of a hybrid system being developed for the Navajo Nation by NCPV engineers at Sandia revealed that battery life would be adversely affected by the way the charge controller was directing electricity from the PV modules. Replacing batteries is expensive, increasing the cost of solar electricity. Changing the charge controller set points in response to these test results resolved the issue before the systems were installed in the field.

## Module Performance and Reliability R&D

To demonstrate the performance of different solar electric technologies, the NCPV conducts tests in the laboratory and in the field of both prototype and commercially available modules. The sophisticated monitoring equipment and analysis methods of the NCPV laboratories provide information that would be difficult for manufacturers to obtain and virtually impossible for end users to get.

In FY 2000, results of a field test begun in 1997 show that one technology, a-Si triple-junction PV modules from United Solar System Corporation, is living up to its ratings. After three years of continuous outdoor exposure, the two 1.01-square-meter (about 10-square-ft), 64-watt modules were placed in the NREL Large-Area Continuous Solar Simulator, which revealed that their efficiencies were 7.26% and 7.18% and that their output powers at standard reporting conditions were 67.3 and 66.6 watts.

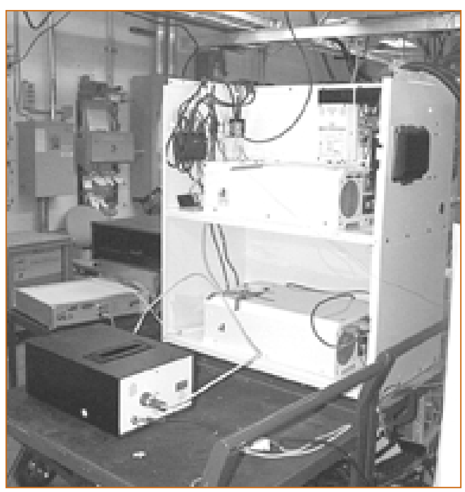
## Addressing Environment, Safety, and Health Issues

The NCPV works to identify and solve environmental health and safety issues in the manufacture, use, and disposal of solar electric systems. In FY 2000, the NCPV and Brookhaven National Laboratories held a workshop on the use of lead-free solder in the manufacture of PV modules. The technology was developed under contract to the PV Manufacturing R&D effort of the program by ASE Americas. ASE Americas shared its patents and technical details with workshop participants from the PV industry. Making PV modules without leaded solder ensures that PV modules can be disposed of at the end of their 30-year life without violating EPA landfill restrictions on lead.

To help understand and characterize the outdoor performance of polycrystalline silicon module technologies, the NCPV began a test of six new PV modules on its Performance and Energy Ratings Testbed (PERT). This outdoor test of commercially available polycrystalline silicon modules, which could last up to four years, will determine the actual power and energy production capacities of these modules under field conditions. The six 40-W modules, two from each of three manufacturers, are mounted on the roof of the Outdoor Test Facility at NREL and connected to data acquisition systems that monitor their current-voltage characteristics once every 30 minutes during all daylight hours. The test system also maintains the modules at their peak-power-point load at all other times, which allows derivation of the total energy produced by each module every day. The first results should be available in FY 2001.

In FY 2000, work by NCPV researchers at Sandia continued using high-resolution infrared cameras to detect and characterize defects in PV modules. This is a quick and inexpensive way to identify module defects that could reduce performance and reliability.

Researchers at Sandia are also studying the successful manufacturing techniques used to produce the modules that have operated effectively for more than two decades at Natural Bridges National Monument, Utah. After more than 20 years in the field, the crystalline silicon modules manufactured by Spectrolab still perform close to original specifications. Detailed analysis in FY 2000 identified several positive features, including the use of polyvinyl-butyral encapsulant, expanded metal interconnects, silicon oxide antireflective coating, and excellent solder/substrate solderability. This information will help manufacturers improve the durability of current and future products.



Sandia/PIX09745

*In FY 2000, NCPV engineers at Sandia evaluated 7 grid-tied inverters and 9 inverters in off-grid configurations. These evaluations helped manufacturers, including those in the PV manufacturing R&D project, develop new products.*

An important tool to design solar electric systems is the model used to predict PV module performance for the complete range of outdoor operating conditions expected at a specific site. NCPV engineers at Sandia and NREL have made significant progress in developing, validating, and documenting performance models to simulate the total energy production (daily and yearly) of the commercial PV modules available today. The performance of modules is characterized under actual outdoor operating conditions at outdoor test facilities and in the laboratory using solar simulators. In FY 2000, NCPV researchers completed a comparison of two candidate PV module energy-rating methods and published the results to support ongoing efforts to develop a new Module Energy Rating standard through the Institute of Electrical and Electronics Engineers (IEEE).

# Systems Engineering and Applications

***The Program—with industry, governments, national and international organizations—improves performance and reliability of systems and introduces technology to domestic and foreign markets.***
**The National Photovoltaics Program Plan**

An important part of the Program's development strategy is to monitor solar electric technology performance to provide feedback to system engineering and R&D efforts. This iterative process from basic research to commercial operation will ultimately reduce the cost of producing, installing, and operating solar electric systems.

## Systems Engineering

When customers calculate the cost of solar electricity, the equation includes the PV modules, all the related or balance-of-system (BOS) components, and the costs of operation and maintenance over a specified equipment lifetime. System engineering support activities at the NCPV work to estimate and reduce all of these costs through testing, modeling, standards development, and technical assistance to initial users.

### Non-Islanding Inverters

For solar electric systems to power standard ac appliances, a necessary system component is an inverter. The inverter converts the dc electricity from the PV modules to ac current. This ac current can be sent into the power line if the solar electric system is connected to the utility grid. If the power line is shut down for any reason, the utility must be confident that no PV or distributed generation source continues to energize the grid. This electricity-flow restriction is to ensure the safety of line workers or other people coming into contact with the line. Electric utilities have been reluctant to connect distributed electric generation systems to the grid because of this potential risk to personnel and equipment during such "islanding" events.

In FY 2000, a new control method for inverters developed over two years by NCPV engineers at Sandia has been approved by testing and standards organizations. The "non-islanding inverter" automatically diverts or turns off electricity flow from grid-connected solar electric systems when an electric distribution line shuts down. Several manufacturers have already adapted their inverters to include the new control method.

### Standards

*Small-systems test procedures*

The PV Program has been working to develop a single test that will be accepted anywhere in the world. This is important for enabling organizations like the World Bank to determine how well a small stand-alone PV system will perform in the field. NCPV researchers at NREL, Sandia, the Florida Solar Energy Center, the Southwest Technology Development Institute, and PVUSA have developed a procedure for outdoor testing based on two small PV lighting kits. This testing procedure has been incorporated by the IEEE SCC 21 Working Group on Small Systems Testing into a new draft of IEEE PAR 1526, *Recommended Practice for Testing Stand-Alone PV Systems*. Additional testing to validate the procedure is under way in a collaboration between the GENEC PV testing group in France and the NREL Outdoor Test Facility in Colorado. Meanwhile, the European Solar Test Installation (ESTI) has developed an indoor test procedure for small stand-alone PV systems. A new draft document by the International Electrotechnical Commission (IEC) combines both the indoor and outdoor test into one procedure that can be conducted almost anywhere in the world. Once this procedure is approved, a significant obstacle to programs promoting solar electricity for off-grid applications will be removed.

*IEEE interconnection standard*

For the solar electric systems market to reach the goals of the PV Industry Roadmap workshop, the procedure for connecting these systems to the utility grid must be simple and acceptable to utilities and system installers. This requires that the procedure guarantee the safety of all personnel and ensure delivery of high-quality electricity to all customers. In FY 2000, more than three years of work by utilities, the NCPV, and many other engineers achieved a very important step toward safe, widespread use of solar electricity. The IEEE standards board passed IEEE Standard 929-2000, *Recommended Practice for Utility Interface of Photovoltaic Systems*, the first standard of its kind allowing utility interconnection of distributed generation equipment (including PV) not owned by the utility. Two things that make this standard unique are its definition of a non-islanding inverter and of a procedure to test inverters for the non-islanding features. This standard simplifies the process of interconnecting a solar electric system to the grid, while including tightly defined requirements for the interconnecting hardware. These hardware requirements can be tested at an independent laboratory, such as Underwriters Laboratories, thanks to a parallel effort to develop the appropriate test procedure. The test procedure included in UL 1741 determines if inverters meet the requirements of IEEE 929, which specifies operating voltage, frequency windows, trip times for excursions outside these windows, requirements for wave-form distortion, and definition of a non-islanding inverter.

### *IEEE standard for concentrator PV modules*

A milestone of the National PV Program Plan was met in FY 2000 when balloting began on a new IEEE Standard, titled *Recommended Practice for Qualification of Concentrator Photovoltaic (PV) Receiver Sections and Modules*. The NCPV has led the three-year development of this standard because concentrating PV systems could be a key terrestrial application of the high-efficiency solar cells now being used in space. An accepted method to identify any weakness in concentrating systems that could cause problems in the field will increase sales of concentrating PV systems.

NCPV researchers at NREL, the State University of New York, and the New York Solar Energy Research and Development Association (NYSERDA) are working to increase the value of solar electricity to commercial customers. They have developed a new solar load controller for customers on time-of-use tariffs in utilities with peak demand driven by air conditioning loads. The solar load controller works by shedding loads when the PV system cannot reach its full peak target. Tests so far show that the controller can shave peak loads, making them match the output of the PV system. Avoiding peak energy charges will translate to significant savings to commercial customers.

The NCPV also works with the Sacramento Municipal Utility District (SMUD). With more than 7,000 kW of solar generating capacity, SMUD has the largest utility-owned distributed solar energy system in the United States.

### Success of the TEAM-UP Project

TEAM-UP (Technology Experience to Accelerate Markets for Utility Photovoltaics) was a partnership between the U.S. Department of Energy and the utility industry to help develop commercial markets for a wide range of solar photovoltaic technologies. TEAM-UP awarded matching grants on a competitive basis to solar electricity projects across the United States. Those awards resulted in 7.2 MW in generating capacity from solar power installations in 40 states. From 1994 to 2000, the Solar Electric Power Association (formerly the Utility Photovoltaic Group or UPVG) managed the TEAM-UP project.

## Partnerships for Technology Introduction

DOE's Domestic PV Applications and Development Project reaches out to more than 500,000 people each year—consumers, architects, builders, engineers, emergency management personnel, utilities, and farmers—to provide information about solar electric systems.

### Utilities and Solar Electricity

NCPV engineers support standards efforts and conduct studies to document the value of solar electric systems as a distributed generation source for utilities. Solar electric systems can be installed at both residential and commercial sites where the electricity will be used. Solar generation can be sized to reduce peak demand at these locations, which can reduce the utility's need to build new capacity and the amount it spends for new conventional generation facilities to meet the peak.

Kyocera Solar/PIX09435

*This solar electric system in Sacramento, California, generates enough electricity to meet the needs of about 180 homes. While providing electricity, it also shades part of the Cal Expo parking lot. The largest parking-lot solar system in the world, this project was a joint effort of the Sacramento Municipal Utility District and DOE through the TEAM-UP program.*

## PV in Buildings

The buildings sector in the United States consumes about two-thirds of the nation's total annual electricity production. Reducing the electricity demands of buildings on the utility grid would have a significant impact on energy consumption. The *Million Solar Roofs Initiative*, spearheaded by DOE, promotes the use of solar thermal and solar electric technologies to reduce the energy demands of buildings. In FY 2000, DOE had 50 partners that had made commitments for one million solar roofs by 2010. Of the total installations in FY 2000, 750 were solar electric systems equal to about 3 MW of capacity.

One of the Million Solar Roofs partners, the Florida Photovoltaic Buildings program, has the goal of contributing 20,000 of the nation's million solar roofs. This state program is a collaboration among the Florida Energy Office of the Department of Community Affairs, the U.S. DOE through Sandia, the photovoltaic industry, the Florida Solar Energy Center, and nine end-user groups. These important end-user groups include municipal utilities, commercial building owners and operators, government agencies, school and church organizations, manufactured building corporations, roofing companies, builders and developers, and homeowners.

This many-faceted program relies heavily on training, certification, and careful administration of incentives to avoid problems with hardware and installations that have plagued other deployment projects in the past. Partnerships, especially with utilities, lead to many of the installations. Revenue for subsidies to reduce the cost of PV systems comes from a variety of sources including state funds, matching funds from partners, contracts, grants, financing, and TEAM-UP awards from DOE. Distribution of funds is linked to quality of the PV systems, which is determined through design review, module rating tests, and system acceptance testing. Training conducted by the Florida Solar Energy Center, with support from the PV Program, gives installers the certification they need to participate in the Florida PV Buildings Program. The Florida program requires systems to meet standards for safety and electrical quality. High-quality, reduced-cost systems have led to good customer satisfaction, as monitored by the careful administration of the program.

One way to expand the market for PV is to incorporate products right into buildings. To develop technologies and foster business arrangements to integrate PV or hybrid products into buildings, DOE initiated the Building Opportunities in the United States for PV (PV:BONUS) in 1993. Several of the products developed under the program were commercially available in FY 2000. For example, Advanced Energy Systems received UL listing for its 1-kW grid-interactive PV inverter and is installing the units for PV applications throughout the United States. Models meeting European specifications will be available soon. Another team, led by BP Solar and Kawneer, a leading manufacturer of architectural aluminum products, received a design award at the 16th Annual European Photovoltaic Solar Energy Conference. Its winning design was a building-integrated sun shade incorporating a-Si PV modules manufactured by BP Solar. And a team with United Solar Systems Corporation received UL listing for its flexible PV membrane that can be applied in the field.

In FY 2001, five contractors will continue their work to install prototype products on buildings, gain UL listings for these products, and move to large-scale manufacturing. These products include powered electrochromic windows, combination opaque curtain wall and PV a-Si modules, hybrid PV and solar thermal systems, and flexible PV roofing membranes.

FSEC/PIX09743

*Training at the Florida Solar Energy Center qualifies installers for the Florida PV Buildings Program, a model for the widespread commercialization of grid-tied, rooftop PV systems. FSEC also conducts applications experiments and field testing of PV systems for the National PV Program.*

Robb Williamson/PIX09227

*Engineers from the NCPV supported the installation of PV systems at Zion National Park in Utah (left) and the BigHorn Center in Colorado (below). These highly visible, attractive projects publicize the feasibility of roof-mounted and building-integrated PV systems.*

Jim Yost/PIX09203

## Remote Systems

In addition to some 200,000 homes in the United States that are not connected to a utility grid, there are countless other off-grid applications for solar electricity. Farms and ranches, communications, pumping, water flow control, and homes in remote areas can be provided electricity more economically using solar electric systems on site than by having grid electricity brought to each application.

In FY 2000, many of the possible applications of solar electricity were presented at the Photovoltaics in Alaska Workshop. Experts in the technology and its many applications spoke to 60 assembled representatives from Alaska's utilities, Native villages, telecommunications companies, the Alaska Railroad, governmental agencies, Alaska's newly formed Million Solar Roofs coalition, and the University of Alaska. The one-day workshop, co-sponsored by DOE and the Alaska Energy Authority, was coordinated by the NCPV.

Stand-alone solar electric systems can be very useful to emergency management personnel. The NCPV hosted the Federal Emergency Management Agency's (FEMA) 5th Annual Technology Partnership for Emergency Management Workshop and Exhibition. More than 500 emergency-management professionals discovered the versatility of solar electric systems in both surviving disasters and quickly replacing damaged power supplies for critical loads.

### *Native American Lands*

When developing applications for solar electricity, the PV Program tries to move from granting subsidies to purchase hardware to providing technical assistance and documenting successful applications. The Program has worked in FY 2000 with tribal authorities to install solar electric systems for people of the Laguna Pueblo, the Yurok tribes, and the Navajo Nation.

The Navajo Tribal Utility Authority (NTUA) estimates that, in FY 2000, between 10,000 and 30,000 Navajos lived without electric power on the reservations. Because these homes are spread out over a wide area, it would be prohibitively expensive to construct and maintain power lines to each home. Providing homes with solar electric systems in the early 1990s demonstrated the benefits of PV on the reservation. The NTUA, with technical assistance from NCPV researchers at Sandia and subsidies for hardware from DOE, the State, and local utilities, purchased and installed 71 home systems of 250 watts each . These systems proved so successful that, in FY 2000, NTUA invested $2 million of its own money to install another 200 PV systems on private homes. The utility asked only for technical assistance to implement their project. NCPV engineers from Sandia helped conduct system acceptance testing, train electricians, and determine recommended maintenance procedures.

The lands belonging to the Yurok tribes in Northern California also offer many opportunities to use renewable energy to supply the population's electrical needs. NCPV engineers at Sandia joined a team to evaluate the tribe's options for using renewable energy to supply electricity to about 70% of the inhabited land that does not yet have electrical service. The resulting report will help the tribe set priorities and apply for grants to develop some of these renewable energy options.

Sandia/PIX09747

*The Bureau of Reclamation uses PV to power motors that operate automatic gates for water flow control in irrigation canals. These systems improve the efficiency of water use and eliminate the need for Bureau personnel to manually operate the gates each day. NCPV researchers at Sandia are working with the Bureau to develop system diagnostics and communications systems.*

Susan Masten, the chairperson of the Yurok Tribal Council, states: "I hope that this collaboration represents the beginning of a relationship between the Yurok Tribe and DOE that will result in significant improvements to conditions on the Yurok Reservation."

***Solar Electricity for Developing Countries***

*India*

To validate performance of U.S. thin-film technologies and compare these technologies with those of international competitors, the NCPV collaborated with the Solar Energy Center (SEC) in New Delhi, India, to install PV systems from U.S. module manufacturers. In a 50-50 cost-shared program, the NCPV purchased the modules and the SEC paid for the BOS and installation costs. The 5-kW systems will be characterized at NREL prior to shipment, and their performance in outdoor conditions in India will subsequently be compared to these measurements. Once this is done for the five thin-film technologies (a-Si/a-SiGe, dual-junction a-Si, triple-junction a-Si, CIS, and CdTe), U.S. products could be introduced into the sizable market for solar electricity in India.

Jim Welch - Remote Power/PIX06004

*Local technicians install solar electric modules on a village clinic as part of a collaboration between the NCPV and the Solar Energy Center in New Delhi, India, to test U.S. thin-film solar modules.*

Sandia/PIX09714

*This solar electric system installed in FY 1999 delivered about 23 megawatt-hours of electricity to the Indian Pueblo Cultural Center in Albuquerque, New Mexico, in its first year of operation. NCPV engineers at Sandia conducted the project's electrical design review and monitor system performance.*

*Mexico*

After six years of installing cost-shared pilot systems in Mexico, one of the PV Program's in-country partners succeeded in obtaining World Bank and Global Environmental Facility (GEF) grants and loans contributing to a $31 million Renewable Energy for Agriculture Program. The Director of Fideicomiso de Riesgo Compartido (FIRCO) is receiving funds for the first World Bank/GEF program using renewable energy in the agricultural sector. For four years or longer, this program will deploy more than 1200 PV and 55 wind systems to pump water for agriculture. Sandia has signed a collaborative agreement with FIRCO to provide technical training and assistance for their new program.

*China*

NCPV engineers at NREL have been working with partners in the utility, government, and non-government sectors to open the Chinese market to the products of U.S. PV manufacturers. More than 200 solar electric systems have been installed on homes in Tibet, and 243 PV/wind hybrid systems have been installed in Inner Mongolia. The Brightness Program, China's largest rural electrification program, will install solar electric systems in 500 villages and on about 450,000 homes during the first phase of the project. National-level policy-makers from China attended a workshop coordinated by NCPV personnel at NREL to address renewable energy technologies, distribution networks, policies, and business models.

## Outreach

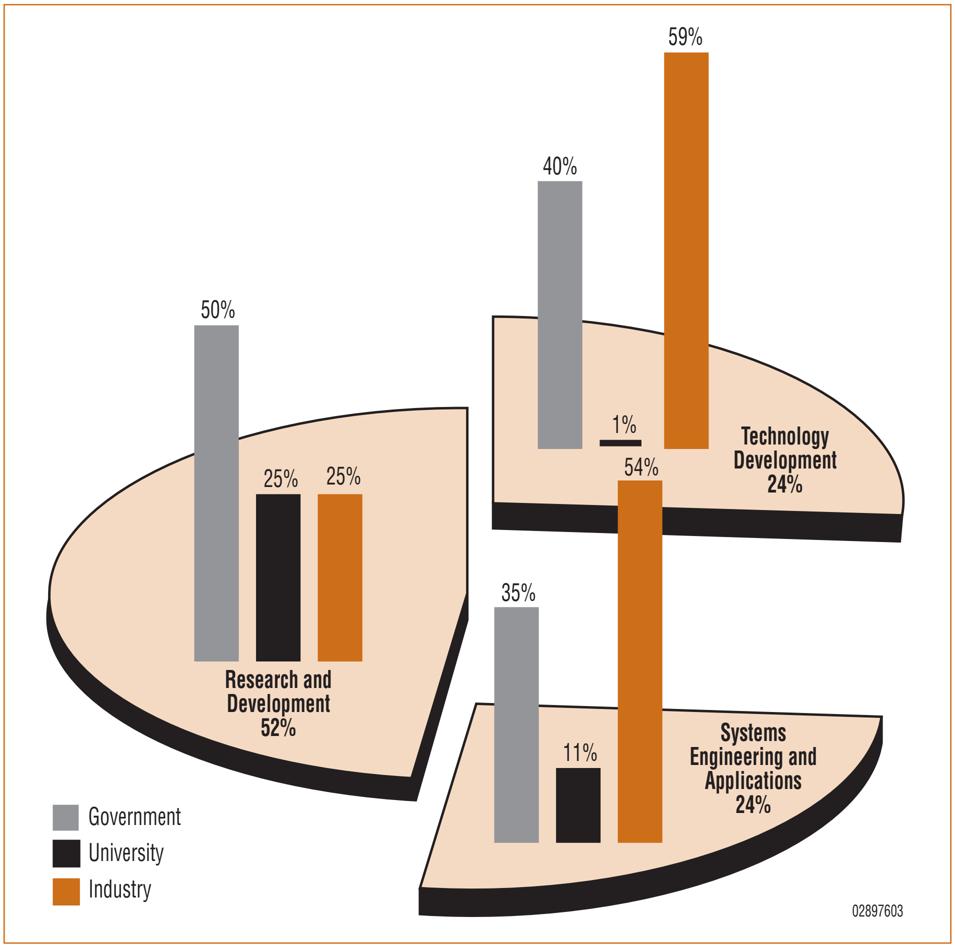
The NCPV distributes information to facilitate the use of solar electric systems in diverse applications. In FY 2000, publications, including *Making the Most of Residential Photovoltaic Systems*, *Photovoltaics and Solar Thermal Technologies in Residential Building Codes*, and *Power Where You Need It*, were distributed by mail, at workshops, conferences, and exhibits. They are also posted on the popular NCPV Web site (*www.nrel.gov/ncpv*). The Web site, with links to useful sites about DOE, NREL, Sandia, and elsewhere, is proving to be an effective way to deliver information about solar electric systems to audiences with varying levels of technical expertise. In addition, the *Solar Energy Showcase* CD-ROM contains 120 high-resolution photos with extended captions on PV, concentrating solar power, and solar buildings. This CD-ROM is popular with the news media. Volume 2 will contain at least 10 photos of solar technologies from each of the 50 states.

Siemens Solar/PIX09826

*Siemens Solar's earthsafe™ systems, like this one in Sacramento, California, are complete solar electric packages. They are connected to the utility grid and allow the user to produce green power and lower their electric bill. The package includes solar electric modules, mounting hardware designed for any roof surface, and an inverter to provide the ac power. These earthsafe™ systems are UL listed, and they come in sizes to produce from 250 watts to 2000 watts of ac power.*

# Program Resources

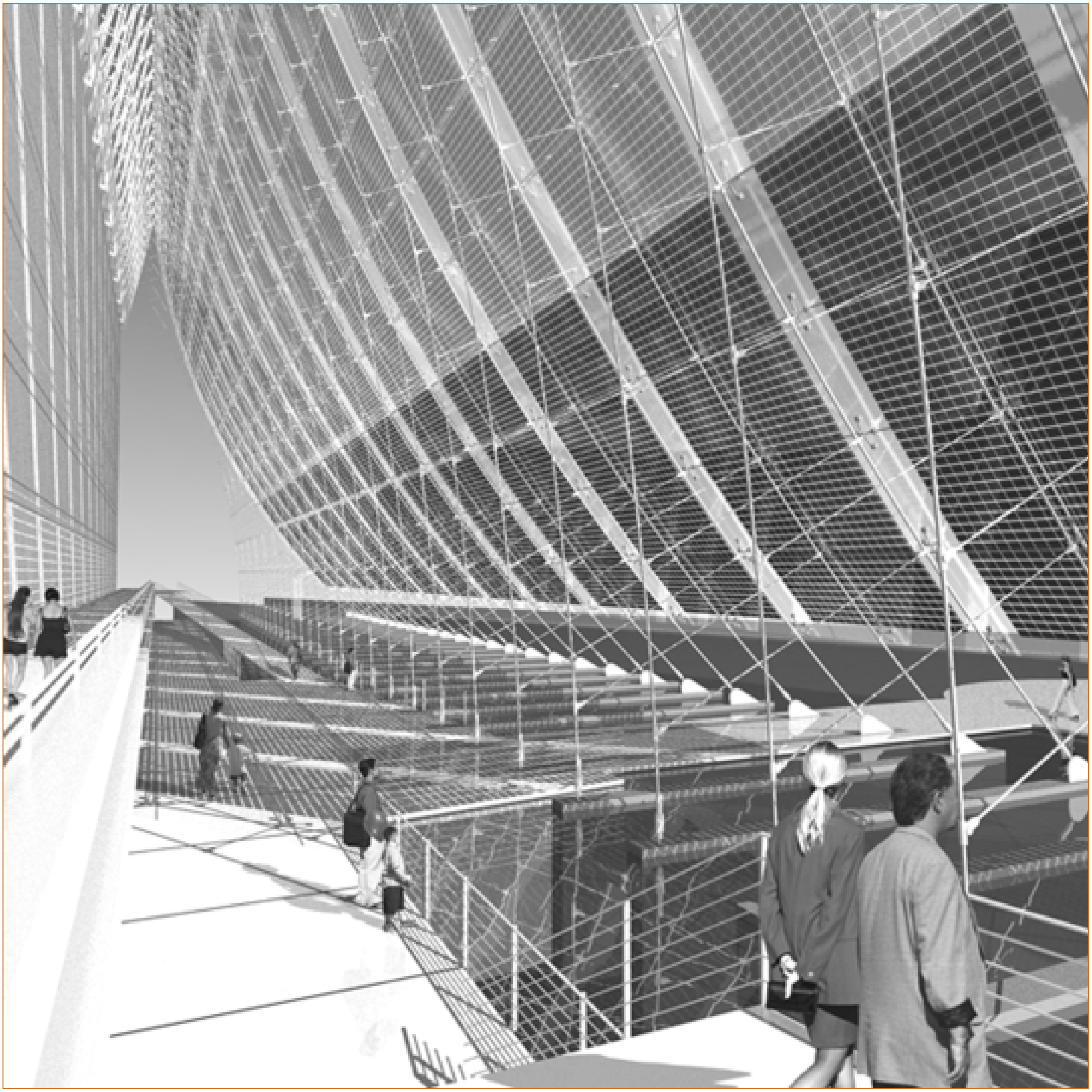
The National Photovoltaics Program, as described in the 2000 to 2004 Program Plan, conducts its business using the National Center for Photovoltaics (NCPV), an alliance of organizations working to help the U.S. PV industry maintain its global leadership position. To reach the milestones listed in the NCPV's Five-Year and Annual Operating plans, 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. The NCPV also draws upon the resources of 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 a hundred university and industry research partners across the country are linked to function in a unified way. The PV Program ensures the widest possible distribution of key scientific and technical material relating to the development and use of PV systems.




*The NCPV awards most of its federal funds through competitive procurement to industry, universities, and other research centers around the country. The federal funds for FY 2000 totalled $65.9 million.*

The Program maintains world-class facilities and researchers at the national laboratories to serve industry. The national laboratories of the Program include the following capabilities.

- Solid-state spectroscopic analysis, experiments with photoelectrochemical processes, and applications of advanced theoretical and computational tools for predicting the behavior of PV materials;
- 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 development of special measurement techniques and instruments;
- User-accessible laboratories for fabricating and evaluating solar electric technologies and for developing and characterizing balance-of-systems components such as charge controllers and inverters;
- Outdoor test beds, indoor laboratories, and field trials for simulated, accelerated, and actual outdoor test conditions, and under varying temperature, humidity, precipitation (including hail), voltage, and radiation levels;
- Measurement systems traceable to world standards to characterize solar resources, including electronic data sets, maps, and models; satellite imagery, meteorological data, and models.



Solomon Cordwell Buenz & Assoc./PIX09743

*The product of a national solar design competition sponsored by DOE and the American Institute of Architects (AIA), the* ***Solar Wall*** *(pictured here as an artist's concept) will cover the currently windowless south wall of the Forrestal Building, DOE's headquarters in Washington, D.C. In summer, when the sun is high in the sky and building electrical demands are at their peak, PV panels in the lower part of the wall will generate electricity for the building (about 100 kW peak). In fall and winter, when the sun is lower in the sky, solar thermal collectors in the upper part of the wall will also use the sun's energy to heat water for the building's heating systems. Designers estimate that the Solar Wall will cut DOE's energy costs by between $30,000 and $50,000 per year.*

## Front cover photos

Fundamental research in photovoltaics leads to advancements in the technology. The square photos show, clockwise from top left:

- PV module framing and manufacturing at Siemens Solar Industries. Siemens Solar/ PIX07832
- The Williams Building in downtown Boston, Massachusetts, has a 37-kW dc and a 28-kW ac PV system integrated into the roof consisting of 372 solar panels. Roman Piaskoski/ PIX07172
- The Department of Environmental Protection building in Ebensburg, Pennsylvania, was selected as one of the top 10 environmental buildings in the United States by the American Institute of Architects on Earth Day 2000. "Green" highlights include a 16-kW PV array, the second largest in Pennsylvania. FIRST, Inc./ PIX09437
- NREL's Ron Judkoff inspects a 7.2-kW photovoltaic array on the south roof of the new Visitor Center at Zion National Park, Utah. Robb Williamson/PIX09264

Center circle photos (left to right): 03525 and 03524

- A vacuum system at Sandia used to investigate metallization systems for crystalline-silicon solar cells. Researchers use Sandia's PV Device Fabrication Laboratory to design, make, and test crystalline silicon solar cells. Jim Yost/PIX03525
- NREL's Kannan Ramanathan inspects the growth chamber of a physical vapor deposition system used for making solar cells from copper indium diselenide. Jim Yost/PIX03524

Inside cover: A 75-kilowatt photovoltaic system on the roof of the Mauna Lani Bay Resort Hotel in Hawaii. PowerLight Corporation/PIX06430

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**Useful Web Sites**
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NCPV: *www.nrel.gov/ncpv*
Sandia: *www.sandia.gov/pv*

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