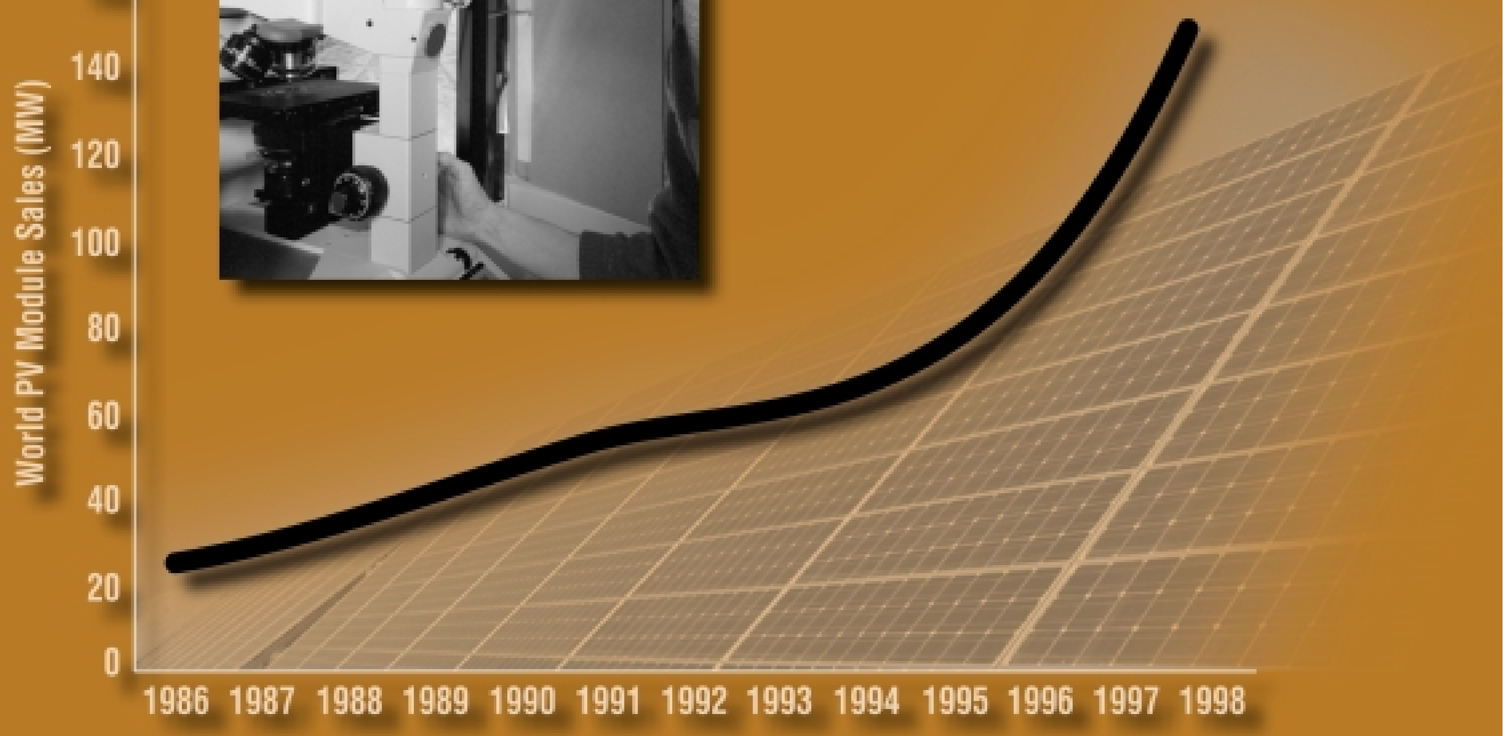
Photovoltaic Energy Program Overview
Fiscal Year 1998



U.S. Department of Energy

PROGRAM HIGHLIGHTS

RESEARCH AND DEVELOPMENT . . . . PAGE 2

- Shared R&D 100 award with United Solar for triple-junction amorphous silicon PV roofing module.
- Won IEEE Electrotechnology Transfer Award by moving high-efficiency $GaInP_2$/GaAs tandem solar cell to industrial production.
- Fabricated 15.4%-efficient cadmium telluride device using process that is easy to duplicate.
- Exceeded planning goal for 1999 by supporting development of 16.6%-efficient cell made of thin-layer crystalline silicon.
- Fabricated and tested a 17.2%-efficient back-contact emitter wrap-through crystalline silicon cell.
- Demonstrated a 12%-efficient solar device to split water into hydrogen (a valuable fuel) and water.
- Met two major planning milestones for CIS (copper indium diselenide): supporting debut of first commercial products; documenting their performance at 10% efficiency.
- Awarded 34 new cost-shared, three-year subcontracts under the Thin Film PV Partnership Program.
- Maintained more than 60 secure Web sites to transfer measurements and characterization data of materials and devices to industry and university partners.
- Completed three years of educational projects for students in cooperation with historically black colleges and universities and solicited project proposals for another three years.
- Awarded 17 subcontracts to universities to upgrade their research equipment and improve their PV R&D capabilities.

TECHNOLOGY DEVELOPMENT . . . . PAGE 9

- Reduced module-manufacturing costs by more than 32% and doubled manufacturing capacity in the last three years of the PVMaT project.
- Supported introduction of new products: ac PV modules (featured in "The Best of What's New for 1998" in *Popular Science*); packaged PV systems; and improved inverters.
- Extended support of PV system and component development and PV module manufacturing technology by issuing 14 new, cost-shared, two- or three-year contracts to industrial partners.
- Introduced highly accelerated lifetime testing (HALT℠) protocols to inverter manufacturers to help detect and correct design weaknesses.
- Augmented module testing facilities with test bed for small systems, high-voltage test bed, expanded outdoor test bed for energy ratings, and outdoor accelerated weathering tracking system.
- Improved inverter production with contracts supporting improvements in quality control.
- Identified conditions surrounding, and developed strategies to deal with, islanding of PV systems connected to the utility grid.
- Extended module performance characterization procedure to characterization of arrays and of systems, and initiated development of more accurate models of energy production.

SYSTEMS ENGINEERING AND APPLICATIONS . . . . PAGE 14

- Contributed to major new standards and certification applying to PV systems: IEEE-recommended practice for utility interface; interim test methods for determining the performance of small systems; PowerMark Corporation accreditation of certification laboratories; and revisions to the National Electrical Code.
- Assessed performance of PV installations owned by federal agencies, operating as hybrid systems, and of utility-owned, grid-connected systems on rooftops.
- Provided technical assistance to major demonstration projects—Million Solar Roofs, TEAM-UP, and the PV Pioneer Program—by supporting training programs for installers, workshops for communities, and public information exhibits.
- Displayed popular PV exhibits at EPCOT Center® in Orlando, FL, and Smithsonian Institution's Cooper-Hewitt National Design Museum in New York City.
- Made spectral solar data and selected solar radiation and cloud cover maps accessible from the NCPV Web site.
- Continued PV:BONUS by selecting seven projects for innovative building-integrated-PV product and business development.
- Provided technical assistance to many countries; met major milestones in Brazil, China, India, Mexico, and South Africa.

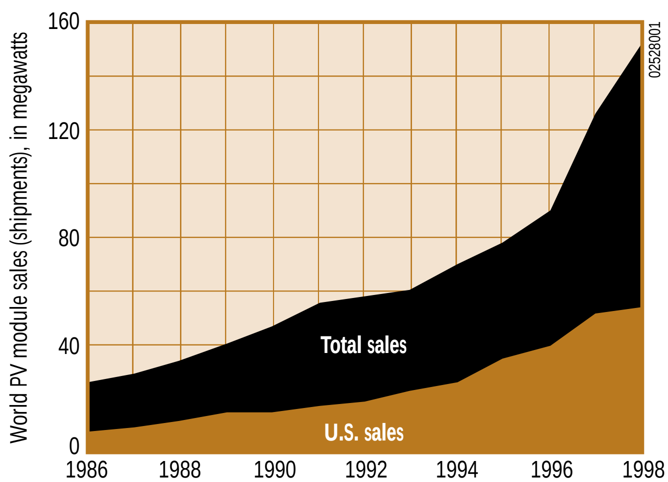
MESSAGE FROM THE DIRECTOR

The manufacture, sale, and use of photovoltaic (PV) devices to generate electricity directly from sunlight has become a billion-dollar industry worldwide. Here in the United States, industrial production capacity for PV modules—the heart of such generating systems—doubled between 1993 and 1997.

The PV community did not achieve this billion-dollar industry by accident. Today's technology is the result of a concerted program of basic and applied research, technology development, systems engineering, and applications validation. The photovoltaic effect, used only to power satellites until rising energy costs sparked interest in applying this technology on Earth, requires special materials and processes, as well as supporting devices, to deliver electricity for an attractive price. In the United States, we accelerated the research process in 1973 with a government-funded program of research to increase the efficiency and reliability of PV devices. Thanks to this research, the cost of electricity generated by PV systems has decreased dramatically, reliability has improved, and the market has soared.

"Clean, competitive, reliable power technologies for the 21st century."
Goal of DOE's Office of Power Technologies.

PV SALES 1986 TO 1998



Source: Paul Maycock, *PV News*, January 1999 and past issues.

But our goal is to make electricity from PV competitive in more energy markets. To do this, we must cut the cost of PV systems in half again by pushing the science and technology. While continuing research to improve technology, we must work with industry to move this technology from the laboratory to the marketplace. Our growing U.S. PV industry must stay on its competitive edge to supply the expanding world market.

We are well positioned to make our vision a reality, employing the planning and implementation resources of the National Center for Photovoltaics (NCPV). Participants in national laboratories, industry, and universities develop the overall vision of our R&D PV Program, with guidance from the NCPV Advisory Board, whose role is to look 10 to 20 years ahead. The NCPV develops a comprehensive annual operating plan designed to support ambitious multiyear plans, such as the *National Photovoltaics Program Plan for 1996–2000*. These long-range plans, developed in cooperation with the U.S. PV industry and universities, respond to the broad policies for energy R&D determined by the executive and legislative branches of the federal government. To achieve the research goals in the Annual Operating Plan, we allocated nearly 60% of the PV Program's budget in fiscal year (FY) 1998 to contracts with industry and universities.

We assign ourselves concrete goals addressed to each stage of a vertically integrated effort to bring technologies on-line—from concept to laboratory to commercial readiness. In this overview, we report on the goals we have met in FY 1998 and on our progress toward long-term goals for research, technology development, and applications. One such goal is ensuring that PV represents at least half of the installations in the President's Million Solar Roofs Initiative. With significant installations, and commitments for many more, we are well on our way to achieving this goal—which is encouraging additional growth in our billion-dollar PV industry.

James E. Rannels

James E. Rannels, Acting Director
Office of Photovoltaic and Wind Technologies
U.S. Department of Energy
Washington, D.C.

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

Research and Development

Fostering technological innovation and scientific understanding

Improving the cost and performance of PV products begins in the laboratories and workrooms of our scientists. As their fundamental understanding of PV materials increases, they fine-tune their processing techniques to steadily improve the quality of experimental PV materials and devices. Then they test the new materials and devices to verify performance.

One important benchmark for measuring performance in PV materials is efficiency—the percentage of sunlight falling on a PV device that is converted to electricity. Because the energy resource is free and renewable, PV-system efficiency is not comparable to that of other energy technologies; but efficiency is used to compare new PV materials and devices against previous designs. Over the years, efficiencies of PV devices have increased from 1% or 2% to as high as 32% for the most advanced materials. Eventually, we expect to have materials and devices that are more than 40% efficient. (Theoretical efficiency is more than 50%.)

We expect the highest efficiencies from materials and devices made in the laboratory, where we have the very latest equipment and highly trained personnel who control every step of every process. Once a record laboratory efficiency is achieved, the challenge is to transfer this accomplishment to industrial production lines. To reach our goals, we must improve our fundamental understanding of materials, processes, and devices; develop new and better low-cost processes and technologies; continue to transfer and scale up laboratory results; reduce module and balance-of-systems costs; improve the reliability and durability of components and systems; validate new systems, applications, and technologies; and help overcome market and institutional barriers.

Among this year's achievements were efficiency records, gains in processing techniques, and new commercial production facilities.

Measurements and Characterization

For the PV Program to have the greatest effect on industrial research and production, the NCPV's Measurements and Characterization groups must provide timely measurements and reports on samples from industry. Companies ship samples by overnight mail to the National Renewable Energy Laboratory (NREL) or Sandia National Laboratories. Research staff immediately begins analysis of the samples. The data are then posted to the company's individual and secure Web site, where they can be downloaded and used. (More than 60 of these sites are now in use within the NCPV.) Data cleared for release by the company are posted to a nonsecure Web site to be shared with other research partners. The system has evolved to provide real-time observations of computer terminals on several major analysis systems, allowing research collaborators to observe the acquisition of data essentially as they are being obtained.

"By combining the talents of scientists performing fundamental research with engineers developing prototype modules, the PV Program can help ensure that a continuous stream of advanced thin-film technology is incorporated into future manufacturing facilities."
National PV Program Plan for 1996–2000

Thin-Film Materials

PV devices made of thin-film materials hold great promise for reaching our long-term goal of cost-competitive electricity from PV for the domestic utility market. This approach holds promise because the components of thin films (a low-cost substrate, thin active semiconductor and metal films, and encapsulation) cost very little in terms of materials, capital investment, and labor. With production volume of more than 25 megawatts (MW) per year and appropriate attention to optimizing processes, making thinner layers, and using materials wisely, the cost of thin-film manufacturing could fall to about $50 per square meter.

Responding to sustained research effort, the efficiency of thin-film devices is steadily rising. In 1998, the best cells in amorphous silicon (a-Si) are more than 12.1% efficient; the best cadmium telluride (CdTe) cells are 15.8% efficient; and the best copper indium gallium diselenide (CIGS) cells are 17.7% efficient. These cells represent the leading edge of technical achievement, and therefore have efficiencies substantially higher than modules.

Module efficiencies are also rising: 7% for a-Si; 8%–9% for CdTe, and, very recently, 11%–12% for CIS-based modules. In the future, with continued research, we expect to see commercial thin-film modules from these three technologies with efficiencies in the 10%–15% range. The 15% efficiency, combined with $50/m^2 manufacturing, translates to module costs between $0.5–$0.33 per peak watt, well within our long-term, cost-competitiveness goals.

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

New subcontracts in the Thin Film PV Partnership Program

Continuing the successful partnership approach used in past years to develop and test new thin-film products, the PV Program awarded 34 new cost-shared subcontracts in the Thin Film PV Partnership Program, for a total value of $60 million over a three-year period. The Department of Energy (DOE) provides $35 million, and the rest of the funding comes from the corporate partners. In addition, the Electric Power Research Institute has promised to contribute $400,000 in cost-sharing of awards for a special topic on multijunction thin-film solar cells.

Research on amorphous silicon

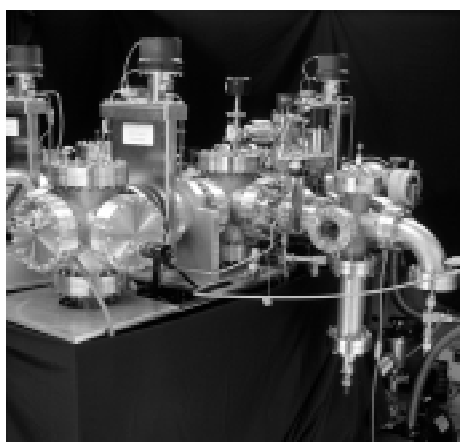
Today, more than 10% of worldwide PV production uses a-Si technology. The NCPV explores ways to raise conversion efficiencies and lower the cost of fabrication using this material.

Cost-shared research activities supported by DOE through the NCPV and the Thin Film PV Partnership Program resulted in United Solar's award-winning roofing product. NREL is currently characterizing the commercial shingles at its Outdoor Test Facility.

In addition to the roofing product, new materials were developed along with innovative device designs to yield efficiency records for a-Si. These efficiencies show significant progress toward our goals for the year 2000 set out in the *National PV Program Plan for 1996–2000*. The 12%-efficient laboratory cell approaches our goal of 13%. The 10.2%-efficient submodule exceeds our goal of 10% efficiency for a prototype module. And the 7.6%-efficient commercial module is nearing our goal for 2000 of 9% efficiency. The 7.6%-efficient module is rated at 71 W, the highest power output of any thin-film module to date.

Processing techniques are another important aspect of solar cell development. In 1998, NREL's Amorphous Silicon National Research Team managed to achieve high efficiency using a faster process. What normally takes industry 35 minutes requires only 2 minutes using the hot-wire technique. First, NREL deposited a cell's active a-Si layer using the patented high-speed, hot-wire technique; then, United Solar finished the cell by depositing the microcrystalline p-layer and the transparent conductive top-contact. The initial efficiency of 9.8% is the highest to date for such fast deposition rates.

Warren Gretz, NREL/PIX06283



Jim Yost Photography/PIX01813

United Solar Systems Corporation (Troy, MI), NREL, and the Amorphous Silicon National Team received an award from R&D Magazine *for one of 1998's 100 most significant technological innovations. The magazine's panel tapped the UNI-SOLAR Triple-Junction Amorphous Silicon Solar Electric Module for the award. United Solar applied laboratory techniques for high cell efficiencies to its commercial module, which uses three active solar cell layers. The module is fabricated on a light, flexible substrate, making it suitable for roofing shingles. For the future, NREL and United Solar are working on advanced processing technologies, such as hot-wire deposition (pictured right).*

Research to understand the science of materials behavior can have far-reaching effects on the performance of PV products. In 1998, a new microscopic model developed by NREL researcher Dr. H. Branz was shown to account quantitatively for the light-induced (Staebler-Wronski) degradation of a-Si solar cells. For the first time, nearly all experimental results concerning the Staebler-Wronski effect can be described by a single model. Although validation of the model will take time, having such a model is a critical step toward reducing or eliminating the effects of light degradation on PV performance.

Using this model and refining production techniques in cooperation with industrial and university partners, the NCPV is moving toward the goal of 13%-efficient laboratory devices made from a-Si.

> *"Our productive and rewarding relationship with NREL and DOE has enabled us to make very important scientific advances."*
> Dr. Subhendu Guha, Executive Vice President, United Solar Systems Corporation

Meanwhile, industrial capacity is expanding to meet worldwide demand for a-Si products. United Solar brought a 5-MW plant on line in 1997 to produce triple-junction products. That factory is now making 3- to 64-W, 7.5%-efficient, Underwriters Laboratories (UL)-approved modules that carry a 10-year warranty and meet international standards (IEEE 1262 and IEC 1646). The company plans to build a 25-MW facility to produce PV roofing product, as well as PV products for space applications.

Solarex operates a 10-MW/year plant in Toano, VA, that produces a-Si alloy, tandem-junction modules that are 66 cm x 122 cm or 0.81 m^2 (26 in. x 48 in. or 8.67 ft^2) with glass-to-glass encapsulation. These modules produce 43 to 50 W. Both Solarex and United Solar are making great strides in raising their yields, throughputs, and performance on commercial modules.

Research on cadmium telluride

PV devices using CdTe can be manufactured using potentially low-cost techniques such as spraying, electrodeposition, and high-rate evaporation. Achieving high laboratory efficiencies using these low-cost techniques is an important objective of the PV Program. In 1998, using a process that is relatively simple and therefore transferrable to industry, a research team at NREL fabricated a device that is 15.4% efficient. The world-record 15.8% efficiency for CdTe was achieved at the University of South Florida, using a more complex process.

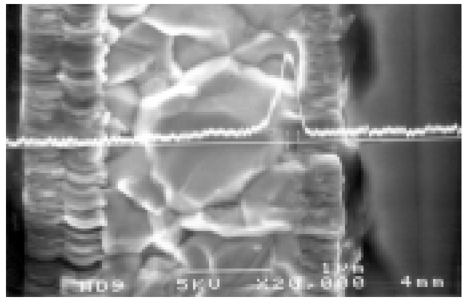
Another successful approach to improving processing techniques is to combine work in the laboratory with production-line processing in industry. Industrial partner Solar Cells, Inc. (SCI) of Toledo, OH, achieved its best efficiency to date, 14.1%, by having NREL deposit the SiO_2 top contact and the MgF_2 antireflective coating, before SCI deposited the CdTe film using its high-rate deposition process being readied for commercial production.

> *"We like cadmium telluride because it fits so well with glass production."*
> Rick Powell, Director of Advanced Development, Solar Cells, Inc.

Meanwhile, commercial production of CdTe products progresses—a goal of the *National PV Program Plan for 1996–2000*. BP Solar R&D and Manufacturing, a participant in the Thin Film PV Partnership, began fabrication of its "power modules" made of thin-film CdTe material in a new plant in Fairfield, CA. The 35.5-cm x 112-cm (14-in. x 44-in.) modules put out 25 to 30 W and appear stable under test.

Research on copper indium diselenide (CIS)

As set forth in the *National PV Program Plan for 1996–2000*, two major goals for CIS research are to transfer our years of research on this technology to industry for pilot-scale manufacturing and to achieve commercial modules with 10% efficiency. Both goals were met in 1998.



Rick Matson, NREL/PIX06674

This image, generated at an NCPV laboratory, of a sample of CIS material shows a well-defined buried junction in the CIS about 2000–3000 Å from the transparent conducting oxide interface. This finding has valuable implications to industry.

The first commercial product using CIS alloys went on the market after years of cooperative research and development aimed at understanding the material and achieving uniform production. Siemens Solar Industries (SSI) of Camarillo, CA, sells 5- and 10-W PV modules made of CIS alloys that are 10% efficient—higher than thin-film products made from a-Si, CdTe, or thin-layer silicon.

The company developed the two new products using copper indium gallium sulfur selenide (CIGSS) under contract to the Thin Film PV Partnership Program. SSI also fabricated an 11.8%-efficient, 3651-cm^2 CIGSS monolithic module, which achieves a key *Five-Year Plan* milestone for the year 2000.

To help companies that are developing CIS products, the CIS National R&D Team is working to provide industry with low-cost processes for forming the solar cell absorber layers necessary for higher-efficiency devices. The electrodeposition and chemical-bath deposition processes developed at NREL have resulted in CIGGS cells with efficiencies up to 14.1%. These processes do not require vacuum chambers and use expensive semiconductor material very efficiently.

Environment, safety, and health issues

The NCPV provides forums for issues related to photovoltaics and the environment. In 1998, representatives from government, industry, and university groups interested in PV met to discuss recycling of PV modules, health and safety issues associated with the Million Solar Roofs Initiative, manufacturing methods that reduce the use of toxic materials, and the role of PV energy systems in reducing greenhouse gases.

Crystalline Silicon Materials

Because most PV systems sold today (nearly 90%) are made of crystalline silicon (c-Si), improvements to this technology have the potential for quick advancement to the marketplace. The PV Program's goal is to achieve higher-efficiency devices made with less-expensive, industrial-grade silicon. In addition, researchers at NREL and universities are exploring new methods for growing c-Si materials that could improve throughput, energy consumption, materials usage, and conversion efficiency compared to existing approaches.

The Best Large-Area, Thin-Film Modules as of FY 1998

Company	Material	Area (cm^2)	Efficiency (%)	Power (W)
United Solar	a-Si Triple-Junction	9276	7.6	70.8
Solar Cells, Inc.	CdTe	6728	9.1	61.3
Solarex	a-Si Dual-Junction	7417	7.6	56.0
Siemens Solar	CIS	3651	11.8	43.0
BP Solar	CdTe	4540	8.4	38.2
United Solar	a-Si Triple-Junction	4519	7.9	35.7
Golden Photon	CdTe	3366	9.2	31.0
Energy Conversion Devices	a-Si/a-Si/a-SiGe	3906	7.8	30.6

Warren Gretz, NREL/PIX00460

South Coast AQMD/PIX07117

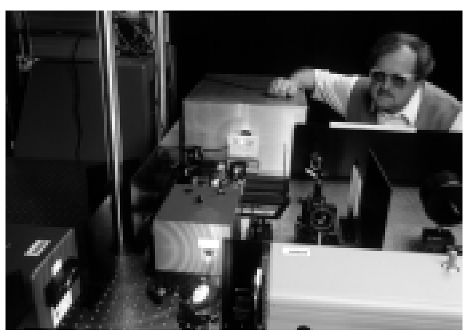
Researchers at the NCPV use the spectroscopic scanning tunneling microscope to identify elements at the grain boundaries of silicon PV material. Such research contributes to increased efficiency and lower cost for commercial applications of silicon PV systems, such as this electric-vehicle charging station at the South Coast Air Quality Management District in California.

Research on materials

The NCPV complements the work in industry by examining next-generation technologies for silicon crystal growth. For example, work is under way at NREL to reduce the cost of a process now used in the computer chip business to purify metallurgical-grade silicon to get a higher-grade feedstock for polycrystalline silicon. This process precipitates metallic impurities at defect cluster sites by increasing heat or by gettering. Similarly, projects at Crystal Systems and Sandia are investigating solar-grade silicon production.

The PV Program works with industry to improve silicon materials. In commercial silicon solar cells, material quality and cell performance are still limited by the effects of impurities either present in the starting material or developed during crystal growth and cell processing. Work this year at the NCPV explains the mechanisms by which certain defects that result from purification activities control the performance of high-efficiency, large-area solar cells. Such understanding of the mechanisms of reduced performance is the first step toward eliminating or mitigating their effects.

Thin-layer c-Si solar cells could be the next-generation photovoltaic technology because they have high efficiencies, use material sparingly, are environmentally friendly, and have the potential to be low cost. To support their eventual development, the PV Program works to produce thinner material, better substrates, more effective light-trapping, and improved interconnection schemes. All of these efforts are aimed at improving cell efficiency. The program planning goal for 1999 was 15.6%. This was exceeded in 1998 when AstroPower achieved a 16.6% efficiency for a 1-cm^2 cell. Module efficiency also climbed from 6.2% to 9.25% for AstroPower's monolithically integrated Silicon-Film™ module.



Warren Gretz, NREL/PIX04527

The quality of a semiconductor material is crucial to the performance of the final device. AstroPower is testing a technique developed by NREL to evaluate Silicon-Film™ material grown in sheets.

> *"This technique could provide us with a cost and time advantage in providing feedback to our sheet-growth facility."*
>
> Dr. James Rand, Director of Advanced Engineering, AstroPower, Inc., of Newark, DE

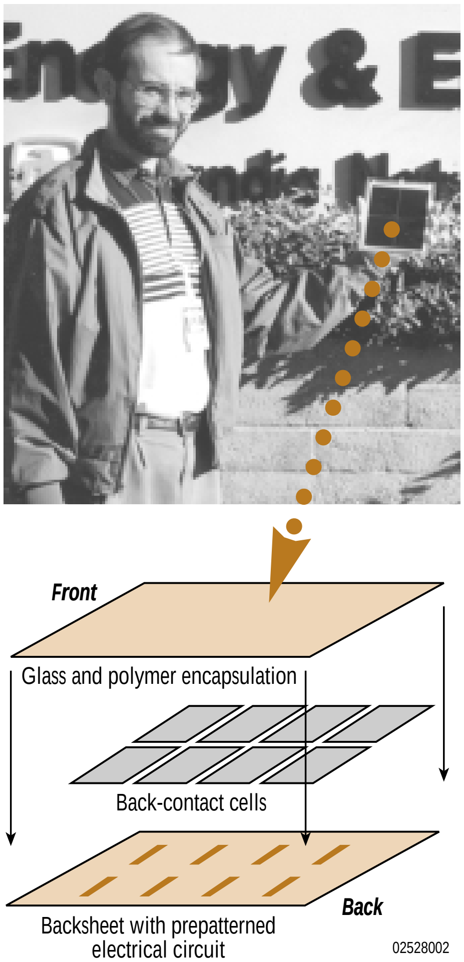
The challenge for improving efficiency is to produce an active silicon layer of sufficient electronic quality about 10 microns thick at a rate greater than 1 micron/min on a low-cost substrate such as glass. To achieve the necessary electronic quality, the grain size of the silicon crystals must be similar. Until now, methods have resulted in only partial solutions. A new gas-phase growth technique initiated at NREL produces continuous, thin silicon layers at a rate of 1–3 microns/min on high-temperature glass. The silicon layers have similar grain sizes with few impurities and favorable electronic characteristics. Further characterization work is under way to analyze the applicability of this material for PV devices.

Research on processes and devices

Improved processing can increase the efficiency of commercial silicon solar cells. In 1998, the PV Program demonstrated improved efficiency using a new process that achieves high-efficiency cells similar to cells achieved in the laboratory, while using high-throughput, lower-cost plasma processing. Experiments at Sandia have demonstrated nearly a 1% (absolute) gain in efficiency in cells made with the process called the self-aligned, selective-emitter process.

Under a Sandia subcontract, the PV Center of Excellence at the Georgia Institute of Technology used potentially low-cost rapid thermal processing (RTP) to fabricate high-efficiency silicon solar cells. RTP solar cell efficiencies of 17% and efficiencies greater than 19% were achieved on monocrystalline silicon with screen-printed and photolithography contacts, respectively. Rapidly formed screen-printed cells processed in an industry-compatible belt furnace resulted in 17%-efficient cells on monocrystalline silicon and 14.9%-efficient cells on multicrystalline string-ribbon material. This research has the potential to transform the silicon PV industry from the production of 300-micron-thick cells of 12%–15% efficiency to the production of 100–200-micron-thick cells that are more than 17% efficient. This would reduce the demand for polysilicon feedstock and produce electricity at a lower cost.

Sandia/PIX07112



To try to simplify assembly, and potentially reduce costs by up to 25%, engineers at Sandia have developed a prototype module from cells with both contacts on the back surface. This solar cell design, called emitter wrap-through, allows module assembly using a low-temperature solder. Connecting the wires and sealing the cells in encapsulant are performed simultaneously to reduce assembly costs. Industrial partners Evergreen Solar of Waltham, MA, and ASE Americas of Billerica, MA, have worked with the PV Program on this project.

Emitter wrap-through (EWT), back-contact solar cells developed at Sandia use laser-drilled holes in a silicon wafer to channel the electrical charges generated by the cell to wires in the back. This cell structure avoids the shading from the top wire-grid structure that collects charges in conventional silicon solar cells. In 1998, a 17.2%-efficient EWT cell was fabricated and characterized at Sandia. Work continues to achieve this high-efficiency cell structure in the industrial manufacturing environment and to develop simplified module assembly using back-contact silicon solar cells.

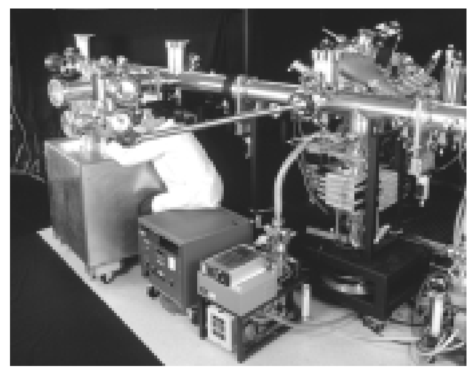
High-Efficiency Concepts

To achieve the PV Program's goal of ever-improving conversion efficiencies for PV materials and devices, research into high-efficiency cells and system components that increase efficiency is ongoing. For example, concentrating PV systems that focus sunlight from a large area onto a smaller area of PV material are being developed. Concentrating systems have two advantages. First, they conserve expensive PV material because they collect and intensify sunlight from the larger lens area onto the smaller area of the PV cell. Second, PV cells operate at higher efficiencies under concentrated sunlight, increasing electrical output per unit area of PV material.

When combined with the highest efficiency solar cells, concentrating PV systems produce the most energy for their size and weight. That is why NASA's Deep Space 1 Probe features a solar array using the PV Program's high-efficiency gallium arsenide cells and concentrating lenses engineered by ENTECH under PV Program development contracts.

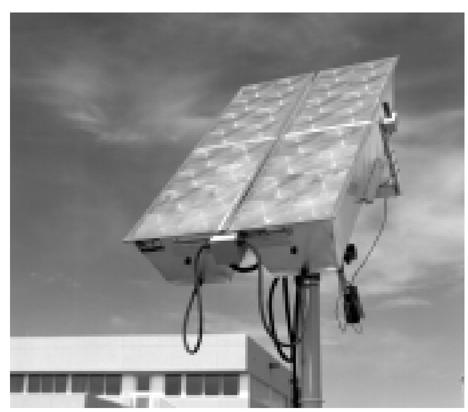
With continued development to reduce manufacturing costs, these high-efficiency concentrating systems will eventually make their way to Earth. To accelerate this process, the NCPV coordinates the PV Concentrator Alliance, a group of large and small companies interested in marketing this technology. In 1998, the PV Concentrator Alliance supported installation of a 300-W Midway concentrating system that tracks the sun during the day at the NCPV's Outdoor Test Facility in Golden, CO. Test results will assist system design and help to develop standards for PV concentrator systems.

The important PV Program goal of transferring new solar cell technology to the production line of industry partners takes time and effort. In 1998, Dr. J. Olson, an NCPV researcher, received the IEEE Electrotechnology Transfer Award for his success in moving the high-efficiency (30%), $GaInP_2/GaAs$ tandem solar cell technology (patented in 1987) to industry. Olson spent many weeks in California traveling to Spectrolab and TECSTAR to help them adapt his techniques to their production lines. This year, TECSTAR licensed the technology, earning the right to sell the cells for commercial space applications. The company plans to use this technology for all of its high-efficiency solar cells for space applications in 1999.



Jim Yost Photography/PIX01464

This NREL-customized cluster system combines several processes to create the PV materials for high-efficiency cells and devices.



Warren Gretz, NREL/PIX06156

Research to combine concentrator technology with very-high-efficiency solar cells is ongoing in the PV Program and in industry. Using lenses to concentrate sunlight onto highly efficient solar cells may provide cost-effective options for the U.S. utility industry in locations with excellent solar radiation. In 1998, several large companies acquired this technology.

While industry recognizes the value of the two-junction technology, the PV Program is looking to the future of three- and four-junction cells. A PV Program goal to identify a manufacturable device structure with the potential to achieve 35% to 40% efficiencies was met this year. In 1998, NREL reported at the 2nd World Conference on Photovoltaic Energy Conversion that three-junction devices using a 1-eV bottom cell under the GaInP/GaAs tandem cell can achieve such high target efficiencies. The candidate material for the bottom cell includes not only high-efficiency compounds such as GaInAsN, but also, CIS. There are materials problems yet to be worked out, and collaborations with universities are a needed element of this effort. With anticipated improvements, the third junction should be ready to incorporate into the multijunction stack for testing next year.

Exploratory and Fundamental Research

University partners are key participants in the NCPV. In 1998, a brief survey of university laboratories revealed that much of their equipment was 10 to 15 years old and that research contracts often did not provide funding for needed equipment upgrades. To enhance the research capabilities of our university research partners, the PV Program requested proposals for new equipment purchases and funded equipment upgrades at 17 universities.

The NCPV strives to keep a good supply of new researchers coming into the field of solar cell research, through university research contracts that, through special targeted projects, support postdoctoral researchers and graduate students. A project to advance knowledge of photovoltaics for undergraduate students in Historically Black Colleges and Universities (HBCUs) through active research began in 1995. The PV Program funded seven colleges to develop research projects in photovoltaics involving undergraduate students. A wide variety of activities has encouraged students to explore careers in PV.

Warren Gretz, NREL/PIX06220

A new device using NREL-developed $GaInP_2$ technology splits water into hydrogen and oxygen directly upon illumination by sunlight. Although the concept has been tried before, the 12% efficiency of this device (compared with less than 7% previously) means double the production of hydrogen using sunlight as the only input.

Projects have ranged from atomic-level microscopy of PV materials and solar architecture to field projects installing PV systems in developing countries. For example, the third successful summer program for high school students at Texas Southern University in Houston, TX, took place in the summer of 1998. In addition, undergraduates in NREL's HBCU PV Research Associates program assisted 13 high school honors students from the summer program on their trip to Port Elizabeth, South Africa. The students helped install PV systems for a rural school electrification program.

After a favorable assessment of these projects with Historically Black Colleges and Universities, the program will be continued for another three years.

Fundamental and exploratory research projects funded by DOE in the 1980s led to today's key thin-film technologies now under development by U.S. companies. Continuing this search for innovative PV technologies, the NCPV solicited proposals for research projects from 750 science departments in our nation's universities. After receiving 71 proposals, an extensive peer review involving more than two dozen scientists selected more than 18 proposals for funding in 1999.

Additional Achievements in Cooperative Research and Development

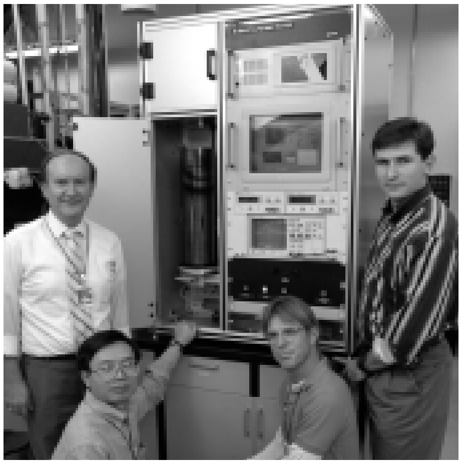
Organization achieving result	What was accomplished	Why it was important
NREL	Fabricated first cell entirely by hot-wire chemical vapor deposition with an a-Si i-layer and microcrystalline-Si-doped layers.	Demonstrates ability to avoid glow-discharge method, potentially increasing manufacturing throughput by more than tenfold; permits combinations of amorphous and microcrystalline layers, offering future efficiency gains.
NREL	Patented substrate formed by reacting metallurgical-grade silicon with boric oxide in air for thin-layer Si solar cells lattice-matched with Si within 0.05%.	Provided a promising manufacturable, low-cost material with good performance characteristics.
Sandia	Demonstrated 33% reduction in reflectance using plasma texturization of self-aligned selective-emitter cell.	New process has potential to improve c-Si cell performance by up to 1.5% (absolute).
Siemens Solar Industries	Fabricated 11.8%-efficient, 3651-cm^2 CIGSS monolithic module.	Demonstrates module efficiency competitive with conventional Si-based PV. Achieves key *Five-Year Plan* milestone for year 2000.
Solarex	Reduced silane gas flow during production by 50% without reducing performance of tandem-junction a-Si/a-SiGe:H modules.	Potential to reduce germane gas flow as well will achieve significant savings in production costs.
United Solar Systems Corporation	Fabricated a dual-junction a-SiGe cell with 14.4% initial, active-area efficiency and a triple-junction cell with 15.2% initial, active-area efficiency.	Shows promise of high efficiency for a-Si devices.
NREL/AstroPower, Inc.	Transferred NREL's newly developed Radio Frequency Photoconductivity Decay Lifetime Spectrometry technique to AstroPower's Silicon-Film™ production line.	Real-time measurements of minority-carrier lifetime at the point of manufacture allow the quality of the semiconductor material to be determined prior to device assembly.
NREL/GT Equipment Technologies, Inc.	Grew a 20-mm-diameter Si tube 210 mm long.	Tubular substrate could be used in fast chemical vapor deposition growth of polysilicon feedstock.
NREL/Cornell University	Determined that amorphous silicon produced by the hot-wire technique has vibrational properties more like a crystal.	These properties may help to clarify why the hot-wire materials exhibit better stability.
Pennsylvania State University	Achieved cells with open-circuit voltages >0.90 V by growing thin amorphous layers with high hydrogen dilution. Such layers act as buffers in n-i-buffer-p cell structures.	Materials at the border between amorphous and microcrystalline films may result in more stable cells.
Georgia Institute of Technology	Demonstrated exceptional surface passivation using low-cost, low-temperature processes.	Surface passivation is increasingly important for thinner silicon solar cells.
Institute of Energy Conversion	Significantly upgraded equipment for a-Si (hot-wire) and CIS deposition.	New CIS system ordered will allow process development on substrates up to 1 ft^2 in area.

TECHNOLOGY DEVELOPMENT

Improving processes and developing products

Key to the PV Program's support of industry initiatives is the Photovoltaic Manufacturing Technology (PVMaT) project. The project helps industry partners decrease costs by exploring manufacturing technology to reduce production costs, by increasing the performance and reliability of modules, and by boosting the reliability of balance-of-systems (BOS) components while reducing their cost. The project goal was to see production capacities increase and manufacturing costs cut in half between 1995 and 1997. According to a survey of PVMaT participants, production capacity has more than doubled, and module manufacturing costs have decreased more than 32% in the last three years.

Meanwhile, the PV Program's outdoor characterization and accelerated testing are demonstrating improved module performance and reliability. Many products now carry UL listing, as well as warranties of 10 years and more for the consumer. In 1998, new BOS products were tested and earned UL listing.


Warren Gretz, NREL/PIX05820

By coupling this tester built at NREL with a diode laser and a low-noise electronics system, Siemens Solar can sample the quality of large silicon ingots before undertaking the costly process of cutting them into wafers and fabricating solar cells.

PVMAT PAYS DIVIDENDS

DOE initiated the PVMaT project to assist the U.S. PV industry in extending its world leadership role in PV manufacturing and the commercial development of PV modules and systems. PVMaT's concept, general management, and procurement approaches were developed by a team comprising representatives from industry, government, and the national laboratories. Multiyear projects are being carried out through cost-shared awards resulting from competitive solicitations. These awards support process-specific R&D on industry-selected manufacturing technology developments. They also support teamed R&D on common problems that industry identifies. And finally, the awards aim to improve system performance and integration, and manufacturing of balance-of-systems components.

U.S. PV module manufacturing

In 1998 under PVMaT, manufacturing progress took place in the more mature crystalline silicon materials, as well as in the newer thin-film technologies. Companies devised ways to increase the throughput, increase production capacity, and reduce costs. They also successfully adapted laboratory techniques to the factory production environment. They controlled parameters such as temperature and pressure for promising materials that are a challenge to manufacture in quantity. Some highlights from the work accomplished in 1998 follow.

ASE Americas, Inc., improved its module design by developing a new reflector material that acts as a low-level flat-plate concentrator for sunlight. The effect of the concentration is to increase module power output by 20% to 30%. Another way to reduce module manufacturing costs is to use environmentally safe processes that require less waste disposal and more efficient use of materials. ASE Americas used a new process developed under PVMaT in 1998 to reduce fluorine-ion effluent in the waste stream by 50%, hydrofluoric acid consumption by 20%, and deionized water consumption by 20%, while increasing production yield by 5%. Since the company began participating in PVMaT, it has reduced its module manufacturing costs by 75% and increased production capacity tenfold.

AstroPower, Inc., incorporated advances in sheet processing of Silicon-Film™ into its 9.5-MW production plant under construction in 1998. Two 24-hour production runs demonstrated a 70% increase in growth speed of sheets—a fourfold increase in sheet-production capacity overall. These improvements in processing have translated to a 13% reduction in module manufacturing cost since 1994. In 1998, AstroPower planned a new manufacturing facility, the culmination of several successful PVMaT projects by the company.

Iowa Thin Film Technologies increased throughput for an important production step of its a-Si modules by an impressive 240% since the beginning of its PVMaT contract. Its work addressed the top conductive contact for the a-Si that is deposited on a polymer substrate. The increased throughput for this production step translates to a 10% reduction in overall module manufacturing cost for its commercial product. In 1998, the company also successfully deposited a-Si in a layer one-half the previous thickness. Being able to deposit this thinner layer on its polyimide substrate has significantly reduced the cost of the company's thin-film product.

Photovoltaics International (formerly Solar Engineering Applications Corporation) is establishing a low-cost manufacturing strategy for linear concentrator modules. The company is perfecting the continuous-processing capability of its lens extrusion technology. A prototype of the roll-formed frame process for fabrication of the receiver assembly is also now operational.

Siemens Solar Industries has been working to produce thinner crystalline silicon cells. Since 1992, the company has reduced module manufacturing costs by 16% and doubled its module production capacity.

Solar Cells, Inc., coated a 60-cm x 120-cm (23.6-in x 47.2-in) CdTe module in 30 seconds that tests at 8.1% efficient. This coating production speed could translate into a 50% increase in capacity for the company's standard 10-MW coating machine. Meanwhile, the modules produced from the previous deposition system have successfully completed qualification tests and demonstrated reliability over several years of outdoor testing. The company markets these production lines to the PV industry to manufacture CdS/CdTe modules.

Solarex has made improvements to reduce the cost and increase the performance of its products made of cast polycrystalline silicon. It has reduced waste from sawing, increased cell size, and increased production capacity within the same space, resulting in production cost reductions of 20% to 40%, depending on the product.

U.S. PV systems and components

PVMaT awards aim to improve the reliability and lower the costs of U.S. PV products integrated into complete PV generating systems. In 1998, industry participants announced significant advances in the form of new products or product improvements resulting from their research activities under PVMaT. The products and systems from these projects have their performance demonstrated at the NCPV test and characterization laboratories and at project sites around the country.

Alternating-current (ac) modules

The concept of a PV module that delivers ac electricity was pioneered under DOE's PV: BONUS project and further developed under the Product-Driven System and Components solicitation of PVMaT. Awards made in 1994 resulted in prototype and commercial products to meet the growing demand for simple, modular systems that are easy to install and maintain.

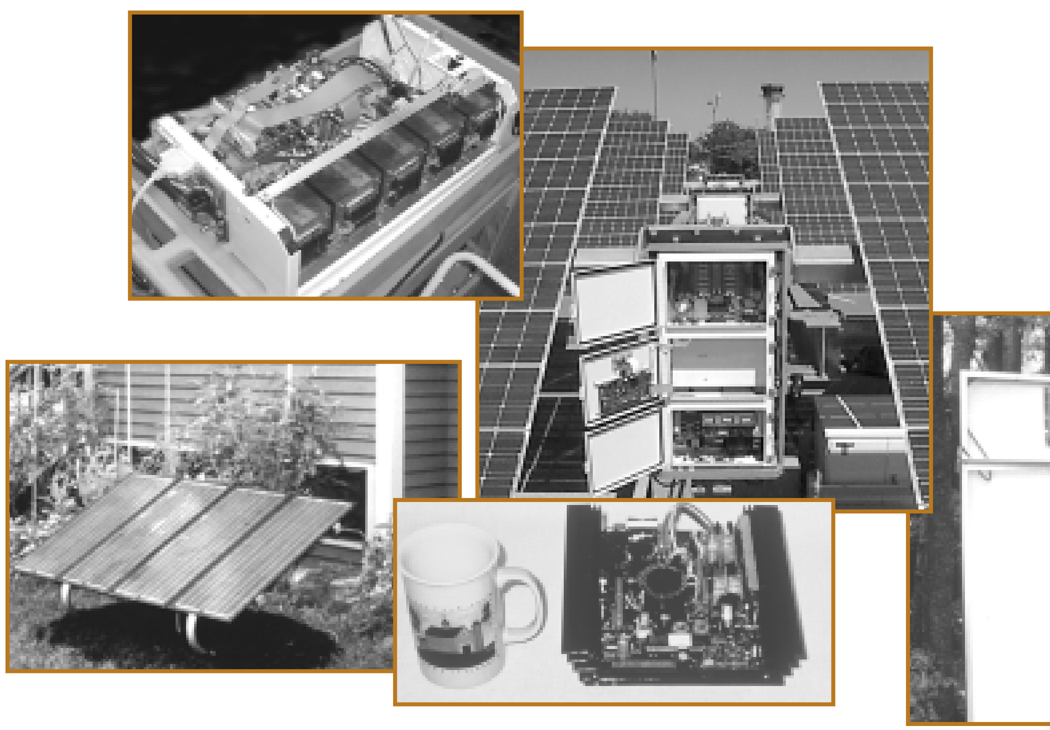
The first production run of a fully functional ac PV module is being "beta-tested" at 12 sites around the country, including NREL and Sandia. These ac PV modules incorporate the **ASE Americas** large-area PV module (using crystalline silicon material) that produces dc electricity with the compact SunSine™300 inverter developed by **Ascension Technology, Inc.,** to supply 300 W of ac power. The entire unit received UL listing, complies with the National Electrical Code, and meets Federal Communications Commission (FCC) standards for electromagnetic interference. Ascension, which markets the finished product, expects to use these ac modules in many projects for the Million Solar Roofs Initiative.

Another ac PV-module design by **Solar Design Associates** began characterization at NREL this year. To develop this product, Solar Design Associates worked with **Advanced Energy Systems, Inc.,** to enhance AESI's MI-250 MicroInverter, adding software controls and power-line carrier monitoring. Then **Solarex** worked with the team to develop a low-cost mounting for its silicon or thin-film PV modules. As part of this project, it also carries UL listing and is FCC-compliant. Solarex also worked with manufacturers to develop low-cost, quick-connect wiring for rooftop arrays. The company also developed a patented snap-together mounting system for a thin-film rooftop PV system.

Packaged systems

Combining PV modules and power conditioning into one package has proved to be a successful product strategy developed under PVMaT. For example, **Utility Power Group** designed, built, and tested a tracking PV system with a prefabricated array and a 15-kW power-conditioning unit. By establishing a prefabrication process to minimize field-installation time, the company reduced area-related, balance-of-systems costs of its single-axis-tracking PV systems by 52%, and reduced total system costs by 23%. By the close of 1998, the company had received more than 60 orders from utilities for this system.

Another approach to designing simpler and less expensive PV systems is to offer a packaged, stand-alone PV power system consisting of PV

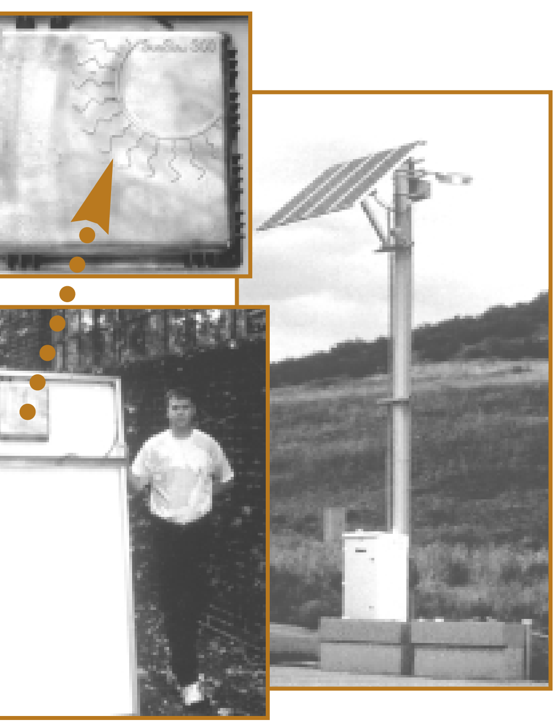


A sample of working prototypes developed with support from the PVMaT project. For more detail, see inside bac modules, solid-state power control systems, sealed batteries, and enclosures for the batteries and power control system. **Solar Electric Specialties** refined two such products that began tests in 1998. The first is a Modular Autonomous PV Power Supply (MAPPS) that is UL-listed. The MAPPS ranges in size from 50 W to 1000 W. A 200-W, 24-volt unit is being characterized at NREL. Minimizing weight and cost, the system mounts to a pole and is suitable for outdoor lighting. An additional product—a PV power supply that includes a small propane generator, inverter, and batteries in a single container suitable for shipping—is economical and versatile for off-grid applications. Called a Photogenset, the unit underwent limited testing in 1998 at Sandia.

Inverters

For larger, grid-connected or hybrid (those with more than one type of electric generation) systems, **Advanced Energy Systems, Inc.,** developed improved three-phase, 50-kW and 60-kW inverters. Its designs incorporate simpler manufacturing steps, remote monitoring of performance, and 95% peak efficiency. Under PVMaT, the company reduced the physical size of the inverter by 70% and reduced overall unit cost by $2,000. The new inverters began characterization tests in 1998 at Sandia and at the National Wind Technology Center at NREL.

For utility-interconnected PV applications, **Omnion Power Engineering Corporation** developed a 100-kW, 3-phase power conversion system with increased efficiency, lower audible noise, and reduced electromagnetic interference. **Trace Engineering** has a working prototype of a modular, 2.5-kW power inverter/charger for PV applications. A significant feature is the ability to convert ac power to dc, or vice versa, for larger systems, expandable incrementally up to 30 kW by connecting the units together. A prototype unit was characterized at Sandia. Making many units of a standard size reduces manufacturing costs, and the "building block" design allows the versatility in capacity needed for different-sized PV generating systems. Trace also offers UL-listed standard power-mounting modules to hold inverters, controllers, and batteries for PV systems.



cover.

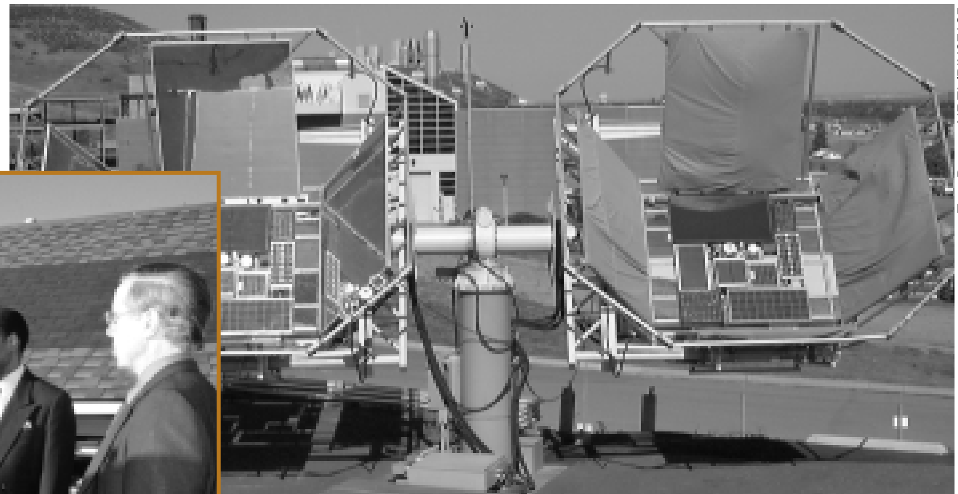
PVMaT 1998 Awards

Support for manufacturing progress continued in 1998 with awards of the following new two- and three-year contracts:

- Manufacture of the Advanced SunSine™325 AC Module
  Ascension Technology, Inc.
- The EFG High-Volume PV Manufacturing Line
  ASE Americas, Inc.
- Silicon-Film™ Solar Cells by a Flexible Manufacturing System
  AstroPower, Inc.
- Production of Solar-Grade Silicon by Refining of Liquid Metallurical-Grade Silicon
  Crystal Systems, Inc.
- Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy PV Manufacturing Technology
  Energy Conversion Devices, Inc.
- Continuous, Automated Manufacturing of String-Ribbon Si PV Modules
  Evergreen Solar, Inc.
- Throughput Improvements for Thin-Film-Based CIGS Modules
  Global Solar Energy, L.L.C.
- Manufacturing and System Improvements for 1- and 2-kW Inverters
  Omnion Power Engineering Corp.
- Advanced PowerGuard® Manufacturing
  PowerLight Corp.
- R&D on Siemens Cz-Silicon Product Manufacturing
  Siemens Solar Industries
- R&D on CdTe Product Manufacturing
  Solar Cells, Inc.
- Improvements in Polycrystalline Silicon PV Module Manufacturing
  Solarex, a business unit of Amoco/Enron Solar
- Post-Lamination Manufacturing Process Automation for Photovoltaic Modules
  Spire Corp.
- Development of a Fully Integrated PV System for Residential Applications
  Utility Power Group, Inc.

Warren Gretz, NREL/PIX03877

David Parsons, NREL/PIX06961



Tom Basso, NREL/PIX07135

Distinguished visitors, such as the President of Mozambique (pictured center), often tour the NCPV's Outdoor Test Facility in Golden, CO. The Outdoor Accelerated-weathering Tracking System (pictured right) was put into operation in 1998.

Materials

Two new materials developed by **Evergreen Solar, Inc.,** to improve PV-panel manufacturing and PV system installation were undergoing tests in 1998. One is a transparent encapsulant that can be laminated to PV panels using a heated roll, rather than a more expensive vacuum technique. The company also tested a material for the back-skin and edge sealant of a PV panel that eliminates the need for a module frame. A mounting rail adheres to the back of the module for rapid, easy panel installation in the field.

System Components Performance and Reliability

The NCPV conducts performance and reliability characterization of PV devices and system components to help improve PV system components, to provide tools and data for the design of PV systems, and to improve customer acceptance of PV systems. This applied research is conducted in close cooperation with PV component manufacturers and system engineers.

Module performance and reliability

Through applied research conducted in close cooperation with manufacturers and users of PV systems, the NCPV test sites and laboratories evaluate and improve the performance, durability, and reliability of PV modules. The NCPV facilities for outdoor testing, accelerated testing, and laboratory simulations are crucial to this work.

In 1998, the PV Program evaluated new module technologies resulting from DOE projects such as PVMaT, the Thin Film PV Partnership, the Concentrator Alliance, and PV:BONUS to help guide their commercial development. NCPV engineers also helped characterize the performance and reliability of commercially available modules and arrays used for utility projects (PVUSA, UPVG's TEAM-UP), federal agency applications, and the private sector. For example, Sandia characterized more than 100 commercial PV modules and delivered nearly a dozen test reports to manufacturers in 1998.

The PV Program continues to augment its testing and characterization capabilities. At the Outdoor Test Facility at NREL, an additional test bed that accommodates many different small systems went into operation in 1998. NCPV technicians validated system test methods and procedures for a PV lighting system. Now the test bed can be used to validate system test methods for small PV systems.

This year, the group of longer-term stress tests for PV modules was expanded by adding a high-voltage test bed. Here, test engineers can explore the effects of corrosion on modules under high-voltage operation using both anodic and cathodic polarities.

The test bed to measure outdoor performance of modules under all climatic conditions was expanded to accommodate as many as 23 PV modules. Information from these tests will be used to develop PV-module energy ratings.

Also in 1998, a new and innovative Outdoor Accelerated-weathering Tracking System was put into operation. The system magnifies the sun's intensity with mirrors so that the degradation of PV-module encapsulants, polymer compounds, and components can be studied under accelerated ultraviolet-light and temperature conditions. Fourteen PV modules from four manufacturers underwent tests in FY 1998.

Sandia researchers extended a comprehensive module characterization procedure to the characterization of arrays and systems. Current work is extending this technique to modeling of annual energy production for PV arrays.

Closely related to module-testing activities is maintenance of solar and optical measurements linked to recognized organizations such as the National Institute of Standards and Technology and the World Meteorological Organization. Careful calibration of equipment used in testing and providing information about testing PV devices are key ongoing activities within the NCPV.

Long-term exposure studies

In 1998, a symposium on module durability sponsored by Sandia and held at the Florida Solar Energy Center, included participants from the U.S. PV industry, national laboratories, and NASA. The group identified progress and continuing issues of PV-module response to long-term operation in the field.

To identify and solve specific durability issues that result from long-term operation, the NCPV coordinates the Module Durability Research Cooperative, a collaborative effort with U.S. industry. Studies are under way to determine the change in encapsulant adhesive strength with age, to develop diagnostic procedures, and to study delamination, glass fractures, and the change in transmittance of ethylene vinyl acetate and glass over time.

The Florida Solar Energy Center and the Southwest Technology Development Institute are hosting controlled, long-term exposure tests in hot/humid and hot/dry outdoor environments. The effort will allow early detection of performance degradation mechanisms and the opportunity to modify manufacturing processes.

Balance-of-Systems Components Development

In addition to PV cells and modules, all PV systems have other components that help to convert, deliver, and store electricity. Today, BOS components represent about half the cost of a PV system. As we work to reduce the cost and improve the performance of PV modules, we are also working to keep the cost of mass-produced BOS components to less than 50% of the total PV system cost. The NCPV's testing and targeted development contracts aim to increase the efficiency and reliability of these components through optimized design.

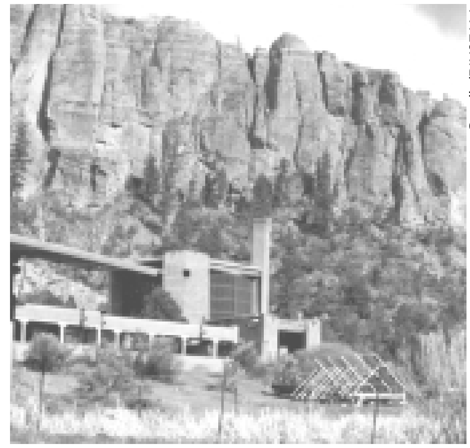
A key BOS component is the inverter, which converts the dc electricity produced by the PV array to the ac power necessary for many applications, including grid-connected applications. To improve the quality and reliability of inverters, the PV Program issued special "Quality" contracts to several suppliers. The contracts supported development of company quality-control programs that resulted in writing specifications for product compliance and inspecting each component prior to product assembly. Unacceptable components were returned to suppliers for enhanced designs or quality. For one contractor, Trace Engineering, the activities supported by the Quality contract reduced incoming component scrap from $2,000 per week to less than $100 per week, and also reduced the number of product failures.

Another issue for inverters addressed in 1998 is a condition called "islanding," which can result when several inverters are used on the same utility-distribution leg. Islanding occurs when a dispersed generation source (such as PV) and a portion of the utility system operate while isolated from the remainder of the system.

Utilities fear islanding because line workers could be exposed to electricity in a line that should be de-energized with the rest of the system. There is also great potential for damage to utility and customer equipment from uncontrolled voltage and frequency swings within the island.

Sandia/PIX07115

NCPV engineers at Sandia test PV islanding conditions to help define recommended practices.



Sandia/PIX07114

Sandia engineers test hybrid PV system at Monastery of Christ near Abiquiu, NM, to determine ways to improve battery charging.

In 1998, Sandia conducted tests of utility-interactive inverters to better understand the conditions that lead to islanding. Several strategies to eliminate this problem have been developed and are being tested. The success of these techniques will remove a significant barrier to utility use of photovoltaics.

Product characterization is also important for new designs of BOS electrical equipment. In 1998, highly accelerated lifetime testing (HALT^{SM}) provided information for important design improvements by manufacturers. Other important components of stand-alone PV systems, such as batteries, are tested under actual PV-use environmental conditions to evaluate performance over extended periods of time. Short tests, such as those performed this year for the World Bank's Sri Lanka project, provide the user with minimum battery performance data in a timely manner. Charge controllers are also important to trouble-free operation of PV systems with batteries. This year, seven different manufacturers benefited from NCPV characterization of their products.

SYSTEMS ENGINEERING AND APPLICATIONS

Building a strong industry and stimulating a healthy market

The PV Program works with industry to characterize, evaluate, and improve its systems, and works with end users, agencies, and industry to deploy and validate cost-effective PV applications for key markets.

In 1998, NCPV activities resulted in significant changes to the certification rules that will guide the PV market. Our active test programs helped improve performance, reliability, and operation by testing and evaluating materials, mechanical, electrical, and safety characteristics of cells, modules, BOS components, and systems. We conducted field measurements and accelerated testing to help extend the useful life of systems to 20 years (short-term goal) and 30 years (long-term goal). We deployed systems and measured performance to demonstrate cost-effective applications in key domestic and international markets.

SYSTEM PERFORMANCE AND ENGINEERING

NCPV activities addressed technical issues and provided engineering solutions and approaches to reduce technical and market barriers to wider use of PV systems in the United States and around the world.

Standards development and certification

With PV manufacturers and markets located around the world, international standards have become the benchmark buyers rely on to assure minimum performance and safety of PV systems. The NCPV represents the United States in the development of the international standards so important in world markets for U.S. PV products. NCPV experts play leadership roles in work carried out by the Institute of Electrical and Electronic Engineers (IEEE) Standards Board within the IEEE SCC21 Photovoltaic Standards Coordinating Committee. In 1998, standards documents were reviewed on rating PV modules, testing stand-alone systems, and determining methods to assess performance of small PV systems. Documents were also drafted to apply standards to PV systems using concentrator technology.

In 1998, the NCPV contributed to the IEEE draft document, *Recommended Practice for Utility Interface of Photovoltaic Systems*, which is already being used by the U.S. PV community for the Million Solar Roofs Initiative. Formal approval and balloting will take place in 1999. In addition, NCPV specialists have an active role in the International Electrotechnical Commission (IEC) committee responsible for international standards for PV technology. This NCPV representation on international standards bodies assures U.S. industry a voice in standards applied to the global marketplace.

NCPV standards experts also help develop programs to certify that PV products meet approved standards. They contribute to the PV Global Approval Program (PV GAP). PV GAP will use the *Interim Test Methods and Procedures for Determining the Performance of Small Photovoltaic Systems* (developed at the NCPV with NEOS Corporation in 1998) as part of its interim test standards for certifying PV systems around the world. Closer to home, the PV Program was instrumental in establishing the PowerMark Corporation, which accredits laboratories to certify PV modules in the United States.

In other efforts at home, NCPV representatives worked in 1998 to update the National Electrical Code (NEC), which governs electrical installations in the United States. The NEC task group addressed how to calculate the amount of current available from a PV module, as well as details about system voltage, inverter terminology, source-circuit requirements, storage batteries, disconnect options, components unique to PV systems, and interconnect requirements. In all, 57 changes to the code proposed by the NCPV to enhance the safety of PV systems are under consideration.

Technical assistance and field engineering

An important goal of the PV Program is to deploy cost-effective applications of PV and to measure PV-system performance in key markets. By providing technical assistance and field engineering support, the NCPV helps ensure that these initial installations are successful and pave the way for wider use of PV.

One way to lower the cost and increase the reliability of PV systems is to move from custom-designed systems to a few carefully designed, standard packages that will meet the needs of several applications. In 1998, the PV Program supported industry's move toward standardized products by specifying standard system configurations for installation with federal agency partners such as the Bureau of Land Management. Ten systems for water pumping and four systems for small-facility power were installed through a standardized procurement system in 1998.

Publicizing the results of such application development projects is key to our goal of increasing markets. In 1998, Sandia documented several years of work with federal agencies, such as the National Park Service, the Bureau of Land Management, and the U.S. Forest Service, in a report titled *Renew the Government*. The report explains the lessons learned from installing 122 systems and provides important guidance for expanding the market for PV in federal agencies. Also in 1998, an economic assessment of three hybrid systems, based on data collected monthly by the PV Program, demonstrated that the systems were performing as expected and established a benchmark for life-cycle cost studies.

State and local governments are also in a good position to develop pilot PV projects that identify and remove barriers to widespread use of PV. An integral part of our technical assistance is documenting what works best and providing that information to guide future efforts. In 1998, 16 projects with states were assessed to identify successful models for next year's projects. To assess the reliability of grid-connected PV systems, the PV Program has analyzed data on the 414 utility-owned, grid-connected PV systems on home rooftops that comprise the PV Pioneer Program in Sacramento, CA. Data on maintenance requirements for these and other systems will help document ways to improve reliability.

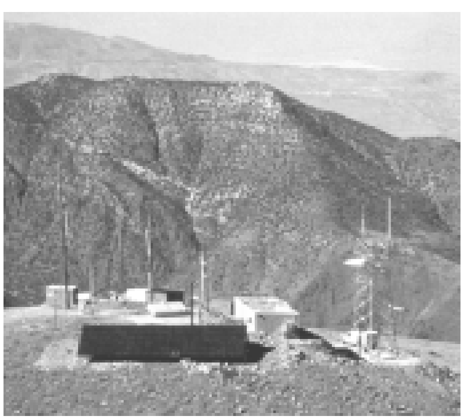
Sandia/PIX07113

NCPV engineers from Sandia worked with PowerLight Corporation to characterize and measure the performance of this 100-kW array on the rooftop of the Mauna Lani Bay Resort in Hawaii.

An outgrowth of work with state agencies is technical support in 1998 to the New Mexico Public Utilities Commission and the Public Service Company of New Mexico for a project to use PV and dish/Stirling thermal technology in conjunction with approval of a new gas turbine peaking power plant. This 5-MW project will be the largest PV installation of its kind in the United States.

Solar resource characterization

Solar resource data that are easy to access and manipulate is an important element in predicting PV system performance in a specific application. In 1998, the NCPV made spectral solar data and selected solar radiation and cloud cover maps accessible from its Web site (*http://rredc.nrel.gov/solar*). A technical report detailing methods to produce high-resolution climatological solar-resource maps was also published this year. In 1999, the NCPV will bring together major researchers and users of satellite-derived solar-resource assessment products to foster wider use of this information resource.



Sandia/PIX07116

At Rogers Peak communications site at Death Valley National Park, CA, NCPV researchers at Sandia estimated life-cycle costs for the 12.8-kW PV array and 35-kW propane generator system.

PV for Utility-Scale Applications (PVUSA)

The PV Program supports PVUSA, which installed the world's first transmission and distribution system powered by PV in 1987. In 1998, this collaborative project for PV worked to prequalify systems and components for programs such as the Million Solar Roofs Initiative and TEAM-UP (Technology Experience to Accelerate Markets in Utility Photovoltaics) installations with the UPVG (Utility PhotoVoltaic Group).

With the increased numbers of PV installations, prompted in part by efforts of the NCPV, the need for skilled installers has grown steadily. In collaboration with PVUSA, DOE has funded the Southwest Technology Development Institute and the Florida Solar Energy Center in providing training programs to support several large PV demonstration projects: the Million Solar Roofs Initiative, TEAM-UP, UPVG, and the PV Pioneer Program in Sacramento, CA. In addition to training installers, these centers also provide information about PV, for example, about the benefits of combining PV with energy-efficient housing construction.

Markets and Applications Development

To accelerate the acceptance of photovoltaics into existing and new markets worldwide, the NCPV supported public education campaigns, training workshops, market and policy analysis, and technical support of various stakeholder groups at state and local levels. Consumer groups, utilities, the PV industry, builders, developers, and the general public received technical information necessary to make informed decisions about using PV.

Domestic market and applications development

To help engender public interest and understanding of solar energy for the Million Solar Roofs Initiative, the NCPV supported specific projects designed to remove technical barriers and increase awareness and acceptance of photovoltaics.

Training, education, and technical assistance

Workshops for communities interested in implementing solar energy, including PV, attracted national organizations and representatives from more than 12 communities.

Another important training and public awareness activity is the biennial Sunrayce Solar Car Race for college students. DOE, General Motors, and Electronic Data Systems collaborate to organize this two-year design competition that culminates in a 10-day, 1000-mile race across the United States. Announcements and regulations are sent to more than 1100 colleges and universities across North America.

Live Oak Solar/PIX07047

A portable PV genset, one of the many PV products that can help supply power in remote locations or in the aftermath of disaster, is transported by helicopter into the California mountains.

Several public exhibits brought information about PV to millions of citizens in 1998. A solar exhibit at EPCOT Center® in Orlando, FL, hosted an estimated 3 million visitors and featured PV modules and PV-powered devices. The NCPV also sponsored a popular PV exhibit at the Smithsonian Institution's Cooper-Hewitt National Design Museum in New York City. And once again, the Pageant of Peace activity installed a PV system on the Capitol grounds to help light the festivities in December.

The NCPV briefed insurance companies on the benefits of using PV in the aftermath of disaster. Modular, lightweight PV power systems can be tailored to the electrical loads, sites, and applications necessary when utility power systems are disabled. Another meeting including utilities, federal disaster organizations, and insurance companies is planned for 1999.

Utility applications and projects

To accelerate the use of PV by utilities, the Utility PhotoVoltaic Group was formed in 1992. By 1998, it had more than 100 members. The PV Program provides technical and financial support to the group to test PV systems in domestic utility applications. A UPVG initiative called TEAM-UP has installed 2.5 MW of PV at 35 utilities across 30 states and involves 130 partners. The group has commitments to install an additional 5 MW in 1999.

Another approach to removing barriers to PV for utilities is the PV4U network of 15 state working groups that promote PV. For example, the PV4U consumer project works to educate and assist state-appointed consumer representatives about PV issues. Another important activity is dealing with issues surrounding installation, metering, and utility interconnection of small-scale PV systems.

Building-integrated photovoltaics

Residential, commercial, and institutional buildings offer significant opportunities for supporting PV systems and reducing energy consumption. However, integrating PV products into buildings is more complicated than it may seem at first glance. Several additional NCPV projects completed in 1998 are designed to smooth the way for building-integrated PV. A sourcebook containing architectural details for integrating PV into building envelopes and a borrower's guidebook for financing solar energy systems will be distributed widely. Adding a PV "module" to a building energy-simulation tool, *Energy-10*, used by architects should make it easier to calculate the output of a building-integrated PV system and to help predict the system's effects on the heat absorption and daylight available in the building. In addition, a study of existing building codes identified areas where these codes may prevent applications of PV integrated into buildings. Work to overcome these barriers will continue.

Through PV:BONUS (Photovoltaic Building Opportunities in the United States), the PV Program helps teams from the PV and building industry develop prototype PV products that could replace conventional windows, skylights, and walls while generating electricity. The first group of contracts awarded in 1993 resulted in prototype products such as the flexible solar shingle and the ac PV modules, whose manufacturability is being improved under PVMaT.

PV rooftop applications such as these will contribute toward the Million Solar Roofs Initiative. To track its progress, visit the Web site (www.MillionSolarRoofs.org). For details on these photos, see inside back cover.

PV:BONUS TWO Continuing Projects

Recipient teams	Project
SAGE Electrochromics; Solarex; Glass Technologies; Libby-Owens-Ford	Self-contained, PV-powered electrochromic windows that control solar gain through color shading
Solarex	Three opaque window modules using thin-film PV to replace spandrel panels, viewglass in curtain walls, and overhanging sunshades
Solar Design Associates, Inc.; United Solar Systems Corporation; SunEarth, Inc.	Hybrid a-Si PV/thermal collector to deliver both electricity and thermal energy
Ascension Technology	Ballast-mounted PV arrays
Advanced Energy Systems	PV string inverter to operate with a single string of PV modules
United Solar Systems Corp.; Energy Conversion Devices, Inc.; National Association of Home Builders Research Center; Phasor Energy; Solar Utility, Inc.	Field-applied PV membrane for commercial flat roofs, covered parking structures, sloped metal roofing, and tile roofing
PowerLight Corporation; AstroPower; Solarex; BP Solar; Siemens Solar	PV roofing products that protect from solar thermal loads in summer and block radiant heat losses in winter

Continuing this successful approach, 17 new projects were funded in 1997 to encourage concept development and business planning for additional products that integrate PV or hybrid products into buildings and demonstrate commercially viability. In 1998, seven of these projects were selected for continued funding in a product- and business-development phase. Eventually, these projects will continue with product fabrication, demonstration, and verification of performance, including a test and acceptance activity.

International market and applications development

Most of this fast-growing market for PV is made up of people who lack a reliable source of electricity—about 40% of the world's population. Often, these people require only small amounts of power for such applications as indoor lighting or pumping water, applications for which PV electricity is often the least expensive and most reliable power choice.

The goal of the PV Program is to provide technical assistance and support, with the aim of finding ways to finance continued beneficial use of PV products around the world. Supporting demonstration projects develops a local installation, maintenance, marketing, and financing infrastructure to meet this goal of sustained use. The basis for the U.S. PV industry's success in the world market has been continued progress in applied research and technology. The PV Program's market development efforts are essential to accelerating the use of PV as part of sustainable economic development.

Ramakrishna Mission/PIX05466

An additional 2000 systems have been purchased and installed since the original 300 solar home lighting systems were installed in the Sundarbans region of West Bengal, India, as part of a joint project between the United States, the government of India, and the Ramakrishna Mission, a renowned humanitarian organization. This project demonstrates the value of "seed" project strategies used to stimulate international markets for PV.

Brazil

DOE's efforts in Brazil have met a major goal of the *National PV Program Plan for 1996–2000*, to demonstrate technology and promote financing of additional projects. The more than 1000 small stand-alone systems demonstrated in eight Brazilian states in cooperation with the national utility have led to a lively market maintained by financing from the World Bank and Brazilian financial institutions.

In 1998, the PV Program worked to establish business relationships for hybrid power systems. Two hybrid power systems are operating successfully in Brazil. This application is the next potential PV market in Brazil but, because it involves several types of equipment, business relationships are more complex. While continuing to document system performance, the PV Program is supporting U.S. companies in their efforts to develop business strategies.

China

China presents a complex political and economic landscape for U.S. business. To assist U.S. PV companies, the PV Program developed information concerning the business environment, opportunities, potential partners, and projects in China. This effort culminated in a workshop held in Beijing to bring U.S. and Chinese company executives together for information exchange and follow-up business discussions. This workshop linked 70 people from U.S. companies, Chinese organizations, and the World Bank.

South Africa

The NCPV is working with Renewable Energy for South Africa, the U.S. Agency for International Development, and the National Rural Electric Cooperative Association to bring electricity to rural residents and businesses. In 1998, this collaboration resulted in a strategic plan for public education and marketing for solar-home-system rural electrification. Developed by a Johannesburg company, the plan draws upon a survey of nongovernmental and community-based organizations active in rural development. It details media strategies to address the significant educational barriers to PV as an option for rural households.


Simon Tsuo, NREL/PIX05466

Developing markets for solar home systems can foster local business opportunities, such as this manufacturing facility for PV panel controllers in China.

Mexico

Our closest neighbor to the south represents a huge potential market for the U.S. PV industry. A 1998 market study, commissioned by Sandia, estimated a potential market for all renewable energy technologies at more than $1 billion. A good share of this market can be satisfied by PV power. Small PV systems can provide electricity to an estimated 5 million Mexicans who have no access to the electric power grid. PV systems can also pump and filter water to an estimated 100,000 households.

The PV Program's training and technical assistance efforts in Mexico have resulted in nearly 200 renewable energy projects in eight Mexican states in collaboration with more than 40 U.S. and Mexican companies, and in partnership with the U.S. Agency for International Development. In 1998, the PV Program provided a list of Mexican businesses for the U.S. PV industry to contact. In addition, a Spanish-language guide for PV water pumping published by the PV Program this year should help in-country personnel explain the benefits and operating characteristics of PV to those who are not familiar with it.

The benefits of DOE's efforts in Mexico have been well documented as pilot projects that are easy to repeat in many locations. As a result, in June 1998, the Mexican and U.S. Secretaries of Energy included the work on PV as an annex to the binational agreement between the two countries, ensuring continued cooperation for sustainable economic development in Mexico.

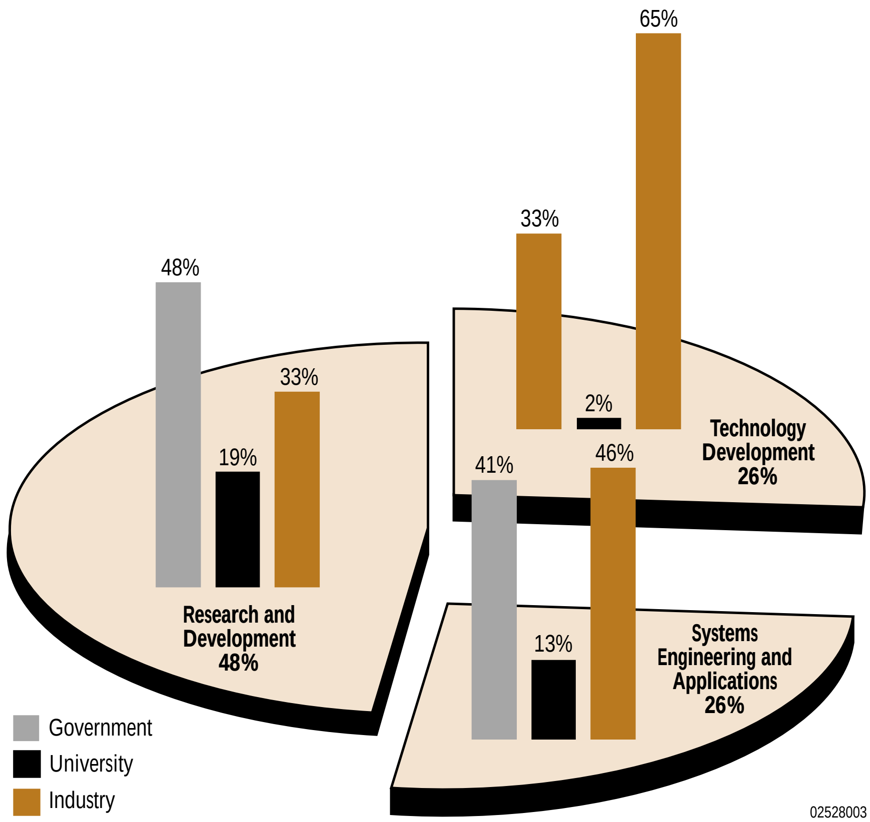
Program Resources

A Structure That Works

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

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

"To mobilize national resources in PV by performing world-class R&D, promoting partnership and growth opportunities, and serving as a forum and information resource for the PV community."
Mission of the NCPV



With an eye toward making PV the power of choice, the NCPV awards most of its federal funds through competitive procurements to industry, universities, and other research centers around the country.

Facilities Available

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

Materials and device development—This area features a full range of film deposition and crystal growth facilities for preparation of PV absorber layers and other component layers needed to complete the solar cell. The facilities provide control of the film development and interfaces necessary to elucidate the fundamental mechanisms that influence cell efficiency, reliability, and process factors such as yield and deposition rate.

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

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

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

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

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

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

Photo captions and credits

Cover photos (clockwise from upper left):

The 75-kW system of PowerGuard® insulating roofing tiles will save the Mauna Lani Bay Resort Hotel in Hawaii enough in utility bills to pay for itself in five years. PowerLight Corp./PIX06431.

Czochralski silicon wafers on a quartz boat entering a furnace at the Siemens Solar factory. Siemens Solar Industries/PIX06142.

These triple-junction a-Si shingles from United Solar Systems Corporation were installed at NREL's Outdoor Test Facility in 1998. NREL is conducting tests to validate the performance and reliability of the system. Warren Gretz, NREL/PIX06288.

NREL researcher uses the scanning Fourier transform infrared microscope to examine novel PV materials. Warren Gretz, NREL/PIX05976.

PVMaT photos, pages 10 and 11 (clockwise from upper left):

Trace Engineering streamlined its product manufacturing and improved reliability through a modular, versatile building-block inverter design for stand-alone, hybrid, or grid-connected applications. Trace Engineering/PIX07207.

Integrated Power Processing Unit and factory-assembled modular panels. Michael Stern, Utility Power Group, Inc./PIX06618.

SunSine™300 ac inverter. Ascension Technology, Inc./PIX05940.

Modular Autonomous Photovoltaic Power Supply by Solar Electric Specialities. Ben Kroposki, NREL/PIX06413.

Module that houses the SunSine™300 ac inverter. ASE Americas/Ascension Technology, Inc./PIX07111.

A 250-watt, utility-tied microinverter, used to support an ac module. Solar Design Associates/Advanced Energy Systems, Inc./PIX05939.

The Evergreen Solar array demonstrates the company's new air-laminated transparent encapsulant and a backskin material strong enough to eliminate the use of a frame. Evergreen Solar/PIX05936.

Rooftop PV photos, page 16 (clockwise from left):

Solectrogen House, an off-grid PV-powered residence in Nicasio, CA. Solar Depot, Inc./PIX04479.

Installation of PV-integrated standing-seam metal roof at the BigHorn Center in Silverthorne, CO. Paul Torcellini, NREL/PIX06682.

PV systems can be used on flat or gently sloping rooftops. PowerLight Corp./PIX06430.

Residence with grid-connected PV panels in Gardner, MA. Bill Eager/PIX00568.

PV cells laminated to skylight glass at the Thoreau Center for Sustainability at Presidio National Park, San Francisco, CA. Atlantis Energy, Inc./PIX04779.

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