Photovoltaic Energy Program Overview
Fiscal Year 1995

U.S. Department of Energy

Contents

Cover Photos: *On left*, the Sacramento Municipal Utility District installed a 210-kW PV system at the Hedge substation in California (SMUD/PIX01026). *On right, from top to bottom:* Large-scale photovoltaic systems can provide grid support for electric utilities (William Wallace, NREL/PIX01541). PV systems are being deployed and evaluated in a variety of applications around the world (Solar Electric Light Fund/PIX01543). Through the support of the PV Program, Golden Photon, Inc., has improved the efficiency of its cadmium telluride modules and manafacturing process (David Patryas Photography/PIX01545). One way that DOE researchers at the national laboratories help the U.S. PV industry is through R&D on deposition of PV materials (Jim Yost Photography/PIX03655).

Message from the Director

This year photovoltaic (PV) systems used sunlight alone to generate more than 800,000,000 kilowatt-hours of electricity throughout the world. These systems installed since 1988 generate enough electricity to power 8 million homes in the developing world or 150,000 homes in the United States. This year, worldwide sales of PV systems grew again by more than 15 percent. And, for the past 2 years, U.S. industry increased its share of this exploding world market. This year, corporate America increased its investments to
expand PV manufacturing capacity, while researchers worked to maintain the technological edge that has fueled our market successes.

We look with pride on the achievements of the fiscal year just ended. While the lion's share of the credit for our accomplishments goes to industry, the government program in cooperative research and development is helping to turn the tide of dwindling market share by making remarkable technical advances. These advances in understanding and improving manufacturing technology, PV materials, balance-of-system components, and engineering applications are giving U.S. industry the edge it needs against heavily
subsidized foreign competition.

We look with hope to our labors ahead. Competing in world markets demands continuous improvements in performance and cost. To reap the rewards of our national investment in this technology success story we must keep the momentum going. The research agenda set forth in the National Photovoltaic Program 5-Year Plan supports high-risk, high-payoff research that will keep U.S. industry on top. The programs of cooperative research that draw on the resources of the national laboratories, universities, and the PV industry provide the feedback loop from the market to the laboratory. This feedback to the laboratory is vital in advancing PV technology to benefit new products. And it is new and better products that will deliver electricity from the sun to the people of the world.

James E. Rannels, Director
Photovoltaic Technology Division
U.S. Department of Energy
Washington, D.C.

1995 PV Program Accomplishments

Research and Development

Refined and continued to transfer to industry the techniques for producing record 17.1%-efficient cells in the laboratory based on copper indium diselenide.

Supported work leading to two companies bringing prototype products of cadmium telluride thin-film technology to market.

Developed a new production technique—hot-wire deposition—that shows promise of more-efficient amorphous silicon solar cells.

Verified a record 30.2%-efficient gallium arsenide alloy concentrator cell at 180 suns.

Developed cells from new high-efficiency material—polycrystalline gallium arsenide—verified at 16.6% in the first year of research.

Demonstrated that rapid thermal processing of silicon can reduce processing time while maintaining high efficiencies.

Technology Development

Successfully completed several PV Manufacturing Technology (PVMaT) contracts having 3-year commitments, exceeding cost and production goals of the program. Awarded new contracts for product-driven system and component technology and manufacturing technology.

Supported work at AstroPower that led to their winning an R&D 100 award for a PVMaT product.

Supported work at Spire Corporation to develop its automated PV module assembler being marketed this year.

Supported work at Solarex leading to a manufacturing process for the commercial production of 8-ft^2 multijunction amorphous silicon modules.

Supported work with Springborn Materials Science Corporation leading to the development of two new encapsulant formulations for the PV industry.

Developed and tested balance-of-system (BOS) components including inverters, batteries, and charge controllers under the BOS project.

Added to laboratory capabilities, including a new outdoor test facility at NREL and a BOS testing laboratory at Sandia.

Systems Engineering and Applications

Completed a major step toward creating a domestic certification program for PV modules and systems.

Assisted Omnion Power Engineering Corporation to achieve UL and FCC approval for their 4-kW inverter.

Supported Utility PhotoVoltaic Group's efforts in 1995 and plans for 1996.

Demonstrated through an expanded load-matching study that PV electricity generation matches utility loads in most regions of the United States.

Expanded efforts to promote PV to federal agencies, including the National Park Service, U.S. Forest Service, Bureau of Land Management, and the military.

Supported the design and construction of six modular houses incorporating PV under the PV:BONUS project. Also accelerated development of PV-integrated roofing products and a module that converts dc power directly to ac power.

Completed international projects in South Africa, Brazil, Mexico, India, and Russia that installed PV hardware and module assembly plants.

Introduction

Accomplishments of the PV Program in FY 1995 stem from work planned and carried out in collaboration with the U.S. PV industry.

The National Photovoltaic Program supports efforts to make PV an important part of our economy through its three main program elements: Research and Development, Technology Development, and Systems Engineering and Applications.

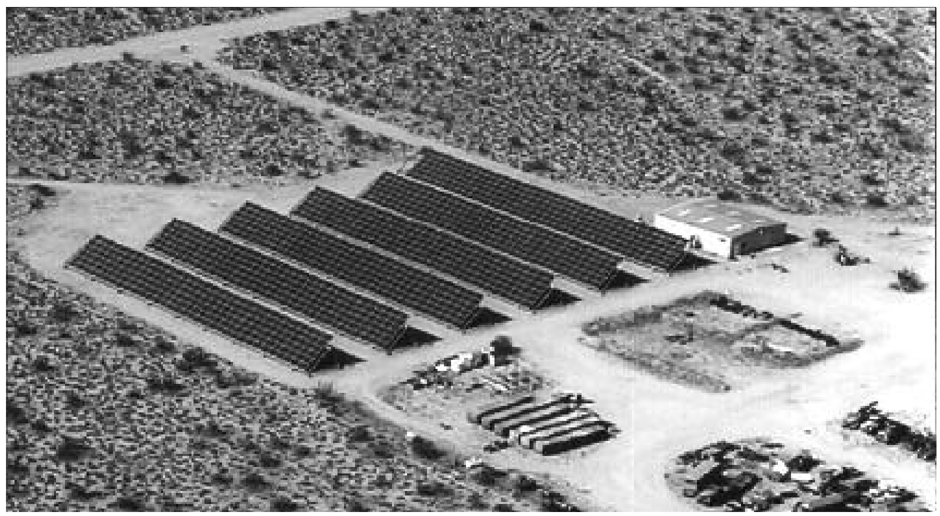
Research and development activities generate new ideas, test the latest scientific theories, and push the limits of PV efficiencies in laboratory and prototype materials and devices.

Technology development activities apply laboratory innovations to products to improve PV technology and the manufacturing techniques used to produce PV systems for the market.

Systems engineering and applications activities help improve PV systems and validate these improvements through tests, measurements, and deployment of prototypes. In addition, applications research validates sales, maintenance, and financing mechanisms worldwide.

All PV Program activities are planned and executed in close collaboration and partnership with the U.S. PV industry.

Fiscal Year (FY) 1995 has seen advances and significant accomplishments in each of these program elements, expanding the foundation on which next year's activities will build.



Tony Garcia, NAWCWD

This 290-kilowatt PV hybrid system stemming from PV Program activities generates electricity for a military operation in China Lake, California.

"There is no doubt that the costs of photovoltaic modules have decreased by a factor of 10 over the past 15 years...This decrease has been as a result of both technological progress and gain in PV production experience."

— Renewable Energy Technologies: A Review of the Status and Costs of Selected Technologies, by the World Bank.

Research and Development

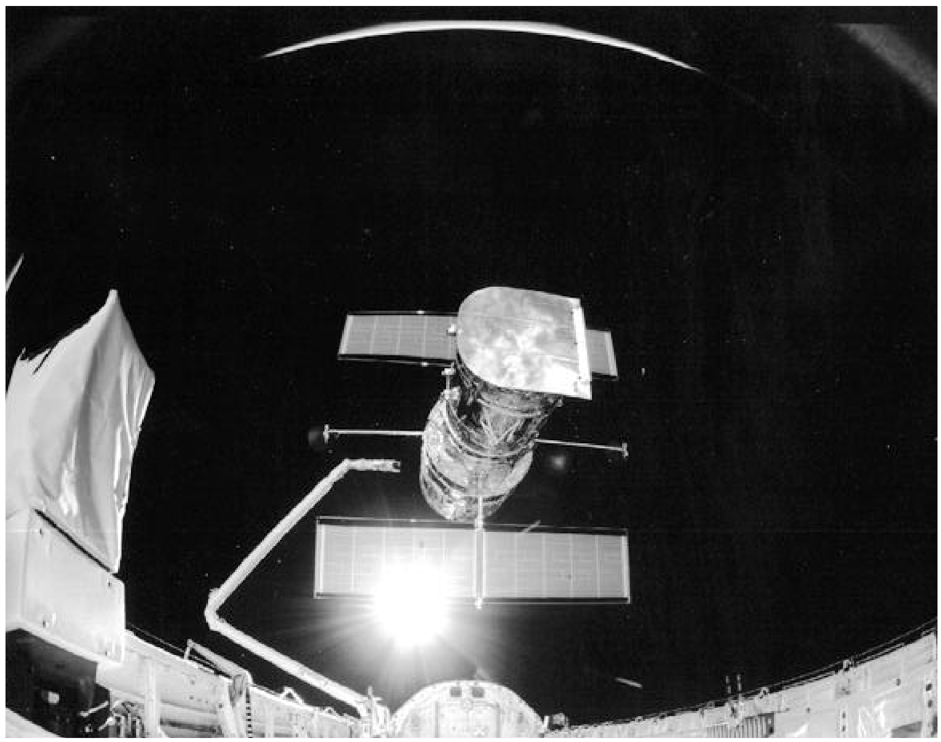
Researchers in DOE laboratories, industry, and universities generate new approaches for increasing the efficiency and reducing the cost of PV.

U.S. industry markets the most advanced PV technologies in the world. Recent innovations have helped U.S. industry regain some of the world market share lost in the 1980s. An aggressive research and development program helps maintain our position of technological leadership so we can continue to reap the economic rewards of our long-term investments.

Through its cooperative research and development activities, the PV Program conducts research in thin films, crystalline silicon, and advanced high-efficiency materials and devices. This year, researchers increased cell efficiencies through basic research and innovative fabrication techniques. Photovoltaic Program personnel transferred these techniques to industry and expanded research partnerships to further advance the technology. In addition, work with universities yielded valuable results and helped inspire the next generation of researchers.

"I believe that this joint DOE/NREL program with subcontractors in fundamental and applied research and development is a very successful model."

— John Coors, Chief Executive Officer, Golden Photon, Inc., Golden, Colorado



PV cells and modules are very reliable in space and on the earth. The Hubble space telescope (pictured here) and virtually all communications satellites are powered by photovoltaic technology. The DOE program over the last two decades has worked to bring this technology to earth.

Thin-Film Materials: Improving efficiencies, performance, and costs

To compete in world markets for bulk power generation, the cost of electricity from PV systems must decline from today's 20¢ per kilowatt-hour (kWh) to around 6¢/kWh. To reduce costs by this much we need new technologies that can be mass-produced from inexpensive materials. Thin-film materials are a promising path to very low-cost PV. At least eight U.S. companies are building plants to produce modules made of thin-film materials for today's markets.

To supply tomorrow's markets, the PV Program's research addresses technical issues to raise the efficiencies of thin-film devices to new records. New records are often the result of laboratory research that expands our theoretical understanding of thin-film materials. In addition, some technical problems only emerge as products are manufactured for the first time. When these problems arise, they must be referred back to the laboratory for new approaches to thin-film devices.

PV technology basics

There are many different technical approaches to converting the sun's energy into electricity. The PV Program conducts R&D on several of the most promising concepts. Program resources are invested in innovative new approaches with the potential for high efficiencies and low cost like thin-film PV, as well as established technologies like crystalline silicon PV.

Crystalline silicon (c-Si) is the semiconductor material used most in the manufacture of PV modules today. Silicon wafer technology is similar to that of computer chips. Wafers for each cell are cut from ingots of crystalline material. Modules are made of individual cells, electrically connected and sealed in a weatherproof package. Small c-Si cells can be used with special lenses that concentrate sunlight to achieve higher efficiencies. These concentrator systems have a large collection area composed of low-cost materials and a smaller area of more-expensive solar cells.

Another variant of c-Si used in manufacture of PV modules today is multicrystalline or polycrystalline silicon. These materials are composed of crystal grains up to 1 cm across bonded together to form a single material.

Polycrystalline thin-film materials are referred to by the chemical composition of their photosensitive materials such as cadmium telluride (CdTe) or copper indium diselenide and its alloys—$Cu(In,Ga)(S,Se)_2$ or (CIGS). To construct thin-film PV modules, very thin layers of semiconductor material (down to 1 micron thick, about 300 times thinner than conventional c-Si) are applied to a low-cost backing such as glass or stainless-steel foil. Polycrystalline Si and gallium arsenide are other candidate thin-film materials. Thin films demand less semiconductor material per device, so the cost of materials is lower. In addition, thin-film manufacturers can take advantage of existing industrial processes such as those used to manufacture and coat glass. Furthermore, thin-film modules can be connected into an electric circuit as a single large piece. They are said to be "monolithic." In contrast, c-Si modules are made from cells that are wired into electric circuits within the module.

Amorphous silicon (a-Si) materials are made of solid silicon, but like glass, they have no crystalline structures. Small a-Si modules are commonly used for solar-powered consumer devices that have low power requirements. By carefully controlling the formation of thin layers of a-Si, and by modifying their composition, PV cells with higher efficiencies are being fabricated. To further increase efficiency, a-Si multijunction devices are constructed in layers, each of which absorbs a different portion of the solar spectrum. This makes the devices more efficient than single-junction a-Si, but adds complexity and cost to manufacturing. The efficiency of amorphous silicon cells and modules is expressed as "initial" or "stabilized," because the efficiency of most a-Si materials—when exposed to light—declines to a stable lower level.

The Thin-Film PV Partnership Program is designed to ensure that companies aggressively scaling up their new thin-film products have the R&D resources to address these issues and to move forward. The PV Program awarded 11 additional contracts in 1995 under the Thin-Film PV Partnership Program.

Besides their specific research contracts, investigators participate in research teams that address technological issues

Thin-Film PV Partnership members

AstroPower, Inc.,
Newark, DE (Si film)

Colorado School of Mines,
Golden, CO (a-Si; CdTe)

Colorado State University,
Ft. Collins, CO (CIS)

Energy Conversion Devices, Inc.,
Troy, MI (a-Si)

Energy Photovoltaics,
Princeton, NJ (CIS)

Florida Solar Energy Center,
Cape Canaveral, FL (CdTe; CIS)

Georgia Institute of Technology,
Atlanta, GA (CdTe)

Golden Photon, Inc.,
Golden, CO (CdTe)

Harvard University,
Cambridge, MA (a-Si)

International Solar Electric Technology,
Inglewood, CA (CIS)

Iowa State University,
Ames, IA (a-Si)

Pennsylvania State University,
University Park, PA (a-Si)

Purdue University,
West Lafayette, IN (CdTe; CIS)

Siemens Solar Industries,
Camarillo, CA (CIS)

Solar Cells, Inc.,
Toledo, OH (CdTe)

Solarex Corporation,
Newtown, PA (a-Si)

Syracuse University,
Syracuse, NY (a-Si)

United Solar Systems Corp.,
Troy, MI (a-Si)

University of California,
Los Angeles, CA (a-Si)

University of Central Florida,
Orlando, FL (CIS; CdTe)

University of Colorado,
Boulder, CO (a-Si)

University of Delaware, Institute of Energy Conversion,
Newark, DE (a-Si; CdTe; CIS)

University of Florida-Gainesville,
Gainesville, FL (CIS)

University of North Carolina,
Chapel Hill, NC (a-Si)

University of Oregon,
Eugene, OR (a-Si)

University of South Florida,
Tampa, FL (CIS; CdTe)

University of Toledo,
Toledo, OH (CIS; CdTe)

Washington State University,
Richland, WA (CIS)

affecting the entire industry. This mechanism brings industrial problems back to the laboratory. The industry partners each contribute 10%–50% of the value of their contract. They are developing precommercial prototype products largely based on copper indium diselenide, cadmium telluride, thin-layer crystalline silicon, and amorphous silicon.

Copper indium diselenide

In FY 1995, PV Program researchers studying laboratory devices based on copper indium diselenide (CIS) pushed the conversion efficiencies to 17.1 percent (for a 0.4-cm^2 cell). This is the highest efficiency recorded for any thin-film cell and demonstrates that a thin-film cell designed for low cost can approximate the performance of a traditional wafer silicon cell (the best polycrystalline silicon cell efficiency is 17.8 percent [1 cm^2]).

Industrial partners are also developing higher-efficiency devices that show promise for large-scale production. Solarex Corporation, working with the PV Program, produced a 40-cm^2 minimodule with a record 12.9% efficiency. In another development, International Solar Electric Technology uses a lower cost, non-vacuum method of depositing copper indium diselenide precursors with little waste. Using this method—and without adding gallium—they produced copper indium diselenide cells having 13% efficiency. By adding gallium, this simpler process should yield cells with even higher efficiencies.


Jim Yost Photography/PIX03524

These two physical vapor deposition systems are used for making various copper indium diselenide PV cells.

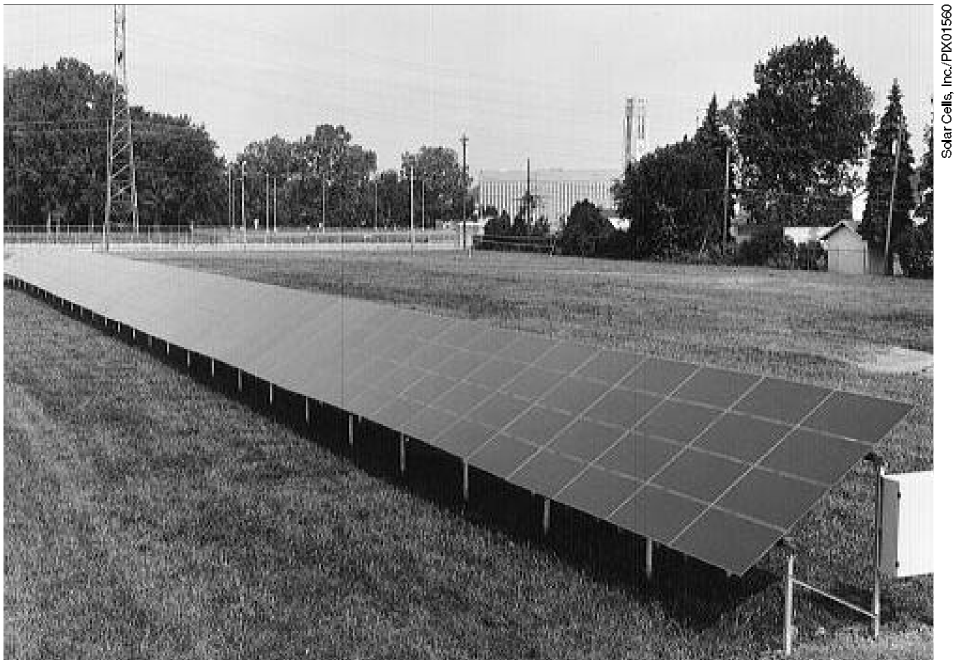
Copper indium diselenide alloys are difficult to make. Proper temperature and timing of process steps are critical to quality results. PV Program researchers work closely with industry to ensure that approaches leading to these high-efficiency materials are well understood. To achieve this, the PV Program has assembled 40 researchers nationwide to devise simpler, more-effective fabrication methods. In FY 1995, the National Renewable Energy Laboratory (NREL) began to license its deposition technology used to achieve world-record efficiencies for copper indium diselenide materials.

Cadmium telluride

Cadmium telluride technology is the newest commercial thin-film PV product. Two U.S. companies are manufacturing modules for remote applications. Cadmium telluride holds the promise of low-cost manufacturing, with more than a dozen methods having been used to make 10% cells, including high-rate evaporation, spraying, screen printing/sintering, and electrodeposition.

The efficiency of small (0.4-cm^2) cadmium telluride devices has increased to nearly 16 percent. Small, high-efficiency cells are made using new techniques in the laboratory. Achieving high efficiencies for larger-sized devices is a central focus of ongoing PV Program activities.

Increasing the efficiency of modules made from this material is challenging because, despite our progress in developing and manufacturing cadmium telluride, our fundamental understanding of its properties is very limited. This year, under the Thin-Film PV Partnership research agreements, teams are working to understand specific material properties important to the companies developing this technology. One team is exploring stability in cadmium telluride materials and devices to learn how to build consistently stable modules.



This prototype PV system is made with cadmium telluride thin-film technology pioneered in DOE laboratories and developed in conjunction with Solar Cells, Inc. The modules feed enough electricity into the utility grid each year to meet the energy needs of four typical American homes.

Producing stable modules requires sophisticated equipment for monitoring production. In a cooperative research and development agreement (CRADA) with Solar Cells, Inc. (SCI), of Toledo, OH, the PV Program developed and built a photoluminescence diagnostic monitor to the company's specifications. SCI will use the monitor in their production line to test the quality of devices as they are produced.

In FY 1995 Solar Cells, Inc., and Golden Photon, Inc., of Golden, CO, brought prototype products to market. The performance of these products will be carefully monitored to improve our understanding of this thin-film material.

Amorphous silicon

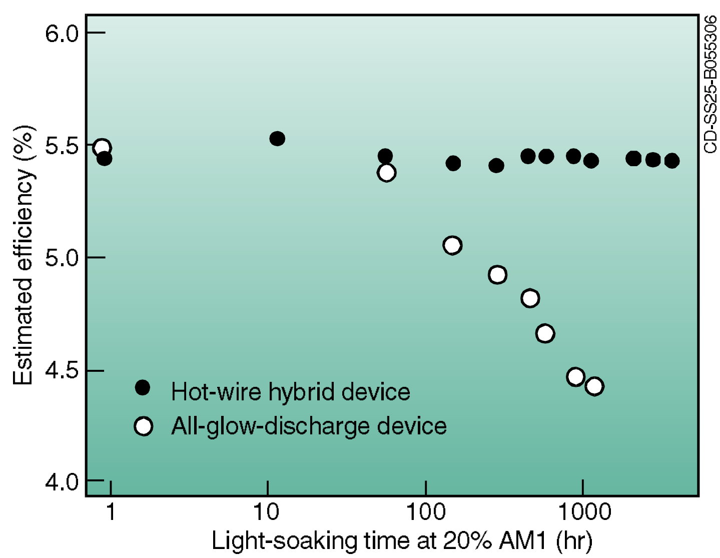
Improving the stability and efficiency of amorphous silicon materials and devices remains an important program task. This year work continued to improve amorphous silicon cells by modifying device structure. The Thin-Film PV Partnership research teams are addressing a dozen issues surrounding the design and fabrication of multijunction amorphous silicon alloy cells.

For example, one team is working on back reflectors that direct unused sunlight back up through the very thin layers of a multijunction cell. Good back reflection can increase the efficiency of these cells by up to 40 percent. Another team is modeling the effects of using different combinations of alloys in the layers of multijunction cells. Modeling allows many combinations to be evaluated quickly and the best possibilities to be selected for laboratory experiments.

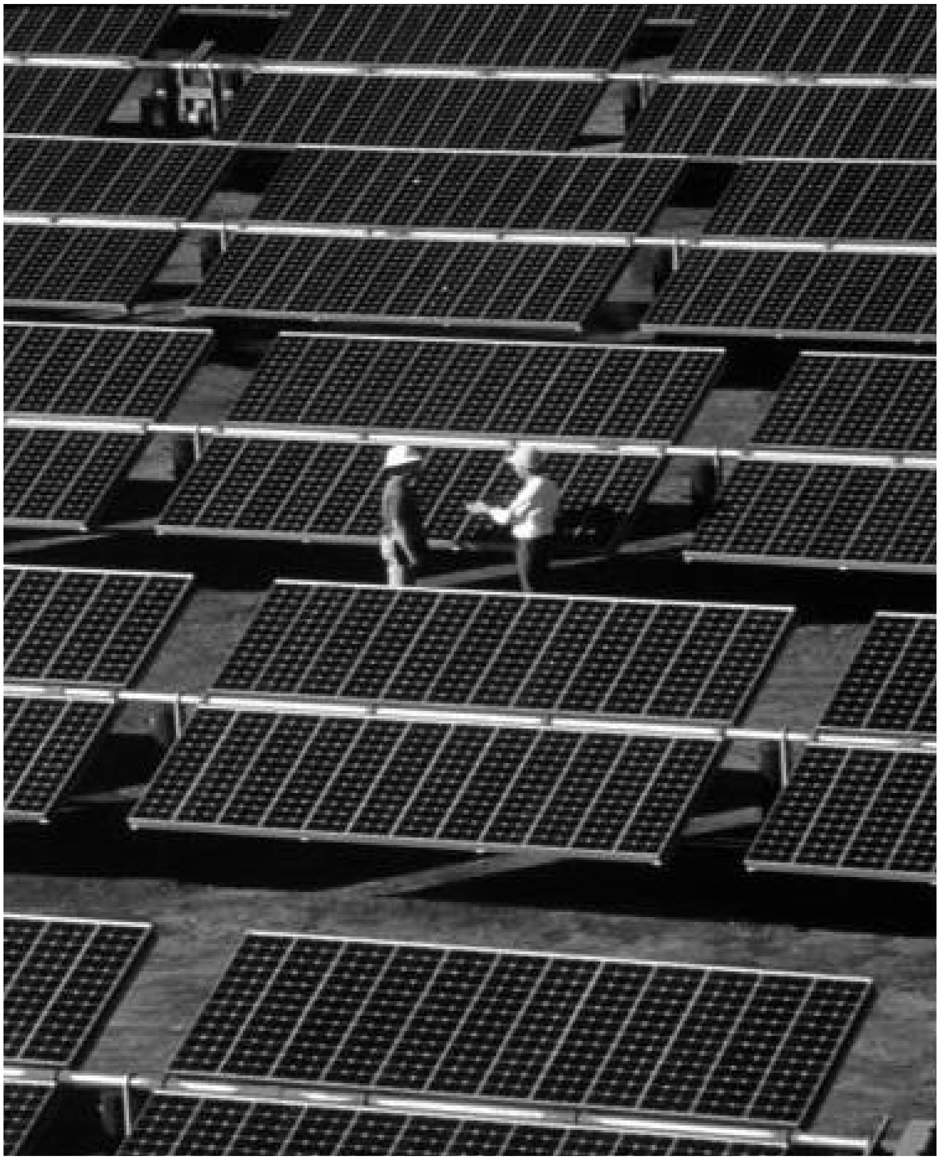
Other experiments to improve production techniques for amorphous silicon show promise. For example, United Solar Systems Corporation found that hydrogen dilution during deposition improved both the initial and the stabilized performance of amorphous silicon alloy cells with hydrogen.

In another development, a new production technique shows promise for increasing the efficiency of amorphous silicon. Amorphous silicon produced by today's glow-discharge method experiences permanent losses in conversion efficiency when exposed to sunlight—a phenomenon known as the Staebler-Wronski Effect. A potentially more stable amorphous silicon material was produced at NREL last year using a hot-wire technique. The extremely high temperature near the wire causes the liquid mixture of material to separate into layers and deposit on the cell surface up to 10 times faster than the glow-discharge method used by industry today. In addition, the material contains less poorly bonded hydrogen, the agent suspected to cause instability in amorphous silicon material.

Tests in 1995 confirm that material created with the hot-wire method is more stable, and further tests show that efficiency can be increased as well. In FY 1996, researchers plan to incorporate material made with the hot-wire technique into devices with higher efficiencies, such as tandem or triple-junction cells. In addition, this technique will be used to deposit other alloys of amorphous silicon, such as amorphous silicon germanium.



The new hot-wire deposition process being developed in the PV Program produces amorphous silicon material that is more stable and does so in about one-tenth the time of other methods.



Crystalline silicon modules produced in the U.S. dominate the world market for PV. The Sacramento Municipal Utility District (SMUD) installed this 210-kilowatt crystalline silicon system at its Hedge substation in California.

Meanwhile, the U.S. PV industry is expanding its production capacity for amorphous silicon PV systems. During FY 1995 United Solar Systems Corporation/Energy Conversion Devices of Troy, MI, and Solarex, of Newtown, PA, began major scale-ups of their amorphous silicon manufacturing capabilities. These new facilities will have an important impact on the U.S. production capacity for amorphous silicon PV.

Crystalline Silicon Materials: Advancing the industry's workhorse

Crystalline silicon dominates the domestic and international PV markets today because of its relatively high efficiency, stability, competitive cost, and durability in the field. In 1994, crystalline silicon materials accounted for 83% of the total world sales of PV. Yet, as laboratory achievements in efficiency are reproduced in industry, crystalline silicon devices will become even more competitive with other forms of energy generation. To make crystalline silicon devices more competitive, cooperative research sponsored by the PV Program focuses on adapting laboratory techniques to make larger cells more quickly and increasing the efficiency of low-cost materials.

For example, rapid thermal processing is an important step toward continuous automated production of silicon solar cells. This process reduces the time to process silicon solar cells by using optical lamps to heat samples very quickly. Speeding up processing time reduces the amount of chemicals and energy used and can achieve better performance from low-cost, solar-grade, crystalline silicon materials.

This year the program's work with the Georgia Institute of Technology—one of DOE's University Centers of Excellence in Photovoltaic Technology—made silicon cells by rapid thermal processing. These cells have measured efficiencies of 17.1% on semiconductor-grade float-zone silicon, 16.4% on solar-grade silicon, and 14.8% on cast-multicrystalline silicon. These efficiencies, comparable to those of cells produced using conventional processes, demonstrate that rapid thermal processing can produce acceptable cells more quickly. This laboratory work is being applied by Solarex Corporation, Frederick, MD, using high-throughput production equipment.

For several years, the program's Multicrystalline Silicon Research Cooperative has provided a framework for industry to benefit from and guide work at the national laboratories in multicrystalline materials and devices. For example, one task under the cooperative was processing material manufactured by Crystal Systems, Boston, MA, and producing a multicrystalline module with 15.3% efficiency. The task was identified, confirmed, and monitored by the team in FY 1994. This activity demonstrated the potential of large-area multicrystalline cells to have such a high efficiency.

This year the research cooperative expanded its membership (and changed its name) to include those working in single-crystal silicon materials and devices. Researchers from U.S. crystalline silicon manufacturers—ASE Americas, Billerica, MA; AstroPower, Newark, DE; Crystal Systems; Solarex; and Siemens Solar Industries—NREL, and Sandia work together to specify and direct work in areas likely to have an impact on future products. Some eight universities also conduct related research in cooperation with the PV Program.

Future products will also benefit from research results presented at the Fifth Workshop on Silicon Point Defects and Defect Processes. Defects related to the boundaries between the crystals in multicrystalline materials provide places for free electrons to recombine, reducing the energy production of the PV cell. The PV Program sponsors research to identify and compensate for defects to improve the efficiency of PV materials and cells.

Engineering higher efficiency solar cells from multicrystalline silicon has been hampered by the enigma of excessive loss of minority carrier lifetime in low-resistivity materials. The poor lifetime of charge carriers appears to be due to the level of iron impurity, according to work performed for DOE this year at the Massachusetts Institute of Technology.

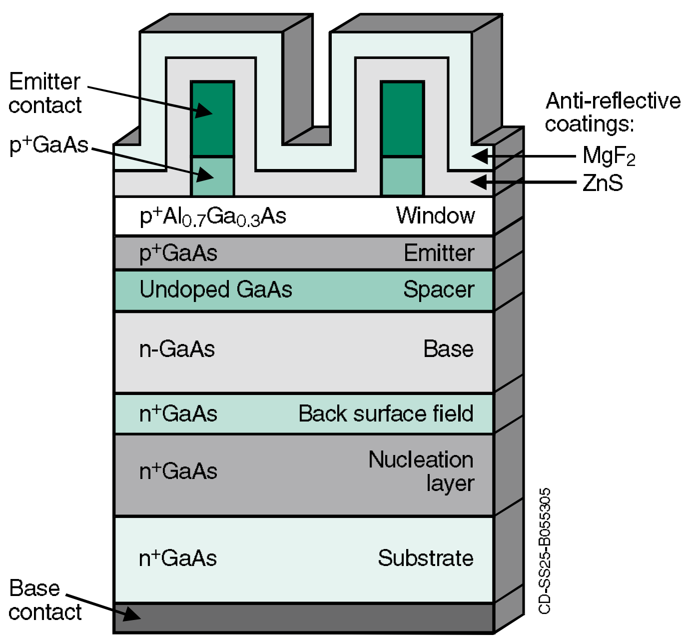
Understanding the role of iron, as well as boron, in these materials is an important step for improving the efficiency of multicrystalline materials. Now researchers can explore ways to overcome or compensate for these interactions to increase the efficiency of PV cells.

Another approach to increasing the efficiency of PV devices is controlling reflectance. The surface of a solar cell, if left untreated, can act as a mirror, reflecting the sun's energy rather than converting it to electricity. Crystalline silicon manufacturers use an inexpensive chemical process to etch the surface of the cell. But this process is not suitable for most multicrystalline materials.

A promising approach to reducing reflectance is being developed and tested in cooperation with the Crystalline Silicon Research Cooperative and Harvard University. Textured dielectric films (first developed for use in amorphous silicon cells) are deposited on the surface of silicon cells. This year the process produced devices matching the performance of conventionally produced cells. And applying a coating should be quicker and less expensive than the mechanical reflectance texturing used in production today.

Meanwhile, the crystalline silicon industry is also moving to larger cells. Companies have found that by eliminating the cost of sawing wafers into squares they do not pay much more for the glass and framing of larger modules containing voids between the cells. The integrated circuit industry is producing silicon wafers up to 500 cm^2 in area, and several PV companies now use 250-cm^2 cells, rather than 100-cm^2 cells, in their modules.

Module manufacturing capacity for the crystalline silicon industry will be expanding in 1996. Solarex Corporation, Siemens Solar Industries, and Solec have all announced plans that significantly increase the U.S. manufacturing capacity for this technology.



Research Triangle Institute, North Carolina, produced polycrystalline gallium arsenide solar cells with conversion efficiencies of 16.6% during their first year of work to apply high-efficiency technology in low-cost materials. Thin films of gallium arsenide are deposited on germanium substrates having millimeter-size grains.

Advanced Concepts for High Efficiency: Tomorrow's technology in process

High-efficiency gallium arsenide cells developed in the PV Program hold the world-record efficiency at 30.2% under concentrated sunlight. Specifically, these cells are monolithic, two-terminal GaInP/GaAs devices. In 1995, researchers made remarkable progress on the next step to develop low-cost, high-efficiency solar cells for tomorrow. They applied their understanding of high-efficiency materials to develop new 16.6%-efficient polycrystalline cells.

Researchers designed this new gallium arsenide polycrystalline cell from the bottom up, based on the physical understanding of what it takes to achieve high

High-efficiency cells made from gallium arsenide alloys being developed in the PV program hold world-record efficiencies at 29.5% for a one-sun cell and 30.2% for a concentrator cell at 180 suns.

efficiency. In addition researchers designed production processes to yield the types of materials needed, rather than beginning with a process to see what it produces.

The production method leading to this high-efficiency device shows promise for manufacturing. The 16.6% cell was made using chemical vapor deposition techniques similar to the way amorphous silicon is made, thus having the potential for large-scale manufacturing. Related projects sponsored by the program are tackling the materials challenge of producing gallium arsenide films of this morphology on glass or other low-cost substrates.

This year improvements in the PV Program's laboratory equipment should help make even more-efficient cells. By using a linear transfer line, a molecular-beam epitaxy growth chamber is being combined with a metal-organic chemical vapor deposition unit—a combination that will allow careful analysis of materials as they are grown. Using scanning tunneling microscopy, atomic force microscopy, and low-energy electron diffraction, researchers can study the atomic structure and microscopic features of a material's surface as it emerges from the growth chamber. Ultimately, this ability will lead to a better understanding of growth processes and improved high-efficiency cells.

Advanced concepts can take many forms. This year a university research contract with Johns Hopkins University yielded a photoelectrochemical solar cell that was 10% efficient. This approach takes advantage of organic dye molecules bonded to the large surface area of the cell. When light is absorbed into the titanium dioxide (a pigment used in ordinary paint), energy is transferred into the semiconductor and collected between the electrolyte-semiconductor junction. Although this novel technology is highly experimental, it has the potential for very low-cost production.

University Programs: Inspiring researchers of tomorrow

The PV Program has several activities to attract the next generation of researchers and technicians to the PV industry. For example, the Georgia Institute of Technology and the University of Delaware Institute of Energy Conversion are Centers of Excellence that operate state-of-the-art laboratories and offer courses in photovoltaic technology to engineering students.

In addition, the PV Program is committed to providing hands-on experience in photovoltaic science to students

Mike Linenberger, NREL/PIX02510

Two years of work ended for 38 teams as the latest Sunrayce solar car race was completed. DOE, General Motors, and others support the race to help college students become experts in photovoltaics and automotive technology. The race route ran from Indianapolis, Indiana, to Golden, Colorado. The next Sunrayce will take place in June 1997.

The PV Program sponsors research at seven historically black colleges and universities across the country. Sixteen students will solve problems in photovoltaic science during the 1995-96 academic year.

attending historically black colleges and universities. This year, six students advanced their interest and skills in photovoltaics through summer internships, sponsored by the PV Program, at Solar Cells, Inc., the Institute of Energy Conversion (University of Delaware), the University of South Florida, and NREL.

University students at architectural schools will have the opportunity to study how to incorporate PV into building design thanks to a curriculum developed under the PV Program. The American Institute of Architects developed materials on PV and building design. This year the course was distributed to universities across the country.

Measurements and Characterization

Each year the PV Program test laboratories at NREL and Sandia evaluate more than 20,000 components, devices, and PV materials for more than 200 different research and industry groups.

Careful testing, characterization, and evaluation is an important part of the process to improve PV systems. Tests establish benchmarks against which improvements are measured. They provide important diagnostic information to industry and researchers trying out new concepts. The world-class testing and evaluation laboratories of the PV Program provide unbiased, third-party test results against which the PV industry can validate its own measurements and measuring equipment.

As an example of the value derived from these laboratories, in FY 1995 the accumulated test results for various PV materials based on copper indium diselenide alloys were published in a reference book for the research community in that technology.

Researchers use this X-ray photoemission spectroscopy system to obtain information on chemical bonding and molecular structure of solid-state materials.

Technology Development

The PV Program sponsors work that applies R&D innovations to tomorrow's PV products.

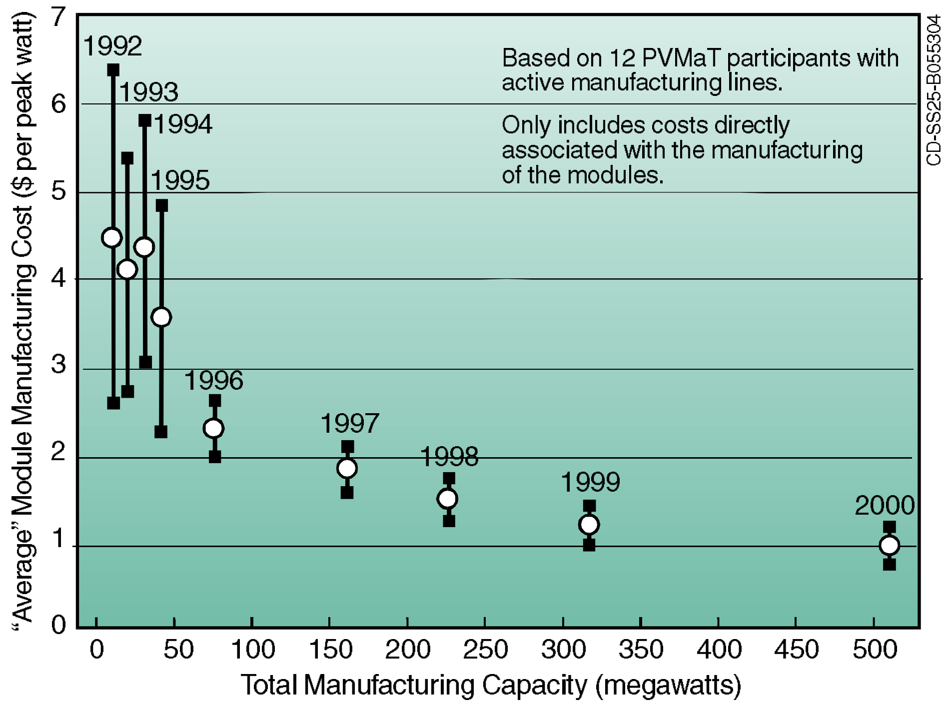
Through its collaborative technology development work with industry the PV Program modifies successful laboratory techniques to enhance the competitiveness of U.S. PV products. This year the nation's PV industry expanded production capacity, launched new products, and increased market share.

Photovoltaic Manufacturing Technology Program: From prototypes to advanced manufacturing technology

DOE initiated the Photovoltaic Manufacturing Technology (PVMaT) program in 1990 to help the domestic PV industry extend its world leadership role. This cost-shared project, conducted in several phases, supports industry to optimize manufacturing and reduce costs, thereby leading to the development of commercial PV modules and systems.

Industry accomplishments under PVMaT this year

This year several companies working under subcontracts awarded in 1992 completed their final year of research. Each company's accomplishments are unique, demonstrating that there are many ways to approach the manufacture of PV devices. In each case, the industrial partner achieved or exceeded their objectives in the project and are actively marketing products that are a



"The PVMaT program is making a positive contribution to the U.S. PV industry. Companies like Solarex are being assisted in the development of improved manufacturing technologies, taking those advances made in the laboratory and developing the manufacturing processes to increase production and lower the cost of PV products."

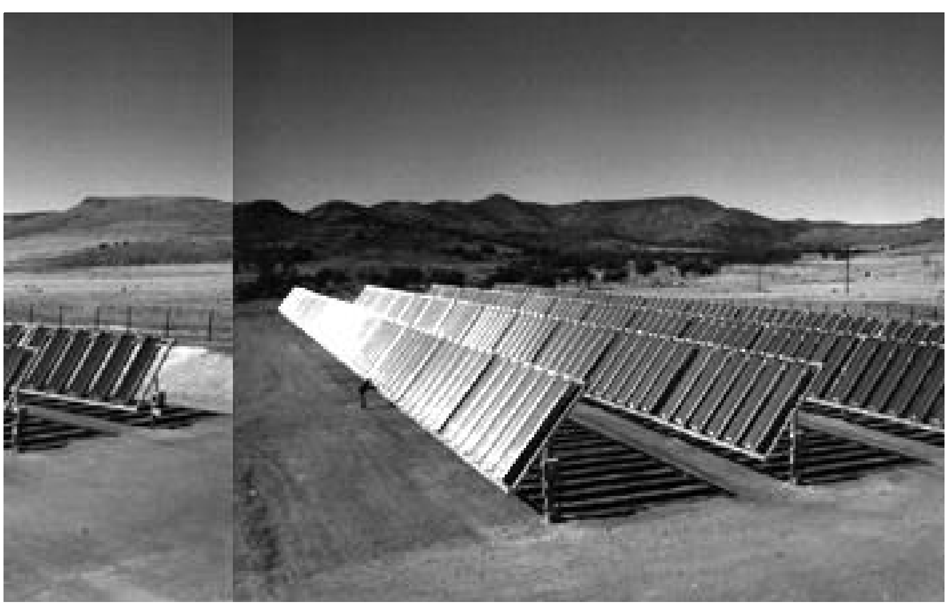
— Harvey Forest, President and Chief Operating Officer, Solarex Corporation direct result of their PVMaT research and development efforts.

AstroPower, Inc., Newark, DE, manufactures PV modules made with its proprietary polycrystalline Silicon-Film™ process. Under its Phase 2A (see box on page 15) subcontract completed this year, AstroPower developed the machine to generate sheets of a thin active-layer for the multicrystalline silicon solar cell on a low-cost substrate. The company also developed the processes for fabricating the sheets into cells and modules. AstroPower developed their laboratory-scale process into continuous sheet production capacity of 3.7 MW/year, exceeding their PVMaT goal.

AstroPower, Inc., received the prestigious R&D 100 award this year for its AP-225 solar cell, conceived and manufactured under PVMaT. The award was given because the AP-225 combines the performance and stability of conventional crystalline-silicon-based solar cells with the low cost of sheet-material production. This Silicon-Film™ product is nearly twice as large and twice as powerful as conventional solar cells.

Energy Conversion Devices, Inc. (ECD), Troy, MI, produces modules made from thin-film amorphous silicon. Under its Phase 2A subcontract, ECD developed a deposition chamber to continuously manufacture rolls of films made from multijunction amorphous silicon alloys. The chamber produces a uniform product, reduces gas utilization, improves module throughput, and reduces the amount of floor space needed in manufacturing plants.

ECD's 4-ft^2 modules have a stabilized efficiency of 8% (compared to 6% before PVMaT), whereas a triple-junction cell using this amorphous silicon technology demonstrated a 9.5% efficiency this year.



ENTECH's concentrating PV system modified under PVMaT operates reliably for the Central and Southwest Services utility in Ft. Davis, Texas.

ENTECH, Inc., Dallas, TX, manufactures PV modules that focus sunlight onto lines of solar cells made from single-crystal silicon. Under its PVMaT Phase 2A contract, ENTECH completed fourth-generation improvements in module design begun under the program's Concentrator Initiative. The company also improved production processes to reduce material and labor costs. ENTECH now offers fully tested and economically competitive concentrator PV modules for small- and large-scale applications.

Mobil Solar Energy Corporation (now ASE Americas), Siemens Solar Industries, Solarex Corporation, and Utility Power Group completed their Phase 2A cost-shared projects in FY 1994.

The companies working under Phase 2B improved their manufacturing techniques and expanded capacity.

Golden Photon, Inc., Golden, CO, is developing a new PV product based on modules made from cadmium telluride material. Under its Phase 2B subcontract, the company is scaling up its advanced production techniques for its 2-MW manufacturing facility, which began pilot operation this year.

Craig Miller Productions/PIX03500

The 1996 Summer Olympics aquatic center incorporates a 340-kilowatt PV system made by Solarex, as well as 9 kilowatts of ac modules in the visitors center. The project is cost-shared evenly among the DOE, Georgia Institute of Technology, and Georgia Power.

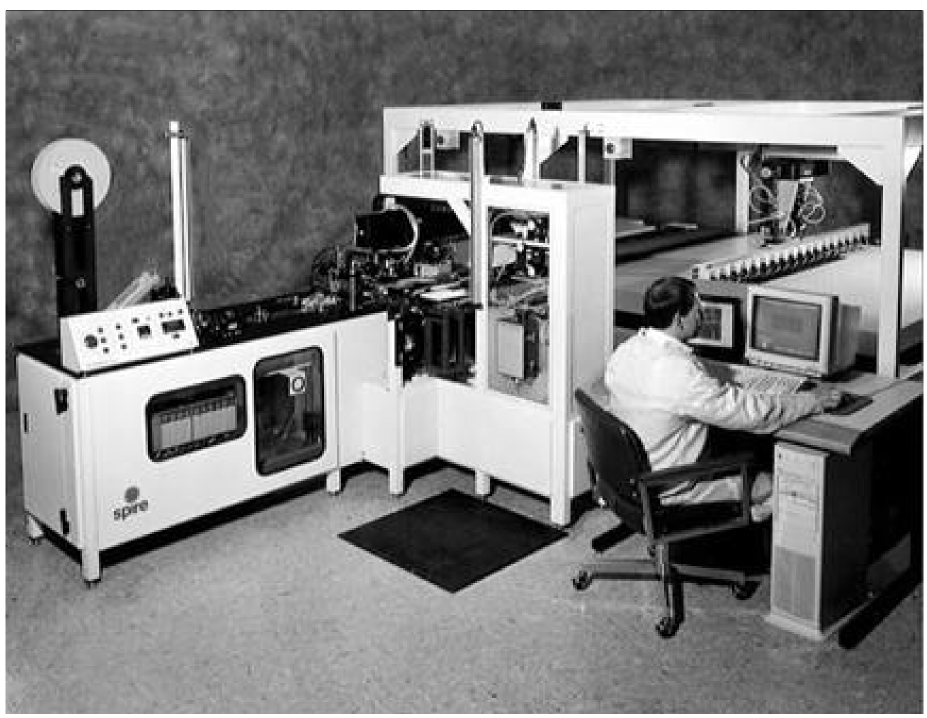
Spire Corporation, Bedford, MA, designs, fabricates, and markets automated equipment for PV manufacturers. Under its Phase 3A subcontract, Spire developed a machine that assembles and solders silicon solar cells into strings. Making cell strings is an important and time-consuming step in producing PV modules. The equipment can be programmed to accommodate the module designs of various manufacturers.

Springborn Materials Science Corporation, Enfield, CT, conducts chemical research to develop new industrial products. Under a Phase 3A subcontract, Springborn scientists sought to understand the yellowing of ethylene vinyl acetate (EVA), a substance used to encapsulate PV modules. Springborn also developed two new encapsulant formulations that have resisted all visible yellowing. After 18 weeks in their Xenon-Arc Weatherometer,

Solar Cells, Inc. (SCI), Toledo, OH, is testing a high-volume manufacturing line for PV modules made from cadmium telluride. Under its Phase 2B subcontract, SCI achieved a two-fold increase in the total module batch throughput during the last year. These are 60-cm by 120-cm pilot production modules. The research results are being incorporated into the design of a 20-MW manufacturing line.

Solarex Corporation, Frederick, MD, increased the size of ingots and wafers under its PVMaT contracts resulting in a 73% increase in capacity. A new wire saw for cutting wafers from cast ingots saves on material costs by reducing the amount of wafer that ends up as "saw dust."

The two companies working under Phase 3A subcontracts made important contributions to the PV industry as a whole.



Spire Corporation/PIX03539

The SPI-Assembler 5000, developed under PVMaT by Spire Corporation, can reduce the cost to assemble PV modules by a factor of 5 over manual assembly methods. Two U.S. manufacturers ordered this equipment in FY 1995.

Phases of the PVMaT Program

Phase 1A: Twenty-two companies identified projects to improve PV module manufacturing. All subcontracts were completed in 1991.

Phase 2A: Beginning in 1992, seven companies carried out their recommenda-tions from Phase 1 to make proprietary improvements and increase their manufacturing capabilities.

Phase 2B: Four companies continue with projects similar to those of Phase 2A. These 3-year subcontracts began in FY 1994.

Phase 3A: Two companies are addressing issues common to the PV industry as a whole. These subcontracts began in FY 1993.

Phase 4A1: This year eight companies began 2-year subcontracts to develop system and component technology for PV products.

Phase 4A2: This year five companies began 3-year contracts to address proprietary manufacturing issues to reduce costs and increase capacity of their module production facilities.

modules encapsulated in the new formulas showed no signs of yellowing, while modules enclosed in the standard EVA showed visible yellowing.

In FY 1996 Springborn will test their two new formulations with PVMaT participants. Ten manufacturers will prepare two modules for each new formulation and one control module with the old formula for a total of 50 modules. These modules will be sent to Arizona State University for indoor and outdoor testing at the Arizona Public Service STAR facility.

Product-driven system and component technology

PV modules represent about one half of the cost of a complete PV system. So the cost of electricity generated by PV can be reduced by improving the other elements of the system such as power conditioning units and trackers. Phase 4A1 of PVMaT addresses the entire PV product and the integration of system components.

Selected from the more than 30 proposals submitted to DOE for this phase of PVMaT, the following companies and their lower-tier contractors began work this year.

Advanced Energy Systems, Inc., Wilton, NH, will design, develop, produce, and test prototype 10-kW and 50-kW inverters for stand-alone, hybrid, or utility-interactive applications. The company will then plan for pilot manufacturing of these new products.

Ascension Technology, Inc., Billerica, MA, has been developing a module-scale inverter to convert the dc electricity from the PV module to ac *at the module*, allowing ac power to be used immediately at the site or fed into the grid. Under its Phase 4A1 subcontract, Ascension Technology will work with ASE Americas, also of Billerica, MA, to design, assemble, test, and certify a complete system package for the ac module.

Evergreen Solar, Inc., Sommerville, MA, will improve PV module materials and assembly methods to reduce costs associated with interconnection, module framing, and mounting the PV array.

Omnion Power Engineering Corporation, East Troy, MI, will develop a prototype 50-kW, three-phase power conversion system to specifications developed by a team of utility representatives. Reliability, conversion efficiency, and cost reductions will be achieved.

Solar Design Associates, Inc., Harvard, MA, has been developing an inverter for the ac PV module under DOE's PV:BONUS program. In Phase 4A1, the company will create a standard, certified, modular, ac PV system using Solarex Corporation's ac module.

Solar Electric Specialties, Inc., Willits, CA, will develop, test, and gain certification for two different system packages under its Phase 4A1 subcontract. One package will be a pole-mounted stand-alone PV system without a generator for backup. The second will be a 1-kW PV system with a backup generator suitable for off-grid applications.

Trace Engineering, Arlington, WA, will develop a 2-kW inverter to be used in parallel or in series, which will be highly efficient and low in price.

Utility Power Group, Chatsworth, CA, will design, fabricate, and test a tracking PV panel with an integrated power processing unit. These panels will then be incorporated into a 20-kW ac tracking array that can be expanded in 20-kW increments.

Manufacturing research and development

Following Phases 2A, 2B, and 3A, these additional contracts for PV module manufacturing research and development were issued this year under Phase 4A2.

ASE Americas, Inc. (formerly Mobil Solar), Billerica, MA, will advance the manufacturing technology for the edge-defined, film-fed growth process developed at Mobil Solar. The company should reduce wafer, cell, and module costs by at least 25 percent.

AstroPower, Inc., Newark, DE, will focus on each process component to manufacture its large-area modules and solar cells made from Silicon-Film^{TM} technology.

Iowa Thin Film Technologies, Inc., Ames, IA, will alter its manufacturing processes to increase throughput of amorphous silicon deposition, laser-scribing, and welding processes to reduce costs.

Siemens Solar Industries, Camarillo, CA, will reduce crystalline silicon module costs with changes in module designs, material sources, and processes.

Solar Engineering Applications (SEA) Corporation, Santa Clara, CA, will reduce manufacturing costs through automation and expanded production capacity of their line-focus concentrator modules.

Module Development: Improving the durability of today's and tomorrow's products

The laboratories and personnel of the PV Program work with industry to develop better modules through testing and evaluation. Module testing at the DOE laboratories supports in-house research, as well as contracts for R&D, manufacturing, and system development. In addition, manufacturers send their prototype modules scheduled for commercial production to the laboratories to confirm their own test results and receive confidential test reports.

The durability of PV modules has increased over the years. Today, manufacturers of crystalline silicon modules offer warranties up to 20 years on their products, while some thin-film modules carry 10-year warranties. This is a significant improvement over earlier generations of PV products.

With megawatts of crystalline silicon PV systems in the field for more than a decade, inevitable signs of wear have appeared on these earlier products. The PV Program works directly with manufacturers and with cooperative groups in industry to understand the mechanisms of wear. They work to devise new techniques and materials to prolong the life of PV systems and improve new products.

After crystalline modules are assembled they are sealed against moisture and dust using a coating called an encapsulant. The encapsulant must withstand prolonged exposure to the sun's ultraviolet radiation and the mechanical stresses of temperature changes and precipitation.

The PV Program is working with industry to understand and avoid problems that appear in about 2% of earlier generation modules. The first problem—delamination—is partial separation of the encapsulant from the solar cells underneath. Performance can decline as much as 5% in delaminated modules, and if moisture accumulates inside the module this could cause other problems as well. The second problem—discoloration—can also reduce module performance if the encapsulant allows less of the sun's energy to pass through to the solar cells.

When developing new encapsulants, both issues must be addressed. The PV Program, through in-house analyses and cooperative research with PV companies, universities, and Springborn Materials Science Corporation, has been evaluating the discoloration of the encapsulant ethylene vinyl acetate. Program researchers demonstrated that chromophores generated during curing are a principal cause of the premature yellowing of EVA. New curing techniques and new chemical formulas that will not discolor were developed. In FY 1995 several new formulations for encapsulants underwent accelerated testing and have resisted yellowing. These will be available to the PV industry in FY 1996.

The PV industry is also working cooperatively to make modules more durable. Delamination in crystalline silicon modules is being explored by program researchers, the Florida Solar Energy Center, Siemens Solar Industries, and Springborn Materials Science Corporation. For example, Sandia and the Florida Solar Energy Center measured how strongly the encapsulant adhered to cell interfaces on modules taken from the field. These adhesion tests were also performed on small sections of modules supplied by Siemens right off the assembly line. These and similar tests should help ensure that new encapsulant formulations have good adhering properties.

Another durability issue is the long-term integrity of solder bonds. Evaluations of old modules taken from the field showed that solder bonds on the backs of modules were cracking and becoming more resistive. As bonds slowly degrade, module performance declines until the circuit opens up and output stops. Metallurgy specialists are evaluating this failure mechanism—common in all electronic equipment exposed to temperature fluctuations—for recommendations in FY 1996 to improve durability.

The long-term durability of thin-film modules is being explored at the program's outdoor test facility in Golden, CO, and by members of the PV industry. Program researchers have monitored the performance of prototype thin-film technologies for up to 10 years. In FY 1995 temperature coefficients and their effect on output were explored and reported at the program's Photovoltaic Performance and Reliability Workshop. In addition, research contracts with Solarex, Siemens Solar Industries, Colorado State University, and others help clarify durability issues and develop solutions.

Battery tests sponsored by the PV Program at Sandia Laboratories helped define appropriate charge and set points and predict battery maintenance intervals in PV systems.

Sandia/PIX03638

Balance-of-systems (BOS): Addressing the other half of the PV system

Through a combination of in-house R&D, testing, and cooperative research contracts, the PV Program is working to reduce the costs and increase the reliability of the non-module components of the PV system.

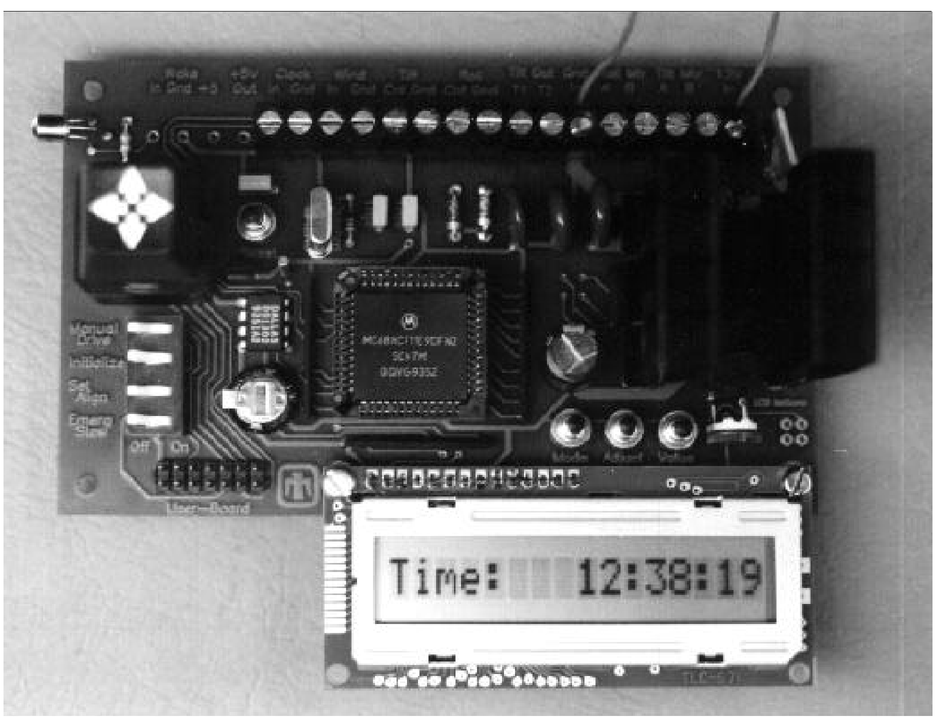
This year, the PV Program awarded several new contracts for balance-of-system (BOS) research and development, in addition to the work under PVMaT directed at non-module components. The program also conducted tests on BOS components destined for projects in federal agencies.

An important part of PV systems is power processors and system control hardware. PV Program testing of these components supports the industry in general and several projects in particular such as military installations, utility projects, and international projects. For specific projects, acceptance testing in the program's unique laboratory ensures that power processors meet manufacturers specifications. Once relevant specifications are met, the hardware is shipped to the project for installation. Over the years program personnel will assess the reliability of the systems.

Hybrid systems—those containing two or more electric-generating technologies—are an important market for PV systems. Integrating the components of hybrid systems so that they work well together is a complex activity with little operating experience for designers to draw on.

The PV Program set up a test bed that simulates a small village. The test bed is used to test inverter performance and to develop control logic based on actual operation. The set-up has lead-acid storage batteries, a diesel generator, and a PV array that feeds the system. The load bank is programmed to simulate the weekly load profile of a small village. During tests, researchers work collaboratively with industry to evaluate resistive, reactive, non-linear, and transient loads (such as motors).

In FY 1995 tests were completed on large hybrid inverters from Abacus Controls and Omnion Power Engineering Corporation, as well as on a number of smaller grid-tied, hybrid, and stand-alone inverters.



Sandia/PIX03637

An array structure that moves the PV modules to follow the sun can increase annual energy capture by 30 percent. This microprocessor-based controller called SolarTrak was developed by the PV Program and is licensed for use in several commercial PV products.

The PV Program is also working to coordinate information among makers of charge controllers and batteries to improve reliability and lower costs. Charge controllers are electronic devices that control how the battery in a PV system is charged. The way charge controllers operate has a significant effect on the life of batteries. Charge controllers must be durable and responsive, and they must integrate a controller logic appropriate to the unique operating environment of the PV application. This year the program completed the second round of testing with Digital Solar Technologies for a microprocessor-based PV charge controller destined for use in large PV telecommunications systems. In another project, Morning Star Corporation developed a pulse-width modulated charge controller that will cost less than $30 for use in small PV systems up to 10 amps at 12 volts.

The PV Program works with manufacturers of charge controllers to improve how they operate. In addition to several research contracts, the program tests charge controllers with equipment that most manufacturers do not have. The program documents the behavior of batteries when they are charged by PV. Test results should help improve this important part of the balance of systems for PV.

Other BOS products were developed for the program under contract this year. For example, Trojan Battery in conjunction with Sandia designed a deep-cycle battery with 40% more electrolyte. More electrolyte means less frequent battery maintenance in PV applications. In another project, Mor Lite designed a more-efficient ballast and fixture for PV lighting systems. Lighting systems designed specifically for PV-powered batteries perform better than those designed for other applications.

Systems Engineering and Applications

The PV Program supports projects that validate PV technology for world markets.

Through systems engineering activities, the PV Program works with industry to address design issues, measure the performance of emerging technologies, and develop standards and certification programs. Applications research deploys prototype PV technologies to validate their performance in specific applications.

Systems Engineering: Objective measurements and standards

Systems engineers and analysts in the PV Program evaluate power and energy production, to support industry and DOE cooperative research and technology development contracts.

This year, a major addition to the program's laboratory capabilities went into operation—the Outdoor Test Facility (OTF). This building is designed specifically to serve the testing needs of PV Program researchers and industry. The facility has state-of-the-art equipment for controlled indoor testing and measurements. In addition, researchers in the OTF monitor module and system experiments conducted at the adjacent field site. Underground cables for data acquisition connect the test area to the OTF control room. Researchers can perform accelerated and exploratory tests and measurements.

The OTF has several new capabilities for the program. For example, better module diagnostics and failure analysis are possible with all the tests performed under one roof. The OTF also has large-area simulators that apply pulse or continuous light sources to modules. Modules up to 6-ft by 8-ft, small panels, and even arrays can be operated under simulated conditions and their performance evaluated.

The amount of energy a PV module generates during a period of time at varying conditions may be more important to the user than the peak power ratings currently furnished. The PV Program has subcontracts with Endecon Engineering of San Ramon, CA, to help develop a module energy-rating method that will lead the industry to consensus on this issue.

Measuring the output of commercial modules at Sandia's outdoor test facility has led to a system characterization method of potential use to owners of large PV systems. The new system characterization model, which began validation testing in FY 1995, can predict energy output for a specific PV system at a specific site, using inputs for time of day, measured temperature, and measured irradiance. After further validation testing in FY 1996, this tool will be used by the military to monitor their PV systems installed under the Strategic Environmental Research and

Warren Gretz, NREL/PIX01990

At NREL's Outdoor Test Facility, photovoltaic modules and systems made by various manufacturers and using various technologies are tested and monitored under actual weather conditions, as well as under controlled laboratory and accelerated weathering conditions.

Greg O'Loughlin, Southern California Edison/PIX03690

Utility planners were surprised that PV made the most sense in certain older residential areas with overloaded underground circuits. Installing PV at Monterey Hills Elementary school made digging up and replacing overburdened circuits unneccessary.

Development Project and by utilities installing systems with the Utility PhotoVoltaic Group.

Standards of performance for PV systems can help establish consumer confidence. The experts in the PV Program are an important resource to organizations developing standards and codes. DOE's Third Photovoltaic Standards and Codes Forum brought together committees from several standards groups, enabling them to complete several important projects. For example, representatives from PV manufacturers, utilities, and research and testing laboratories reached consensus on standard procedures for module qualification testing. This standard, when approved by the Institute of Electrical and Electronics Engineers (IEEE), will serve the PV industry as the U.S. standard. Other workshop attendees completed a major revision of the American Society for Testing and Materials standard for measuring module and array performance.

The PV Program staff developed a draft procedure for determining system ratings and acceptance this year. At present there is no U.S. laboratory accredited to certify the performance of PV systems. U.S. manufacturers have had to go overseas for this service.

In addition, the PV Program supported Arizona State University to develop guidelines for accrediting laboratories to certify PV module performance. The effort also generated criteria for certifying PV modules. The report published this year, *Photovoltaic Module Certification/Laboratory Accreditation Criteria Development*, recommends the testing required for a module design to be certified, the criteria for accrediting a test laboratory, and a model for a U.S. PV certification program.

Another form of certification, Underwriters Laboratories (UL) listing, of PV products is an important step in an expanding marketplace. The PV Program worked with Omnion Power Engineering Corporation to gain UL approval for its 4-kW inverter. UL does not currently have a standard for testing PV concentrator technologies. Sandia, manufacturers, and UL staff are working to develop a test standard based on UL's standard for flat-plate modules and Sandia's concentrator test document.

PV Program specialists are also working with various standards groups. For example, the *IEEE Guide for Terrestrial PV Power Systems Safety* is being written for single-phase and three-phase systems up to 50 kW in size. Others include *IEEE Recommended Practice for Determining Performance Characteristics and Suitability of Lead-Acid Batteries in PV Systems*, *IEEE Recommended Practice for Field Test Methods and Procedures for Grid-Connected Photovoltaic Systems*, and *National Electrical Code*. Consensus standards will help PV companies demonstrate product performance and durability, especially for utility markets. The National Electrical Code for acceptance of systems is important for building inspectors and electrical inspectors to approve PV system installations.

Photovoltaic Applications: Validating PV technology worldwide

The PV Program works with industry and potential users of PV systems to validate the benefits of PV in specific applications. This year projects with utilities, federal agencies, the buildings industry, and foreign governments generated information neccessary to expand these markets for U.S. PV products. Several follow-on projects promise additional benefits for the domestic PV industry.

PV for utility applications

Electric utilities represent a large existing market for PV systems, and the potential for future utility applications for lower-cost systems is tremendous.

Activities continued in FY 1995 aimed at developing sustainable markets for both grid-connected and grid-independent PV applications of benefit to electric utilities and their customers. In one of these activities, Southern California Edison installed PV to relieve the stress on overburdened circuits in residential neighborhoods.

To avoid upgrading an overloaded circuit, Southern California Edison installed a pilot project on Monterey Hills Elementary School this year. In FY 1996, the utility plans to install PV at three other public buildings. In all, the utility expects to install 500 kW of PV under its Solar Neighborhood

Program, with support from DOE. The projects will all be monitored and assessed so that the benefits of this application can be evaluated by other utilities.

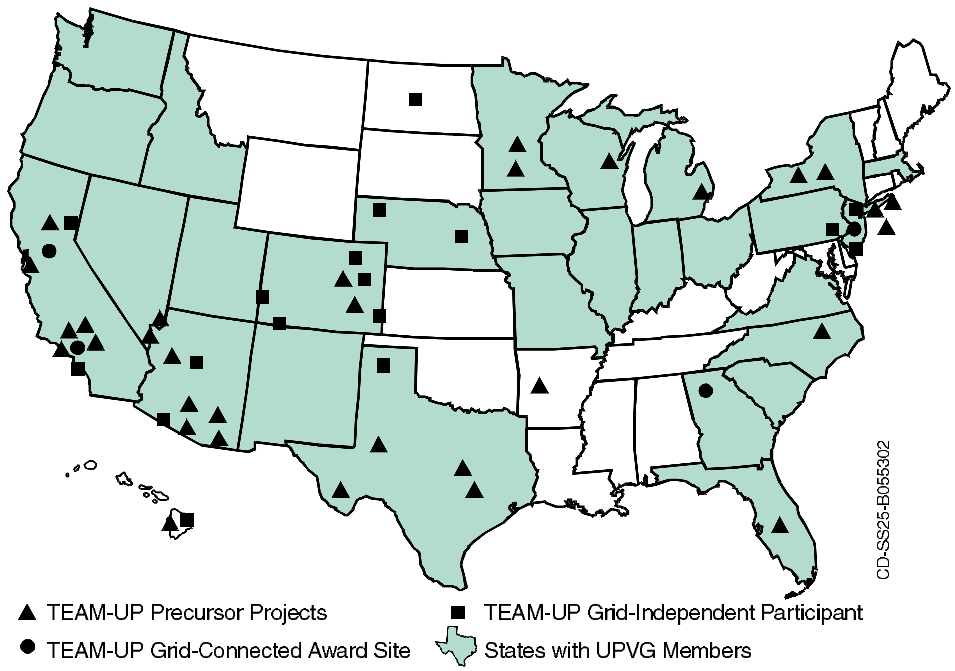
Another California utility, the Sacramento Municipal Utility District, installed PV projects totalling 934 kW in FY 1995 as part of a multiyear DOE commercialization effort for grid-connected PV. Three rooftop PV projects and three systems at utility substations began operations this year. A project review committee ensures that information on the system is collected and eventually disseminated to other utilities.

Utility PhotoVoltaic Group (UPVG)

In 1992, a group of utilities particularly interested in PV and its potential for large-scale power generation formed UPVG to accelerate cost-effective PV applications to benefit electric utilities and their customers. Its members now include nearly 90 utilities, the Electric Power Research Institute of Palo Alto, CA, as well as the American Public Power Association, the Edison Electric Institute, and the National Rural Electric Cooperative Association, all of Washington, D.C. Collectively, the member utilities of UPVG represent more than 40% of total U.S. electricity sales. The activities of UPVG are funded through membership fees and a grant from DOE's PV Program.

"The utility industry is changing and utilities are looking for new business opportunities in this more competitive environment. Photovoltaics provides one of these opportunities."

— Christine A. Ervin, Assistant Secretary for Energy Efficiency and Renewable Energy, U.S. DOE.



A 6-year program to install PV at these locations has been proposed by the Utility PhotoVoltaic Group for cost-sharing with the U.S. Department of Energy. TEAM-UP stands for Technology Experience to Accelerate Markets in Utility Photovoltaics.

For FY 1996, UPVG plans to support thirteen grid-connected PV applications projects. These projects are designed to validate PV in a variety of utility applications. Data from the projects will be widely circulated to promote further installations of PV by utilities.

Several other activities, supported in part by DOE, are promoting deployment of photovoltaics. The National Association of State Utility Consumer Advocates directs a Photovoltaic Education Project. The Pace University Law School conducts Renewable Energy Technology Analysis aimed at quantifying the indirect benefits of PV such as avoiding harmful emissions and increasing utility system reliability. And the PV4U state working groups bring together diverse organizations within a state to influence legislation, encourage utilities to consider PV, and provide information to decision makers.

PV for Utility-Scale Applications (PVUSA)

Early in 1986, several utilities, DOE, a state government, and some local governments joined together to install, operate, and monitor PV systems connected to a utility grid. So far, the PVUSA program has purchased and installed more than 1,700 kW of PV at test sites around the country. PVUSA operates a main demonstration site in Davis, CA, where systems using state-of-the-art module technologies and utility-scale systems feed electricity into the grid. Several additional PVUSA systems are operated at host utilities across the country. PVUSA also cooperatively monitors other PV systems of utility interest.

In 1995 the PVUSA project continued to demonstrate new module technology for utility-grade PV generating systems. A new 10.8-kW system using cadmium

Two new PV arrays from Solar Cells, Inc., and Amonix Corp., were added to the PVUSA test facility at Davis, CA, this year.

telluride thin-film technology was supplied by Solar Cells, Inc., to the Davis demonstration site. In addition, two systems incorporating concentrator technologies were installed in 1995 under PVUSA. A high-concentration (260x) PV array nominally rated at 19 kW was installed at Davis by Amonix Corporation, Torrance, CA. Central and Southwest Services, a utility in Ft. Davis, TX, also purchased a 21x linear concentrator system from ENTECH Corporation of Dallas. The nominal 83-kW system will be monitored as a PVUSA system.

PVUSA installed the first PV system to validate grid-support at the Kerman substation near Fresno, CA, in 1993. Electricity from the nominal 498-kW PV system helps offset afternoon peaks in electrical demand at the substation and effectively reduces the load on the substation. The data from this test have been combined with later grid-support applications of PV to show utilities how this application could benefit their activities.

Developing tools for utilities

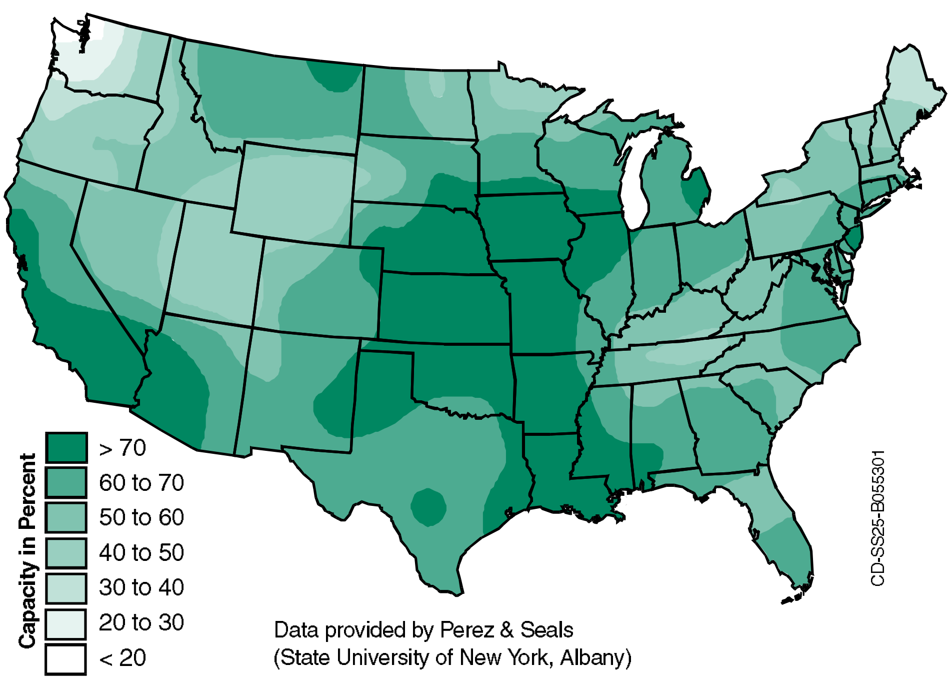
In FY 1994, PV Program analysts concluded a five-utility study on the potential for distributed PV. From their extensive calculations, the analysts developed a simplified technique to determine where PV has value in a distributed application such as grid support or preventing voltage sag at the end of long lines. Whereas each of the original studies required months of effort from several experts, the new QuickScreen technique can be performed by one person (with access to the utility's basic economics) in half a day. An experienced user can perform a QuickScreen analysis in less than an hour.

The simplified analysis was performed for the original utilities studied, and the results varied by less than 10% from the original analyses. About 40 utilities are now using the prototype version of QuickScreen. After fine-tuning in light of utility comments, QuickScreen will be available in FY 1996 to utilities interested in distributed applications of PV.

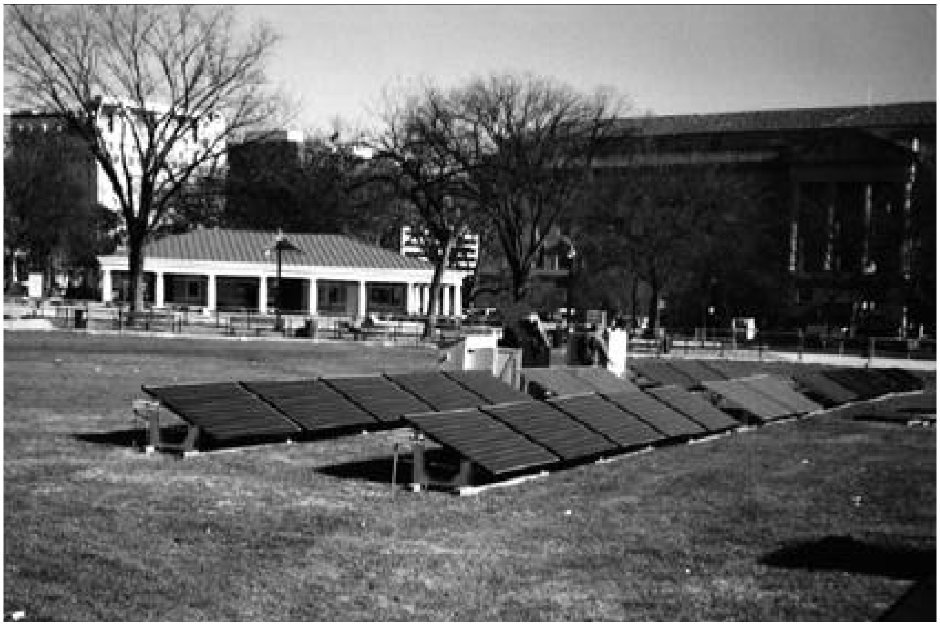
PV for federal agencies

By assisting other federal agencies in their PV projects, DOE effectively leverages its funding to achieve wider opportunities for validating PV technology. Technical assistance from the PV Program promoted 25 projects this year, paid for with funds from other government agencies.

In FY 1994 , the National Park Service and DOE collaborated to assess how PV was being used in the parks, how well it was performing, and where more PV made sense. In FY 1995, several projects identified during the study as having high value and low obstacles were well



The PV Program evaluated the match between actual utility load and the projected output of a PV system for more than 40 utilities across the United States. This map shows the distribution of the effective capacity of PV in the United States, assuming a 2-axis tracking system and 2% PV penetration into the utility grid.



John Thornton, NREL/PIX03614

PV Program personnel, working with several other agencies and U.S. PV companies, arranged for this PV array to help power the National Christmas Tree during the Pageant of Peace in FY 1995. Thousands of visitors witnessed the system's operation during the festival.

under way. For example, PV Program personnel assessed the Chaparral area of Pinnacles National Monument in California. They recommended a hybrid PV system, high-efficiency loads, and conservation to reduce existing electrical loads. DOE then assisted in specifying a 10-kW PV-engine hybrid system, which includes a 20-kW propane generator that will replace two 100-kW diesel generators and eliminate the use of diesel fuel at Chaparral.

In FY 1996, twelve more pilot projects are planned for parks, including Grand Canyon, Rocky Mountain, and Yosemite National Parks.

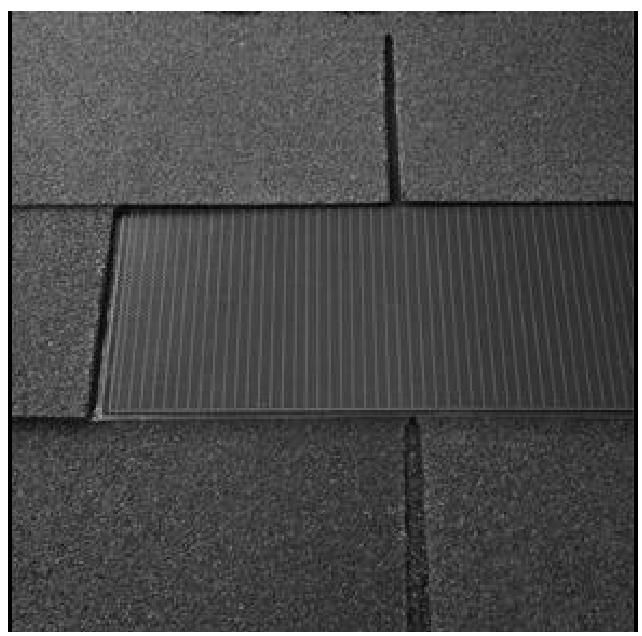
The U.S. Forest Service also has many PV systems operating at its facilities across the country. After a survey similar to the one conducted for the parks is completed, pilot projects to expand the use of PV by the Forest Service will get under way in FY 1996.

The U.S. Bureau of Land Management, an agency that administers 12% of the total U.S. land area, is expanding recreational facilities on its lands. These facilities will require power. To help ensure that some of that power is generated with the sun, PV Program personnel will survey more than 60 districts in 13 state offices. As with the parks and forests, the project with the Bureau of Land Management aims for pilot projects that expand the ways in which PV is used in the agency.

The military, as an agency with a potential of more than 3000 MW of possible projects, is a huge market for PV systems. Sandia engineers, who also work in the PV Program, are assisting the military in installing PV systems for the Strategic Environmental Research and Development Project (SERDP). This project, which has identified cost-effective applications of PV within the military, is funded cooperatively by the Environmental Protection Agency and the Department of Defense. Through SERDP, Sandia is helping the U.S. Marine Corps, Navy, and Air Force to specify, design, and install large (75-kW to 300-kW) PV systems at military bases around the country.

PV integrated into buildings

Buildings consume nearly two-thirds of the electricity generated in the United States, and there are many ways that PV technology can provide some of this electricity. In addition to large generating stations located in rural areas, PV can be incorporated right into building structures to generate electricity for use in the same buildings. Promoting the interaction of industries to develop PV building products is the goal of DOE's Building Opportunities in the U.S. for PV, or PV:BONUS.



United Solar Systems Corp./PIX03636

The shingle modules developed under PV:BONUS by Energy Conversion Devices, Inc., blend so well with conventional roofing that they can be used on new homes where covenants would prohibit more typical PV modules.

This manufactured home, designed by FIRST, Inc., was assembled at the site with all features in place to accommodate the PV system.

Under PV:BONUS, teams are working to develop PV products for buildings. Each team contains several organizations representing groups like building materials manufacturers, building contractors, PV suppliers, utilities, colleges, system designers, architecture and engineering firms, and building owners. The objective of these efforts is to develop products that will introduce PV into markets other than conventional ground- or roof-mounted systems.

For example, PV systems that double as electrical generators and roofing material have extra value to the building owner. One PV:BONUS team, led by Energy Conversion Devices, Inc. (ECD), is developing flexible, lightweight roofing materials and has tested a PV shingle that can replace asphalt shingles. The shingle module is being installed on a house being built for the 1996 Summer Olympics in Atlanta, GA, by United Solar Systems Corp., ECD's joint venture partner.

Another project, led by Fully Independent Residential Solar Technology, Inc. (FIRST), of Hopewell, NJ, focuses on incorporating PV products into the increasingly popular modular, manufactured house. Modular houses are constructed in a factory and assembled at the building site. The PV:BONUS team incorporated PV systems into two prototype modular homes in FY 1994. In FY 1995, the first six PV modular homes were built and sold, each located in a different utility service area in northeastern states. In FY 1996, nine townhomes will be designed and constructed in a low-income housing project in Philadelphia. Work also continues to develop new roof-integrated modules for this application.

Today's PV modules produce direct current (dc) electricity, which must be converted to alternating current (ac) for buildings connected to utility power. The need for this conversion complicates building design and adds cost. Therefore, a PV:BONUS team, led by Solar Design Associates, is applying advances in power electronics and integrated circuits to deliver utility-grade ac power from the back of individual PV modules. The team tested five of these prototype PV devices in FY 1995. In FY 1996, 9 kW of ac modules will be installed at the entrance to the aquatic center for the 1996 Summer Olympics. The ac module team will continue its work to reduce the cost of the product under a PVMaT manufacturing contract.

PV for international applications

In 1994, more than 75% of this country's PV production was exported. The export market, mostly in developing countries, is the fastest-growing PV market today. And much of this market will be for the more than 2 billion people currently living without electricity. Often these people require only small amounts of power for indoor lighting, water pumping, and refrigeration. Building or extending the electric grid or providing power by other means such as with diesel generators is not economical in these cases. Even at today's prices, PV can be the most cost-effective source of electricity, once organizations for its sale, installation, and maintenance are in place. The PV Program sponsors activities to validate PV technology and to establish the organizational and institutional connections for the sale, installation, and maintenance of U.S. PV products.

South Africa

South Africa has been identified as one of the 10 largest emerging markets for U.S. PV exports. Because a main obstacle to development in South Africa is energy distribution to remote regions, and because sunshine is the area's most abundant resource,photovoltaics has a bright future there. In 1995, that future seemed closer than ever as Energy

"[This PV module assembly plant] means jobs for South Africans as well as Americans who are a part of these joint ventures."

— Energy Secretary Hazel O'Leary, at the dedication of Suncorp Manufacturing in Johannesburg, South Africa.

DOE/PIX01994

In a joint venture between Spire Corporation of Bedford, MA, and Suncorp Manufacturing, a black-owned South African business, an assembly plant was constructed that produces enough PV modules in one year to light 30,000 homes in South Africa.

Secretary Hazel O'Leary helped dedicate a PV module assembly plant in Johannesburg.

The joint venture will begin by producing almost 5,000 modules in its first year, using solar cells manufactured in the United States. And besides the manufacturing jobs, the venture will create 250 jobs in marketing, sales, installation, and maintenance in South Africa. The PV Program played a key role in bringing this PV module assembly plant on line by providing project management, logistical support, and technical guidance to the project.

Brazil

The Federal Republic of Brazil and DOE began working together in 1993 to bring electricity to rural communities in Brazil by installing PV systems. In the first phase of this pilot project, Brazilian utilities in two states and the national ministry of energy (known as CEPEL) installed PV lighting systems in 750 homes and 14 schools in rural northeast Brazil. The local utilities maintain and evaluate the systems.

After utilities in five additional states asked to participate in the project, DOE and CEPEL expanded the electrification program into the northeast and Amazon regions of Brazil. Phase 2 projects include additional applications such as water pumping, telecommunications, and refrigeration. Furthermore, two village power systems are being installed that use more than one source of power, from PV, wind, and diesel fuel, for example. The village power systems have a large enough capacity to supply the minimal electrical needs of a small village.

Mexico

Studies suggest that within the next 12 years Mexico will require 28 gigawatts of new electric power generation. Today, some 100,000 rural villages in Mexico have no electricity, and extending the electric grid to these villages would be very costly. The PV Program is working with the U.S. Agency for International Development and several Mexican states to share the cost of PV pilot projects for important applications. For example, in the state of Sonora, the PV Program will provide technical assistance for agricultural water pumping projects. In the state of Chihuahua, DOE will share the cost of projects for water pumping, irrigation, refrigeration, ice making, communications, and facility power. In addition, Sandia is working with the World Wildlife Fund, Conservation International, the Nature Conservancy, and local Mexican organizations on pilot projects to demonstrate renewable energy in environmentally sensitive areas and for the buffer-zone communities around them.

Roger Taylor, NREL/PIX01270

In Cacimbas, Ceará, Brazil, 50-watt PV systems provide homes with electricity for fluorescent lighting.

The World Bank

Many energy projects have been financed in developing countries and, increasingly, renewable energy projects are gaining the attention of lenders at the World Bank organizations. The International Bank for Reconstruction and Development (World Bank) has issued loans in excess of $300 billion to governments and government agencies, supporting more than 6000 development projects in about 140 countries. The International Finance Corporation, a member of the World Bank group, finances private-sector projects in developing countries through syndication and equity investments in projects.

Information is a valuable asset for lenders and borrowers alike, and the PV Program works with units of the World Bank and organizations within borrowing countries to clarify the technical status, costs, and benefits of U.S. photovoltaic technology. For example, PV Program personnel are contributing to a study of renewable energy in China conducted by the World Bank in partnership with the State Economic and Trade Commission and the Energy Research Institute of the State Planning Commission in Beijing. Meanwhile, a Memorandum of Understanding is being developed between DOE and the World Bank for analyses of many renewable energy technologies being considered for developing countries.

India

Last year, a presidential mission to India resulted in more than $1 billion in commercial deals for the U.S. PV industry and several major governmental agreements. This year, two follow-on missions boosted the number of agreements between U.S. and Indian companies even more.

In addition to commercial agreements, DOE and the Indian Ministry of Non-Conventional Energy Sources (MNES) identified several rural electrification initiatives for PV use. The first two got under way in FY 1995. DOE is procuring PV systems from U.S. vendors for water pumping, street lighting, home lighting, and solar lanterns headed for Dhanawas, Haryana. In the second project, DOE will buy more than 300 PV lighting systems, as well as systems for refrigeration, spice grinding, water pumping, and battery charging to be deployed in Sudarbans, West Bengal. In Sudarbans DOE is working with the Ramakrishna Mission—a well-respected humanitarian organization—that will support the installation and maintenance of the systems.

These projects will validate U.S. PV technology to provide electrical power to villages. For these applications, the technology, structures for installing and maintaining systems, and methods of collecting revenues from users will all be validated. Information on the project will be presented to agencies, such as the World Bank, that are in a position to finance additional projects.

Russia

A new partnership got under way in 1995 between the U.S. government, U.S. private industry, and a Russian state enterprise. The partnership will soon have Russian scientists and engineers using their talents to make solar modules instead of military equipment. The PV Program is providing technical assistance to help start up a photovoltaic manufacturing plant in Moscow. The Sovlux facility, owned jointly by Energy Conversion Devices of Troy, MI, and Scientific and Industrial Enterprise KVANT of Moscow, will make thin-film amorphous silicon modules.

The project is part of a joint DOE and U.S. Department of State program to help Russian scientists and engineers apply their expertise to non-military applications having commercial benefit. With financing from KVANT, Energy Conversion Devices designed and built the plant in Michigan, then shipped it to Moscow for construction in 1993. However, when the Soviet Union was disbanded, funding ran out before the facility became operational.

To get the facility on line, the PV Program awarded KVANT a 7-month contract in FY 1995 and signed a cooperative research and development agreement (CRADA) with Energy Conversion Devices, with funding from the joint DOE/Department of State program. Under the CRADA, PV Program personnel will provide technical assistance for the start-up. For example, the first materials, cells, and modules to be produced will be sent to the United States and subjected to the sophisticated testing available only in the national laboratories. Results will help factory engineers adjust the equipment to produce the highest-quality product possible.

By 1996, the factory should be able to produce up to 2 MW of solar modules annually for sale in Russia and the surrounding republics. And Energy Conversion Devices, a U.S. company, will reap 50% of the benefit of this potentially huge market, thanks to a little push from DOE and the State Department.

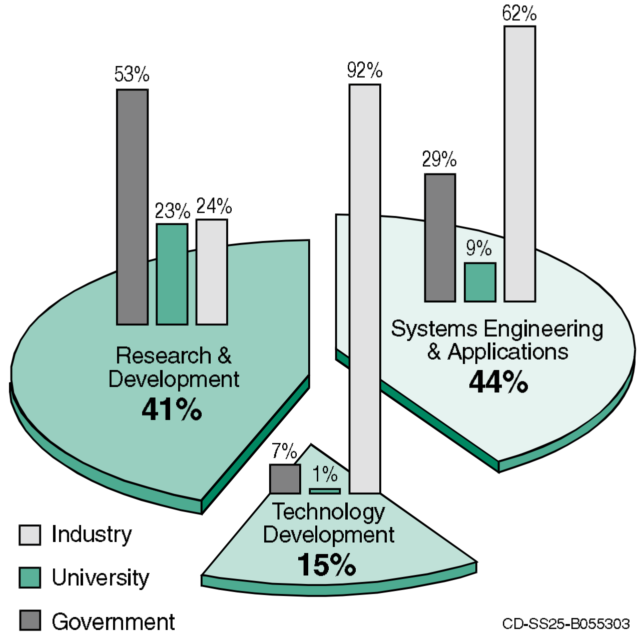
The above examples highlight some of the PV Program efforts to facilitate overseas markets for U.S. PV products. Various efforts are also under way to promote PV projects in China, Egypt, Indonesia, and Central and South America.

These activities—aimed at improving PV systems and enhancing the markets for PV in utilities, federal agencies, and international applications—are part of DOE's balanced strategy to make PV an important part of the U.S. economy.

Program activities continue to advance the technology base through research and development. Advances and innovations are incorporated into new products through technology development. And systems engineering and applications activities help validate PV technology for expanding markets. Continuing efforts in FY 1996 will maintain the momentum and continue progress on each of these fronts.

Program Resources

The PV Program distributes funding within the program elements and supports the U.S. PV industry through the researchers and facilities of the national laboratories.



The distribution of the National Photovoltaic Program budget for FY 1995.

The resources of the federal PV Program are available to the U.S. PV industry to advance its products. The PV Program directs research at the National Renewable Energy Laboratory and at Sandia National Laboratories. Brookhaven National Laboratory in Upton, NY, supports the program in environmental, safety, and health research, while DOE field offices help manage research contracts.

National Renewable Energy Laboratory

The National Renewable Energy Laboratory (NREL) in Golden, CO, was established by Congress as the nation's primary center for renewable energy research and development. NREL staff members are responsible for most of the fundamental, supporting, and materials research conducted under the program. Module and systems engineering and development, in collaboration with industry, and applications and market development are other important activities.

NREL manages PV-related R&D activities conducted in house and through subcontracts with universities, other research centers, and both small and large businesses. These activities include cost-shared, multiyear government-industry partnerships, national team-research efforts, and technology initiatives.

Research teams investigate a wide variety of promising semiconductor materials and devices, and basic research at NREL includes investigations that explore the physics governing the behavior of solid-state photovoltaic materials. NREL's scientists also support the PV Program with device measurements, cell modeling and fabrication, and characterization of materials and devices using advanced measurement equipment and techniques.

NREL also conducts simulated and actual outdoor tests on cells, modules, and arrays for industry. Test data help to improve PV devices and modules and to develop performance criteria and standards for the PV industry. Solar radiation data are compiled to help create computer models, which are critical to designers and manufacturers of solar systems, and instrument calibrations are provided in accordance with national and international standards.

Sandia National Laboratories

Sandia National Laboratories in Albuquerque, NM, is a multiprogram R&D laboratory of the U.S. Department of Energy. Sandia is responsible for addressing the technical aspects of national security issues, which include energy-supply security and weapons research and engineering. It has the broadest range of energy-related R&D activities, gathered at one laboratory, in the nation; Sandia's researchers work on solar, wind, fossil, geothermal, and nuclear energy technologies.

Under the National Photovoltaic Program, Sandia is principally responsible in assisting industry in developing crystalline silicon cells, concentrating collectors, and systems and balance-of-systems technologies. Although these activities vary greatly in scope, the emphasis in each is to work with industry and users to accelerate the development and acceptance of PV technologies.

These R&D activities are designed to help the industry develop cost-effective commercial products more rapidly than it could alone. Cell research activities support promising new concepts and provide valuable services through the Photovoltaic Device Fabrication Laboratory. Indoor and outdoor measurement and evaluation facilities support industry in the measurement, evaluation, and analysis of PV cells, modules, and systems.

Systems-level work at Sandia concentrates on applications engineering, systems engineering and performance, and technology assistance to overcome the remaining technical and institutional barriers to full market acceptance of PV technologies. Sandia's Design Assistance Center distributed more than 17,000 technical assistance publications in FY 1995.

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