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“The mission of the U.S. Department of Energy Photovoltaics Program is to make photovoltaics a significant part of the domestic economy, both as an industry and as an energy resource.”

Cover photos: 1.—DOE researchers use state-of-the-art instruments, such as this atomic processing microscope, to characterize solid-state materials (Jim Yost Photography/PIX02032). 2.—The walkway into the Olympic aquatic center is constructed from PV modules that each have its own tiny inverter to convert dc electricity to standard ac power (Bruce Green, NREL/PIX04565). 3.—PV can be used in many ways to reduce electrical loads created by buildings. These PV shingles, developed with support from DOE, can take the place of regular asphalt shingles (Energy Conversion Devices/PIX04566). 4.—In this hybrid power system, a 77-kilowatt PV array helps reduce the run time of two diesel generators for the Air Force (Idaho Power Company/PIX01585). 5.—The Ramakrishna Mission Initiative, a cost-shared project with DOE and India’s Ministry on Non-Conventional Energy Sources, identified about 20 kilowatts of non-grid-connected applications and will include some 300 individual home PV systems in Sundarbans, West Bengal, India (Harin Ullal, NREL/PIX04579).
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Message from the Director

As of 1996, we have 550 megawatts of photovoltaic generating capacity installed worldwide. Although this represents a large number of photovoltaic (PV) systems, it is still only about half the capacity of a single nuclear power plant. Photovoltaics has the potential to contribute much more than this to our energy mix, with little or no side effects such as global warming or toxic waste. In addition, a burgeoning PV industry has much to contribute to our economic growth. Our work in the National Photovoltaics Program this year and in the years ahead is important to realizing this potential.

This year, through collaborations with the U.S. PV industry and universities, we made significant gains in conversion efficiencies for nearly all materials being developed. These increases reassure us that our diverse research program, which includes several technologies, is still the wisest strategy. A breakthrough will come in one or more of these materials and will lead to improved PV products.

The National Photovoltaics Program's research and development has contributed as well to significant gains in the marketplace. Worldwide photovoltaic module sales grew more than ever before. In 1996, the U.S. PV industry posted a 15% increase in module shipments over the previous year and maintained its 44% share of the growing world market. In the U.S., for example, more than 50 projects totalling 2 megawatts of generating capacity were installed at federal facilities. This year, as in the past, the fruits of our research efforts are passed to industry through teamed research, licensing agreements, and cooperative research and development agreements.

Our teamed research agenda is further enhanced this year by our creation of the National Center for Photovoltaics, which will serve as a focal point for the nation's capabilities in photovoltaic research, development, deployment, and outreach. The National Center unites geographically scattered initiatives into a single, coordinated effort. By facilitating greater communication and cooperation between staff at all of the program's facilities and with industry, the National Center enhances the capabilities of each to promote the U.S. PV industry.

The PV industry has sustained a growth of 18% over the last dozen years. Through our continued research, development, and demonstration of improved PV products, we look forward to continued growth and the significant contribution of PV to our global energy mix.

James E. Rannels, Acting Director
Office of Photovoltaic and Wind Technologies
U.S. Department of Energy
Washington, D.C.
1996 PV Program **Accomplishments**

Advancing Research and Development

- Supported national research team resulting in a record 12.1%-efficient laboratory cell for amorphous silicon.
- Supported work in cadmium telluride devices leading to new efficiency records for a prototype module (9.1%) and a laboratory cell on low-cost glass (14.7%).
- In-house research produced a new efficiency record of 17.7% for a copper indium diselenide cell.
- Supported work at the Georgia Institute of Technology that demonstrated a record 18.6% device made with multicrystalline material commonly used by industry.
- Advanced the designs for an emitter wrap-through crystalline silicon cell and a self-aligned selective emitter cell.

Developing Technology for Tomorrow’s Products

- Demonstrated the benefits to industry and the public of production improvements stemming from the first three phases of the PV Manufacturing Technology (PVMaT) program.
- Supported development through PVMaT of new commercial products, including ac PV modules, innovative inverters, and charge controllers. These products are being tested at the national laboratories’ test centers.
- Supported development of new PV system components that are now available to the industry for licensing, such as new mounting systems and manufacturing equipment designs.
- Developed and transferred to industry a new way to evaluate module quality by taking tiny core samples for analysis.
- Validated a model to predict PV system performance in any location.
- Developed safe-handling procedures for cadmium telluride and copper indium diselenide manufacturing based on toxicology studies.

Engineering Systems and Applying PV

- Participated in nearly 2.5 megawatts of PV installations under way for federal agencies and supported other government agencies to plan and implement cost-effective PV systems.
- Worked with states to identify facilities with high energy costs where PV is cost-effective now. Completed a new analysis that highlights U.S. states with economics favorable to PV.
- Supported the Utility PhotoVoltaic Group’s efforts to expand the use of PV by utilities, resulting in 800 kilowatts installed and 5.6 megawatts planned for the first round of grid-connected PV applications.
- Promoted development through PV:BONUS of award-winning building materials that incorporate PV into grid-connected buildings.
- Continued to document PV system performance in international projects in China, Brazil, India, and Mexico, while working to promote U.S. products overseas.
- Developed procedures for accrediting laboratories to certify PV modules and supported establishing PowerMark Corporation to certify PV modules through third-party testing.
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Introduction

The PV Program collaborates with the U.S. PV industry in the research and development of photovoltaics.

The three main program elements of the National Photovoltaic Program work together to make PV an important part of our economy. Research and Development, Technology Development, and Systems Engineering and Applications projects are planned and carried out in partnership with the U.S. PV industry.

Research and development efforts generate new ideas, test the latest scientific theories, and push efficiencies of PV materials and devices toward their limits, with the goal of continuing to improve the cost effectiveness of PV products.

Technology development projects apply innovations from the laboratory to products, improving PV technology and manufacturing techniques.

Systems engineering and applications activities help improve PV systems through testing and analysis. Deploying prototypes in various applications familiarizes users with PV, giving them the experience to accept this new technology. Evaluating the performance of PV systems paves the way for widespread, cost-effective projects.

To make PV an important part of our economy, the PV program works with industry through the national laboratories. The National Renewable Energy Laboratory (NREL), Sandia National Laboratory (Sandia), and Brookhaven National Laboratory (Brookhaven) perform in-house research and work with industry under contracts, licensing agreements, cooperative research and development agreements, and informal collaborations.

Building on the foundation of previous years' work, the PV Program made significant advances in each of these program elements during Fiscal Year (FY) 1996.
Advancing Research and Development

Research to develop new materials and solve industrial problems

DOE’s PV partnerships are cost-shared projects with industry to stimulate PV device innovations and to move these innovations out of the laboratory and into the marketplace. For example, the Thin Film PV Partnership Program includes teams of DOE laboratory researchers, industrial partners, and university laboratories to help bring promising thin-film materials from the laboratory bench to pilot production. Another partnership, the Crystalline Silicon Research Cooperative, coordinates the efforts of DOE, industry, and university members to improve the efficiency and lower the cost of devices made from crystalline silicon.

One big advantage of the partnership programs is the voluntary coordination of research focus, both cost-shared and private, on key issues critical to advancing the technology to pilot production. The team efforts of the partnership programs are realized at each step of the progression from innovative processing of PV materials, to device designs, to prototype cells and modules.

It is still unclear which material will ultimately be the best. Therefore, we distribute our research dollars among several materials that hold the most promise for low-cost mass production and stable, reliable performance. In our National Photovoltaics Program Plan for 1996–2000, we have set goals for our research program. Some of these goals are stated as efficiencies for laboratory cells, prototype modules, and commercial modules for each type of photovoltaic material.

Thin-Film Materials: Partnerships in progress

Thin-film materials offer several potential advantages over devices made of crystalline silicon. Devices made from thin-film materials use less semiconductor material than crystalline PV cells, so material costs may be lower. In addition, thin-film manufacturers can take advantage of existing industrial processes such as those used to manufacture and coat glass. Glass-processing techniques interconnect the thin-film cells without separate handling and testing of cells, as in crystalline silicon.

The United States leads the world in thin-film PV technology because the DOE research program has invested in research and development of thin-film materials for more than a decade. Through partnerships with industry, universities, and national laboratories, the program supports R&D on processes, materials, and devices up through prototypes that are ready for pilot production. Then the program’s technology development projects address issues of manufacturing. Finally, as thin-film products enter the marketplace, systems engineering and applications projects validate performance and promote widespread use.

Before the potential advantages of thin films can be attained, some challenges must be met through careful research. The physics of thin-film operation is not as well understood as for crystalline silicon, which has benefited from massive research in the integrated circuit industry. In addition, although the potential for continuous, industrial-scale manufacturing is real, it is challenging to convert laboratory processes on small cells to pilot production of modules, while maintaining efficiency.

The DOE PV partnerships work on thin-film technologies—including amorphous silicon, cadmium telluride, and copper indium diselenide—to advance devices and processes toward cost-effective production of electricity.

Amorphous Silicon Materials and Devices

Amorphous silicon is solid silicon, but like glass, it has no crystalline structure. By carefully controlling the formation and chemical content of thin layers of amorphous silicon, researchers are fabricating—and industry is

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<tr>
<td>a-Si</td>
<td></td>
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<tr>
<td>Laboratory cell*</td>
<td>10.9%</td>
<td>12.1%</td>
<td>(United Solar-stabilized) 15%</td>
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<tr>
<td>Cells</td>
<td></td>
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<tr>
<td>Laboratory cell*</td>
<td>13.9%</td>
<td>16.7%</td>
<td>(Golden Photon, Inc.) 16%</td>
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<tr>
<td>Prototype module*</td>
<td>8.4%</td>
<td>9.1%</td>
<td>(Solar Cells, Inc.; 8 ft) 10%</td>
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<td>CIS</td>
<td></td>
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</tr>
<tr>
<td>Laboratory cell*</td>
<td>17.1%</td>
<td>17.7%</td>
<td>(NREL) 20%</td>
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<tr>
<td>Module*</td>
<td>13.0%</td>
<td>13.6%</td>
<td>(Siemens; 50 cm²)</td>
</tr>
<tr>
<td>Prototype module*</td>
<td>10.2%</td>
<td>13%</td>
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* Cell efficiencies are for cells & modules on low-cost soda-lime glass typically used in manufacturing, not on expensive borosilicate glass that resulted in higher efficiencies earlier.

Conversion efficiencies have improved over FY 1995 values and continue to advance to the year 2000 goals in a-Si, CdTe, and CIS technologies.
manufacturing—PV cells with higher efficiencies. Efficiencies for amorphous silicon devices are expressed as “initial,” which means before exposure to sunlight, or as “stabilized,” which means after at least 600 hours of exposure to light. Amorphous silicon material experiences permanent losses in conversion efficiency—a phenomenon known as the Staebler-Wronski Effect.

One way to boost efficiency is to construct multijunction amorphous silicon devices in layers, each of which absorbs a different portion of the solar spectrum. As a result of work with the DOE teamed research program, United Solar Systems Corporation announced it has produced a laboratory cell with a stabilized efficiency of 12.1%. This new record cell is a triple-junction amorphous silicon alloy cell.

To make this record cell, United Solar researchers made three improvements over previous triple-junction cells: improved the conductivity and transmission of the transparent conducting oxide on top of the cell, improved the back reflector so that more light is used by the cell, and improved the tunnel junctions between the layers of the cell.

In other research to improve cell efficiency, the national team worked with Solarex researchers on a method to dilute the deposition plasma with hydrogen, stabilizing cells and causing less degradation in efficiency. Solarex reduced deposition time in its factory by 30% and significantly increased throughput.

Work is also under way to make amorphous silicon more attractive by devising faster ways to produce it. The “hot wire” process being developed at NREL allows deposition rates four to six times faster than conventional methods. The national teams are now working on ways to increase the efficiency of the resulting materials while maintaining high deposition rates.

**Cadmium Telluride Materials and Devices**

Low-cost manufacturing of the cadmium telluride technology is promising because more than a dozen methods have been used to make cells. These methods include using industrial processes such as high-rate evaporation, spraying, screen printing/sintering, and electrodeposition. The DOE PV program works closely with industry leaders developing this technology's potential.

This year, Golden Photon, Inc., significantly improved the efficiency to 14.7% of a cadmium telluride cell made on low-cost soda-lime glass. Their two approaches to improving performance involved a cadmium telluride recrystallization step and deposition of a very thin layer of cadmium sulfide. Cadmium sulfide is needed for the cell design, but if the layer is too thick, it can also absorb light at the top surface of the cell, which reduces efficiency. At Golden Photon, Inc., researchers managed to thin the layer enough to increase efficiency.

At the module level, Solar Cells, Inc., achieved greater than 9% aperture-area efficiency on an 8-ft² module made of cadmium telluride. This is the highest conversion efficiency for any thin-film module that large and meets an important milestone for the Thin Film PV Partnership Program. The process will be used in Solar Cell's new multi-megawatt production facility in 1997.

Cadmium telluride modules demonstrate good stability over time. Modules made by Solar Cells, Inc., have been installed at NREL for two years, and test data show no reduction in performance. Under an expanded module testing activity, modules will be tested outdoors in the hot humid climate of the Florida Solar Energy Center to further demonstrate performance.

All high-performance CdTe cells and modules use tin oxide as a transparent conductive oxide (TCO) top-contact. However, researchers at NREL have developed a new material that surpasses tin oxide in both conductivity and transparency. They demonstrated the new TCO contact with a 13.6%-efficient cell. The new formula has been made available to the PV industry for possible licensing.

**Copper Indium Diselenide Alloys Materials and Devices**

Pushing up the world-record efficiency for a solar cell using CuInGaSe₂ (CIGS), NREL scientists fabricated and tested a 17.7%-efficient cell. Researchers attribute the increased efficiency to the higher-quality material they are producing in the laboratory and to subtle improvements in the graded alloy design.
However, an important barrier to this technology advancing beyond the laboratory is the lack of a successful manufacturing process. NREL is working with several alternative processes for fabricating CIGS devices and is demonstrating them with others in the Thin Film PV Partnership Program. NREL, in partnership with Davis, Joseph and Negley Corporation, used electrodeposition to produce a device with an efficiency of 13.7%. In another effort, NREL scientists, using flexible stainless steel, demonstrated a 13.2% device.

Several companies and universities working on CIGS cells are making cells without cadmium sulfide layers. Eliminating cadmium sulfide simplifies module manufacturing and reduces environmental issues of using and depositing cadmium. Under the DOE program, a project that includes NREL and Washington State University has made a cell without cadmium sulfide that is 12.7% efficient. The new cell uses a modified zinc oxide to compensate for the absence of the cadmium sulfide.

Last year Solarex Corporation researchers fabricated a 13% CIGS mini-module (40.4 cm²). This year, Siemens Solar Industries fabricated a 50-cm² mininodule that achieved 13.6% efficiency. The Siemens module consisted of 12 cells interconnected monolithically in series by laser and mechanical scribing techniques.

Technology developed at the national laboratories is made available to industry. For example, NREL has signed new non-exclusive licensing agreements with three companies and is negotiating with two more to manufacture products based on NREL-developed CIGS technology. In another case, through a cooperative research and development agreement, one of Energy Photovoltaics' scientists arranged to explore and optimize some of its processing schemes at NREL's deposition facilities. The deposition systems at NREL allow greater control and flexibility of film growth than is currently possible at Energy Photovoltaics. Using recipes developed under the agreement, NREL fabricated a CIGS cell with a confirmed efficiency of 13.9%. This process could be a promising new approach for the company.

In other work under CRADAs, industry is applying approaches developed at the national laboratories. Daystar Technologies is using NREL's new technique for processing thin-film absorbers in CIGS material to Daystar's patented process for applying filament-cell substrates to modules. Another CRADA is in progress with Martin Marietta Technologies, Inc., to fabricate copper indium diselenide (CIS) and/or CIGS solar cells using NREL patents. NREL personnel will help relay their experience on processing conditions and sequences. The processing, performed in the Dynamic Research System (scale-up apparatus), will demonstrate the performance and properties of materials made using the new techniques.

The PV research program also transfers technology to industry through informal collaborations. Under such collaborations, NREL scientists visit company facilities to solve specific problems. In addition, researchers from companies come to the DOE laboratories to participate in tests and analyses of their proprietary materials and devices.

Applying its proprietary non-vacuum method to deposit CIS absorber films, International Solar Electric Technology is setting up a pilot line to manufacture thin-film modules of about one-foot square. The company sees a niche market for these small modules that will introduce CIS to commercial production.

Crystalline Silicon Materials: Making a good thing better

More than 80% of the almost 90 megawatts of PV modules sold in 1996 were made of crystalline silicon. Modules using crystalline-silicon PV cells have excellent stability and a proven track record: some of the
earliest PV modules using crystalline-silicon solar cells still operate satisfactorily after 20 years in the field.

Commercial crystalline-silicon solar cells use two types of crystalline substrates: single-crystal silicon and multicrystalline silicon. Single-crystal ingots grown by the Czochralski method can be as large as 300 millimeters in diameter and weigh up to 300 kilograms. Single-crystal silicon is considered a high-quality material because it has very few crystalline defects and can be easily textured to improve light absorption. As a result, solar cells using single-crystal silicon have the highest efficiencies of any commercial PV technology for terrestrial applications.

Multicrystalline silicon is made of the same pure silicon as single-crystal silicon, but the ingots are cast in large square blocks measuring up to 58 centimeters on a side and weighing as much as 200 kilograms. The material is composed of silicon crystals measuring up to 1 centimeter across. Multicrystalline-silicon cells may operate at lower efficiencies compared to single-crystal silicon cells for two reasons. First, multicrystalline-silicon material typically has more crystalline defects that cause internal recombination losses, reducing efficiency. Second, multicrystalline-silicon material is more difficult to texture, a process that can increase light absorption and efficiency in cells. Both single-crystal and multicrystalline-silicon ingots must be sliced into wafers for processing into solar cells.

Laboratory PV cells made of crystalline silicon have achieved efficiencies of up to 24%, whereas large-area commercial cells have efficiencies that average between 12% and 15%. Clearly, there is ample opportunity to improve the performance of commercial cells by transferring high-efficiency features and new production techniques from the laboratory to commercial manufacturers. Most DOE-sponsored research on crystalline silicon is directed toward assisting this transfer. Although some laboratory work is still directed at improving basic understanding and world-record efficiencies, our main objective is to improve the performance and reduce the cost of commercial crystalline-silicon PV cells and modules.

Understanding Impurities and Defects

Commercial materials and processes for crystalline silicon frequently introduce more performance-limiting defects and impurities than is found in high-efficiency laboratory cells. The PV program supports a project to improve the performance of commercial cells and materials. Scientists are striving to understand the role of—and develop methods to ameliorate the effects of—defects and impurities. This project involves seven universities performing work on crystalline-silicon material science. Researchers at the national laboratories assess materials, while the PV industry provides important feedback and guidance to the effort.

As part of this effort researchers at Duke University developed a physically based, numerical model of impurity gettering—a processing step used to remove impurities from PV materials. The model allows analysis of different gettering methods. Researchers used the model to predict the benefit of gettering using a simultaneous phosphorus diffusion/aluminum alloy. Researchers have also used the model to examine the difficulty of dissolving precipitates using conventional thermal processing. The results demonstrated the need to investigate non-conventional processes for gettering, such as rapid thermal and ultrasonic processing, to remove impurities.

One of the most common metallic impurities in silicon is iron. Researchers at NREL are examining the role of iron in silicon by growing a set of silicon crystals under tightly controlled conditions. The crystals are grown using the float-zone method. Then specific amounts of iron and boron are added in a process called doping, yielding a known crystal defect structure. Characterization of these samples will increase our understanding of the fundamental mechanisms of iron incorporation in silicon crystals.
In other crystalline work at the Georgia Institute of Technology, a new efficiency record of 18.6% (1-cm² area) was demonstrated for a solar cell on a multicrystalline-silicon material commonly used by industry. The high performance was achieved, in part, through careful optimization of phosphorus diffusion and aluminum alloy processes. These optimized processes improved the bulk properties of the material through gettering. This work demonstrates that there is substantial room for improvement in commercial cell performance. Crystalline-silicon material science has a key role to play in achieving this potential.

Enhancing Device Design and New Processes

In addition to materials research, the DOE PV program funds work on new device designs and new processes that can move high-efficiency features of laboratory cells into commercial production. This year, Sandia patented a new cell concept (the emitter wrap-through cell) that places both current-collection contacts on the back surface of the cell. This arrangement, which requires some special production techniques, eliminates the shading losses of conventional front-contact cells. It also simplifies cell connections when the modules are assembled. A prototype device measuring 42 cm² demonstrated an efficiency of 16% using commercial Czochralski single-crystal silicon.

Another new concept that attempts to improve the performance of commercial production cells is the self-aligned selective-emitter cell. The cell features a lightly diffused junction between the grids, and a heavily diffused junction beneath the grid. This geometry (selective emitter) maximizes current collection between the grids while minimizing contact resistance beneath the grid. The process sequence has several features with the potential for low-cost production. The process requires no alignments and uses plasma processing for etchback and surface passivation of the emitter.

Initial tests of the new cell concept used multicrystalline-silicon cells from the production line at Solarex, a business unit of Amoco/Enron Solar, Frederick, MD. The tests demonstrated a 1% absolute gain in efficiency using the new process on 103-cm² cells.

Other work addresses the advanced processing techniques with higher throughputs and lower energy demands that industry desires. A family of promising new processing techniques uses photons to provide the energy for the process. These advanced techniques include low-temperature optical processing, high-temperature rapid thermal processing, and solar-furnace processing. Researchers at NREL demonstrated that using a solar furnace to process material accelerated dopant diffusion compared to conventional thermal processing. Researchers working at the Georgia Institute of Technology demonstrated an efficiency of 16% for 4-cm² cells fabricated on Czochralski silicon using rapid thermal processing, commercial (e.g. screen-printed silver) metallization, and low-temperature surface passivation and antireflection coating.

Advanced Concepts

Advanced concepts, some of which are already being used in space, are being evaluated for their potential contribution to the next generation of terrestrial PV devices. A special group of semiconductors called III-V materials, which include gallium arsenide, are used to make the highest efficiency solar cells. These high efficiency cells are also quite expensive at present. To lower the cost researchers at NREL are examining methods to grow “single-crystal-like” gallium arsenide on glass or other low-cost substrates. This year they grew gallium arsenide on molybdenum-coated glass substrates (supplied by NREL’s CIS team) at various growth temperatures and arsenic pressures. Future work will focus on growing materials that incorporate other constituents, while removing defects and impurities.

The 30% efficient tandem cell (GaInP/GaAs) technology, invented and developed at NREL, is in production at both TECSTAR and Spectrolab companies for use in space. The market for...
tandem cells for space application is expected to exceed hundreds of millions of dollars per year. And today the cost of these cells is competitive for terrestrial concentrator systems working at concentrations between 500 and 2500 suns. For the next generation of cells, NREL has begun evaluating 3- and 4-junction concepts with the goal of achieving efficiencies greater than 35%.

Working With Industry

Involving industry in the DOE PV research program is basic to the program's success. Industrial involvement during research ensures the ultimate success—the incorporation of research results into commercial processes and products. Our research project in crystalline silicon has several cooperative research agreements designed to do just this—conduct research that industry can use. Sandia recently completed a cooperative research project with Siemens Solar Industries (Camarillo, CA) that investigated the performance potential of the company's commercial Czochralski silicon. The research revealed that the material is inherently capable of performing at 20% efficiency. Actual large-area cells were measured at 18% efficiency. Sandia also recently began a cooperative research agreement with ASE Americas (Billerica, MA) to help characterize cell and module performance and fabrication processes.

Researchers at NREL are working under several cooperative research agreements with industry. They worked with AstroPower (Newark, DE) to set up a system that measures materials lifetime by monitoring photocurrent decay. They also characterized multicrystalline-silicon material in the DOE laboratories for Crystal Systems (Salem, MA). In another cooperative agreement, NREL is working with EBARA Solar (Pittsburgh, PA) on their dendritic web process. The process, originally developed at Westinghouse with support from DOE, produces a unique, high quality, very flexible, crystalline-silicon ribbon. These ribbon substrates could have many applications in PV products.
Developing Technology for Tomorrow's Products

Activities that make U.S. PV products more widely used

The Photovoltaics Program works with PV companies in several ways to modify successful laboratory techniques for industrial production. One approach, taken by the PV Manufacturing Technology (PVMaT) program, uses cost-shared development contracts with industry to improve PV manufacturing. Researchers from Sandia and NREL monitor these contracts, with results published in technical reports.

Another approach popular with industry is the cooperative research and development agreement (CRADA). Under a CRADA, researchers at the national laboratory (NREL or Sandia) and their industrial partner contribute in-kind resources to the research project. In addition, the facilities of the national laboratories are available for analyzing products and materials supplied by the industrial partner.

PVMaT Repays Investments

To enhance the worldwide competitiveness of the U.S. PV industry, Congress approved funds for the Photovoltaic Manufacturing Technology project in 1990. Sharing costs between the National Photovoltaics Program and the individual manufacturers, the total funding to date for PVMaT—including 43% from industry—is about $108 million.

PVMaT's success in reducing the price of U.S. PV products repays both manufacturers and U.S. taxpayers for their investments, according to an analysis conducted this year by the PV program. Using data collected from ten PVMaT industrial participants, analysts estimated the benefit to the public of reduced prices, as well as the return to manufacturers for reduced production costs.

The first three phases of PVMaT focused on reducing module costs and increasing capacity for the U.S. PV industry by improving the manufacturing processes of modules. During Phase 4A, which started in FY 1995, manufacturing R&D was extended to address entire integrated PV systems, including components such as inverters. Phase 4A1 addresses PV products and improvements to subsystems, whereas Phase 4A2 continues to emphasize improvements in PV module manufacturing. At this time, the PV program has awarded eight 2-year Phase 4A1 subcontracts and five 3-year Phase 4A2 subcontracts.
Recapture of PVMaT Research Funding

Data on the economic value of the PVMaT program were collected from the 10 PVMaT manufacturers. Each one identified the resulting benefit to the public (through reduced prices for PV products) and to the industry (through increased profits, investments in new production capacity, or new R&D efforts). These benefits were normalized to the government (DOE) funding and the industry cost-shared amounts to determine the percentage of cumulative recapture. The companies’ projections indicate that the public recaptures their investment in the program in 4.1 years and the industry recaptures their investment in 4.4 years.

Systems and Components for PV Products

In some cases, half the cost of PV systems is represented by the modules. Therefore, improving system integration and the rest of the system components—such as mounting designs and power processing hardware—could lower the cost of PV systems significantly. Phase 4A1 contractors under PVMaT address several elements of the PV system. These contracts address complete systems with optimized components or specialized components for PV generation.

Advanced Energy Systems, Inc., Wilton, NH, developed a prototype 50-kilowatt inverter for hybrid applications such as conditioning PV and/or wind-generated electricity for village power or remote military applications. The new design implements simpler manufacturing steps and remote monitoring. WPI Power Systems, Inc., of Warner, NH, built the inverter and helped with the design. In FY 1996, prototypes were sent to Sandia and to the National Wind Technology Center, near Boulder, CO, where DOE researchers are testing them in combination with diesel generators, wind turbines, and batteries. In FY 1997, the team will develop a similar product for grid-connected applications.

Ascension Technology, Inc., Waltham, MA, is working with ASE Americas Corp., Billerica, MA, to develop an ac PV module that puts out 240 to 300 watts. This ac PV module combines ASE Americas’ PV module, which produces dc electricity, with Ascension’s ac inverter attached to the back. Each inverter/module combination produces ac power and can feed power to a utility. The new product, called the SunSine 300, makes system design and field installation much easier than using conventional PV modules and a single large inverter for the entire array.

For example, these self-contained units could be added to a site whenever the user decides to expand the system. Prototypes of this design are being tested at NREL and Sandia and will soon be available commercially.

Evergreen Solar, Inc., Waltham, MA, is developing new materials to facilitate continuous, in-line manufacturing of PV modules for high-volume mass production. Currently, most module encapsulants require a vacuum curing stage that can only be performed in batches, thus slowing production. Evergreen is developing an encapsulant that can be processed in a continuous assembly line, without curing in a vacuum. In addition, Evergreen developed a novel backskin material—hard like the bumpers on cars—that serves as the frame for modules and can also be processed continuously. Evergreen Solar has submitted patent applications for its new materials, which, after approval, will be available for licensing to the industry at large.

Omnion Power Engineering Corporation, East Troy, WI, working with Soft Switching Technologies, Inc., is developing a 100-kilowatt prototype 3-phase power conversion system for utility-interconnected PV applications using a resonant core inverter. Their goals include a cost of less than 50 cents per watt in high-volume production, 96%-97% efficiency, compliance with electromagnetic interference standards, audible noise at less than 50 decibels, and listing for the product by Underwriters Laboratories (UL).

Solar Design Associates, Inc., Harvard, MA, leads a team in refining the design of what they refer to as their “AC PV Module” developed under the PV:BONUS (Building Opportunities in the U.S. for PV) program. The AC PV Module includes a regular dc PV panel and a small ac inverter attached to the back of the panel. A digitally controlled, 250-watt microinverter is being developed by Advanced Energy Systems, Inc., of Wilton, NH. The unit has microprocessor control and full communication capabilities. Solarex supplies the PV panels for the AC PV Module and has also worked on improved mounting systems for flat-roof, sloped-roof, and
ground-mounted installations of this new product. Prototypes of the AC PV Module are now being tested at both NREL and Sandia.

Solar Electric Specialties, Willits, CA, is working to design, fabricate, and gain UL listing for two PV power systems for off-grid applications. SES is a systems integrator that uses currently available components, although they work with suppliers to enhance their suitability for each system element for PV. They have designed a 200-watt, pole-mounted, stand-alone PV power supply to minimize weight and cost, while meeting UL requirements. The UL listing is very important for any commercial or private use. During FY 1997, SES will develop a 1-kilowatt photogener, which combines a generator, inverter, and PV power supply.

Trace Engineering, Arlington, WA, will develop, test, and modify its manufacturing to produce a lower cost, higher performance 2-kilowatt ac inverter for the PV industry. The inverters, which can be combined by 2-kilowatt increments to serve larger systems, will be able to convert ac power to dc, or dc power to ac, if required. This standardized, unitized approach to manufacturing is expected to reduce costs and improve reliability.

Utility Power Group (UPG), Chatsworth, CA, has designed, built, and tested a prefabricated, tracking PV array that includes a 20-kilowatt inverter and power conditioning unit called an Integrated Power Processing Unit (IPPU). The IPPU includes power conversion from dc to ac, a power controller, and data-gathering access, all packaged as one unit for ease of installation. Designed for utilities or large power users, each IPPU serves up to 15 kilowatts of PV modules in a large field.

To reduce the high cost of installing PV arrays in the field, UPG has also designed a system to factory-assemble PV panels into larger units. Factory assembly reduces installation costs by up to 40%.

Applying this technology to a TEAM-UP (Technology Experience to Accelerate Markets in Utility Photovoltaics) project for the Utility PhotoVoltaic Group, UPG installed a 15-kilowatt system at the Hedge substation for the Sacramento Municipal Utility District in California in 1996. All components are operating to full design specifications.

Solar Cells, Inc. (SCI), Toledo, OH, is developing a high-speed manufacturing process for 60-cm by 120-cm, thin-film cadmium telluride modules. SCI completed and fine-tuned a system that increases production capacity from 10 substrates per day (about 100 kilowatts per year) in a manually operated system to 480 substrates per day (4.8 megawatts) in a more automated system. While perfecting this new continuous processing of glass substrates, SCI solved problems with machine jams, breakage from rapid temperature changes, and breakage due to substrate vibration. The processing time for laser-scribing the modules was also shortened from 90 minutes per substrate to 6 minutes, through testing and reprogramming the scribing protocols. Solar Cells, Inc., expects to continue increasing its production capacity to 20-30 megawatts per year in the near term, with significantly reduced production costs.

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of cast polycrystalline silicon. Solarex assessed each production step: casting the material, sawing ingots, processing cells, laminating, and finishing. Improvements incorporated into the processing of cells should reduce costs and increase the minimum average cell efficiency to 15%. For example, Solarex has modified its casting stations to produce larger ingots. From these ingots larger bricks can be cut, yielding larger cells for modules. By FY 1997, Solarex's entire plant will be processing these larger ingots with the newer processing steps. Another improvement—replacing blade saws with wire saws—has reduced production costs by 10 cents per wafer. With other improvements, including identifying and qualifying a new low-cost backsheet material, an improved mounting system for frameless modules, and an improved electrical termination process, Solarex expects to produce cost-effective cells with an average efficiency of 15.5%.

ASE Americas, Inc. (formerly Mobil Solar), Billerica, MA, manufactures photovoltaic wafers, cells, and modules using an edge-defined, film-fed growth process developed at Mobil Solar. ASE's goal is to reduce wafer, cell, and module manufacturing costs by 25%, relative to pre-PVMaT Phase 4A2 levels. In this effort, ASE is using a PVMaT-developed lower-cost, environmentally safe process to remove their diffusion glass from wafers. They have also improved the process for integrated interconnects, termination, and cell fabrication. With these changes and improvements in solar cell fabrication technology, ASE expects to produce cost-effective cells with an average efficiency of 15.5%.

AstroPower, Inc., Newark, DE, is reducing the manufacturing cost of its commercial Silicon-Film™ cells and modules. Their approach is to make the AstroPower Silicon-Film™ material in wider sheets that make better use of the material, require less labor per area of modules produced, and allow greater variety of products for different markets. The company's current commercial product is 15.5 cm wide, with sheets from prototype production measuring 30 cm wide. AstroPower expects to increase their production capacity of Silicon-Film™ sheets to 20 megawatts per year in the future.

Iowa Thin Films Technologies, Inc. (ITF), Ames, IA, is increasing their throughput of amorphous silicon deposition on continuous polymer substrates, and the subsequent metallization, laser-scribing, and welding processes to reduce costs. In FY 1996, ITF increased throughput in the printer and scribe from 2 inches per minute to 14 inches per minute by changing the control strategy for aligning the material in the printer. Work on their submodule lamination process has increased throughput from 20 ft² per hour to 240 ft² per hour. Other areas of improvement included developing new water-soluble insulating ink printing and roll-based laminating processes, identifying alternative methods for welding shunts in cell-interconnects, and automating busbar attachment and web cutting. These improvements have reduced manufacturing costs by 68%.

Siemens Solar Industries, Camarillo, CA, is reducing the cost and improving the reliability of their commercial, Czochralski, crystalline-silicon modules. They are testing prototype modules made from larger, 225-cm² cells, which can reduce module costs per watt by 18% and increase manufacturing process yields by 15%. Breakage can reduce yields by 20% to 40%, so Siemens is also investigating lowering costs through reduced breakage while continuing to thin the cells. In addition, a new prototype junction box combines low cost with improved design.

Photovoltaics International (formerly Solar Engineering Applications (SEA) Corporation), Sunnyvale, CA, is reducing manufacturing costs for its linear concentrating PV modules by expanding the continuous processing of key...
components. The lenses and side panels of the modules are being extruded, and design is under way for a 50-megawatt-per-year production facility for these components. In addition, the company is developing an automated receiver assembly process, new roll-forming technology for fabricating panel frames, and is investigating a new way to bond plastic collector components without using solvents. Photovoltaics International's long-term goal is to produce 50 megawatts per year of concentrator modules at a cost of $2.00 per peak watt.

**Industrial Expansion**

More than 55 megawatts of new PV manufacturing capacity are now in various stages of development—almost 60% of the current worldwide annual sales. Siemens Solar Industries is expanding its operations, with new investments in facilities in Vancouver, WA, and Camarillo, CA. United Solar Systems Corporation is starting up a manufacturing plant in Troy, MI, to produce the new PV roof shingle. Solarex, a business unit of Amoco/Enron, is building a new plant in Toano, VA, that will employ up to 100 people.

Of the 55 megawatts of PV production capacity under development, almost 29 megawatts of new thin-film manufacturing capacity are now on line or are planned for completion by 1998.

**Module and Array Development**

Assessing the performance of modules and arrays is an important part of the DOE PV technology development program. Researchers are developing new ways to predict system performance in the field. In addition, ongoing work with manufacturers assesses the wear and tear on modules and how manufacturing processes can be changed to increase durability.

Manufacturers now offer 20-year warranties on crystalline-silicon modules and up to 10-year warranties on thin-film modules. To provide even longer warranties, they want to understand the complex changes that can occur in their product after years of exposure to sun, wind, dust, moisture, and daily temperature cycles.

The DOE PV program developed and is transferring to industry a method to extract information about PV modules by taking core samples. Taking tiny core samples with a vertical mill and coring tools, researchers at Sandia and the Florida Solar Energy Center analyzed more than 500 samples from 10 different modules. The 5/16-inch-diameter samples are analyzed using all the laboratory tools available, to find undesirable compounds at material interfaces or degraded solder bonds that lower performance. Such detailed analysis could not be performed on whole modules. Depending on what is found at material interfaces, the source of contamination is sought. These findings have already led to changes in manufacturing techniques.

In addition to gaining valuable information about the internal chemistry of modules after years in the field, the researchers have perfected the sampling technique and are preparing detailed instructions on how to use it. Several companies have already set up the tools required and will use them to sample for quality control during production (for example, encapsulant adhesion) and for post-mortem analysis of modules from the field.

This core sampling technique was developed during work with individual PV manufacturers to solve problems unique to their products. By making the laboratories of the DOE PV program

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*The DOE laboratories test industry's modules outdoors (left) under natural sunlight and indoors (right) using solar simulators. This new solar simulator can accommodate the largest new modules by illuminating a 5-ft by 7-ft area with an irradiance level matching ASTM standards.*
available to industry with the assurance of confidentiality, researchers identified the sources of contaminants and other mechanical problems. Companies then went on to modify their manufacturing processes.

Another approach to increase reliability is to develop monitoring systems and to use models that predict expected performance in the field. In the past, some utilities have hesitated to offer PV services in lieu of extending utility lines to customers, even when PV could save money. They hesitated because they could not continuously evaluate how the system was performing. The DOE program, through Sandia, is working with Southern California Edison and Arizona Public Service to provide on-line monitoring of remote PV systems 24 hours a day. With this kind of monitoring, the utility can anticipate a problem developing and maintain the reliability of utility systems that customers expect.

For customers, predictability of system performance reduces uncertainty and risk. To help decrease uncertainty, Sandia researchers have developed and validated a model to predict the performance of a PV array for all operating conditions. The model uses inputs for time of day, measured temperature, and measured irradiance—along with data on the PV array design—to predict output. The model was validated using four systems ranging from 1.5 to 340 kilowatts.

Knowing expected output is important to system designers, buyers, and operators. Predicted output, given site conditions, can be used as a design tool for sizing systems; compared with measured output to verify that the system is operating according to design; and, compared with real-time measured output to monitor the functioning of all system components.

Testing PV System Components

To reduce the cost and increase the reliability of PV systems, the PV program sponsors in-house R&D, testing, and cooperative research contracts for non-module components. For example, some of the PVMaT contracts address specific components, such as inverters, controllers, trackers, and batteries. Other contracts seek to improve the entire system through packaged designs.

The national laboratories are important test centers for balance-of-system products. For example, the inverter test facility at Sandia conducts three general kinds of tests. Benchmark testing, when a product comes off the assembly line, characterizes products to enable system designers to properly apply them. Development testing supports manufacturers, PVMaT projects, and efforts in reliability. Acceptance testing verifies that the system or component meets its specifications. Such tests help to spot problems before systems are placed in the field.

Test procedures are evolving to simulate operation in the field. In the laboratory, many types of electrical loads are needed to simulate field conditions—loads that manufacturers would not have. Power supplies including a PV array, a generator, and a large battery bank are available in the laboratory, to support the full range of applications, especially of hybrid inverters.

The testing laboratories of the PV program also support the PV industry with focused product testing. Companies including Trace Engineering, Ascension Technologies, Morningstar, Abacus, Omnion, Outside Power, and Kenetech worked with Sandia researchers this year to test their products. The testing program also assists government agencies, such as the National Park Service and the Navy, and provides technical information at conferences such as Soltech, the IEEE Photovoltaics Specialists Conference, and program reviews.

Testing has been a crucial part of the PV program’s R&D efforts, especially in developing new inverters. The Utility Photovoltaics Group developed a new high-efficiency inverter that includes maximum power point tracking for control of electrical quality and incorporates a control system for array tracking. PV program engineers also work with companies to improve their off-site testing and quality-control programs.

Batteries are an important component of stand-alone PV systems that can add significantly to the cost of PV-generated electricity. An analysis
performed this year shows that when battery-charging efficiencies and performance lifetime are taken into account, battery costs can be as high as $0.25 to $1.30 per kilowatt-hour over the life of the system. Improving the life expectancy and utilization of batteries, through improved charging algorithms and preventive maintenance, can significantly reduce the cost of electricity from a PV system.

The DOE PV program sponsors battery test and development programs at Sandia and the Florida Solar Energy Center to improve battery performance in PV systems. Batteries can be connected to operating PV systems or can be subjected to accelerated testing through repeated cycling. The program’s unique testing facilities and new standardized test procedures allow battery manufacturers to understand the unique demands of a PV system and design products for this growing market.

In addition, the program works to improve charge controllers and charging algorithms, which have a large impact on battery life. To prevent overcharging or undercharging, charge algorithms programmed into controllers use various set points to guide operation. The program has sponsored work to develop and test charging algorithms that can extend battery life.

Environmental, Safety, and Health Issues

Some of the materials used to manufacture PV cells and modules are toxic, carcinogenic, or otherwise hazardous and must be handled according to strict guidelines. The DOE PV program sponsors research and analysis at Brookhaven National Laboratory and at NREL and Sandia to assess health and safety issues and to develop hazard control strategies for new PV materials, processes, or applications. Research involves three basic approaches to environmental, safety, and health problems associated with PV.

First, researchers develop and promote safe-handling procedures and equipment to keep dangerous materials isolated. This year Brookhaven National Laboratory conducted a toxicology study of precursor compounds used to make thin-film cadmium telluride and copper indium diselenide modules. As a result of this study, safe-handling procedures will be applied to more compounds used by the industry.

Second, researchers work to reduce the toxic waste stream of laboratories and factories through efficient material use and recycling. This year the program completed a detailed study of recycling strategies for cadmium telluride and copper indium diselenide modules. Analysts concluded that all of these metals are recyclable with current technology. They also found that it will be most economic for manufacturers to treat old modules or factory waste to remove constituent metals before transferring the materials to commercial recyclers.

And third, while simplifying processes and reducing the absolute amount of material used in PV cells, researchers sometimes reap benefits from improved environmental safety and health impacts. Reducing the complexity of handling and the amount of materials needed reduces costs. For example, researchers this year achieved good efficiencies on a copper indium gallium diselenide type cell by replacing the cadmium sulfide window with zinc oxide, eliminating an entire layer.
Engineering Systems and Applying PV

Projects that validate PV technology for worldwide markets

Strategic R&D and technology development are the foundation of our efforts to make PV a broadly competitive energy source. But systems engineering and applications are essential to maintaining the connection between technology and real-world markets and uses.

Promoting Projects with Government Agencies

Federal, state, and local governments operate many facilities where PV is a cost-effective way to supply electricity today. To help open this market, the DOE PV program works to get information and technical assistance to staff at all levels of government. This year more projects than ever before were completed in cost-effective installations using PV.

In FY 1996, more than 50 projects totaling nearly 2.5 megawatts of capacity were installed at federal facilities, and another 2.5 megawatts are in the planning stages. The agencies made their decisions primarily by comparing the first-cost of PV to the alternatives. Other issues such as environmental concerns, energy security, and noise levels of engine generators weighed heavily in favor of PV.

Department of Defense

A study conducted by the Department of Defense (DoD) and DOE shows that more than 700 megawatts of PV is cost-effective today for DoD. Each year, the DoD, a big energy user, consumes 300 million gallons of fuel to generate 3000 gigawatt-hours of electricity, for an average cost of between $0.40 and $1.00 per kilowatt-hour. The Defense Department also purchases about 35,000 gigawatt-hours of electricity at a cost of $2 billion per year ($0.06 per kilowatt-hour).

Through Sandia, DOE has supported the Army, Navy, and Air Force since 1985 with technical consultants. In addition, the DOE program has worked with the Coast Guard for hybrid systems, the Marines at Camp Pendleton to reduce energy consumption, the Navy at the Atlantic Underwater Test and Evaluation Center, the First Marine Expeditionary Force Mobile Power Center, and others. The most significant effort, which is now bearing fruit, is integrating PV into the federal procurement system, making it easier for federal agencies to purchase PV systems. The program also assists users in the military that are ready to develop projects by helping them with design and performance issues.

Nearly 2 megawatts of the PV systems under way for the military are stand-alone or hybrid systems. At Superior Valley, CA, the world’s largest stand-alone PV system went into operation this year at Edwards Air Force Base. The system includes 350 kilowatts of PV, 3.5 megawatt-hours of battery energy storage, and a 300-kilowatt power-processing unit. Five more hybrid PV systems are being built on remote ranges at the Naval Air Warfare Station. In all, 12 large-scale diesel replacement projects are under way in the DoD that use PV.

Before these large installations could become a reality, the proper power-processing equipment had to be developed. The military, through their Strategic Environmental Research and Development Project, has spent $4.4 million implementing new hybrid power systems. Much of the equipment for these systems has been tested at the PV program’s power-processing test facility at Sandia.

This 77-kilowatt PV array is part of a hybrid power system that includes two 160-kilowatt diesel generators and a battery bank. The hybrid system provides high-quality, 3-phase power 24 hours a day for the remote Grasmere bombing range, where sophisticated electronic equipment simulates enemy activities for pilots flying training missions from Mountain Home Air Force Base.
Dedicated in August, 1996, this PV/propane hybrid power system replaced generators that consumed 65,000 gallons of diesel fuel per year. In addition, the PV system will help eliminate oil spills and reduce air pollution on Lake Powell.

PV on Public Lands

The U.S. government is the nation's largest landholder. The National Park Service, the U.S. Forest Service, and the Bureau of Land Management all have large recreational areas requiring electric power. For years, the PV program, through Sandia, has been working with these agencies to evaluate their satisfaction with the PV installations they have and to assess the number of additional cost-effective installations they could consider.

This year heralded the installation of larger PV systems in high-value applications at the National Park Service. The largest, a $1.35 million PV/propane hybrid system, replaced the diesel generator at the marina in Crow Canyon National Recreation Area. The significant environmental benefits from eliminating the diesel system were the major factor in the Park Service's decision to replace existing diesel generators.

The Bureau of Land Management is working with Sandia to specify pilot PV projects in the Western states. The Bureau office in the state of Utah developed standardized specifications for PV systems with help from Sandia.

The U.S. Forest Service and Sandia published Photovoltaic Technology in the U.S. Forest Service—Renew the Forests this year. This document reports results from surveys of previous PV installations and assesses future cost-effective applications.

State Partnerships

Working at the state level, the Interstate Renewable Energy Council (IREC), supported by DOE and others, launched its training program Park Power: Using Solar Energy for Public Spaces (also known as the Workshop in a Box) for state employees to understand options for using renewable energy. The objective of the program is to encourage state and local governments to buy renewable energy products. The first training session, to
familiarize those who will be using the workshop materials with their use, was held in August 1996. Forty attendees, including 17 state coordinators, and staff from the National Park Service, the U.S. Forest Service, the DOE/Federal Energy Management Program, Sandia, and NREL, learned to use the tools, which include slide presentations, video, and tutorial materials.

Photovoltaics for Utilities, another state-level outreach program supported by DOE, now has state groups working to promote PV projects. A memorandum of understanding was signed to assess state facilities for high-value PV applications and to promote communications among the states. In Arizona, California, Colorado, Delaware, Hawaii, Idaho, Maryland, Massachusetts, Nevada, New York, North Carolina, Pennsylvania, Texas, Virginia, and Wisconsin, state energy offices are teaming with utilities to identify facilities with high energy costs for total operational cost analysis. For example, Virginia identified 100 facilities with energy costs between $0.16 and $30.00 per kilowatt-hour.

Projects with Utilities

With restructuring, utilities have more reason than ever to explore renewable energy in general and PV in particular. Photovoltaics’s modularity, known costs, short construction time, and reliability make PV an attractive way to diversify a utility’s generation mix. And the utility market holds great potential for spurring the increased production capacity necessary for reducing the manufacturing costs of PV.

National Solar Enterprise Zone

The National Solar Enterprise Zone is one of many projects under way this year that involves utilities. Located at the DOE’s Nevada Test Site, the National Solar Enterprise Zone project goal is to install up to 100 megawatts of renewable power generation capacity in southern Nevada. The nonprofit Corporation for Solar Technology and Renewable Resources (CSTRR) manages the project, reviews proposals from independent power producers that will set up generation facilities in the zone, and will broker the sale of electricity produced.

The DOE PV program supported this activity by having personnel at the national laboratories provide technical support to industry and assist in resolving project issues. CSTRR received preliminary power purchase commitments from the U.S. Environmental Protection Agency and the U.S. Army for a total of 22 megawatts committed by the end of FY 1996.

Utility Photovoltaic Group

Some utilities have been interested in PV for many years. In 1992, a group of these utilities formed the Utility Photovoltaic Group (UPVG) to speed up the availability of lower-cost, reliable PV systems for themselves and their customers. Among UPVG members, there are more than 80 utilities, the American Public Power Association, the Edison Electric Institute, and the National Rural Electric Cooperative Association. 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. In addition, NREL and Sandia provide technical assistance, such as analyzing power output of inverters, checking basic design and energy production predictions provided by vendors, and reviewing proposals.

This year UPVG’s activities solidified utility partnership in PV development; demonstrated applications and markets in PV-friendly pricing, building applications, and off-grid services; and spurred increasing competitiveness in PV products. In 1996, proposals were approved for Round One: 5.6 megawatts of generation for 340 installations. Eleven teams were selected that
each include one or more utilities, as well as PV suppliers and system installers. By far the largest project is the proposal from Amoco/Enron for 3.45 megawatts of grid-connected generation for Hawaiian Electric Company. By the end of FY 1996, about 800 kilowatts of grid-connected PV had been installed for Round One. Round Two also solicited 2.4 megawatts of generation for 1300 proposed installations.

Integrating PV into Grid-Connected Buildings

Between the extremes of megawatt-sized fields of PV generators and single panels on thatched huts is a huge potential market for PV integrated right into the structure of modern buildings. A recent market assessment conducted by the Utility Photovoltaic Group identified a potential market of 485-585 megawatts of PV used in buildings for systems priced at $3 per watt.

Building-integrated PV, or BIPV, makes sense for several reasons. First, two-thirds of the electricity generated in the United States is used in buildings. Generating some of this electricity right at the building reduces the cost of transmission and distribution. Second, the considerable space on the roofs and walls of buildings can be used for PV generation capacity. Third, PV products for buildings can replace conventional windows, skylights, walls, and roofing materials, while generating electricity at the same time.

Even though the market looks promising, developing PV products that integrate into the building structure is technically complex and involves segments of the buildings, PV, and utility industries that are normally separate. The need for such unlikely partners to develop a product is a key reason why a government program can accelerate development and use of PV products integrated into buildings. The DOE PV:BONUS (PV Building Opportunities in the United States) project, initiated in FY 1993, sponsored several new products and organized the demonstrations of these products by assembling industrial teams that included architects, building contractors, manufacturers of building materials, utilities, and PV system designers.

Prime examples of the benefits of this project are the award-winning roofing materials developed and demonstrated by a PV:BONUS team led by Energy Conversion Devices, Inc., Troy, MI. Two new products—a flexible solar shingle and solar electric metal roofing—were developed with support from laboratories to Marketplace

AstroPower's manufacturing line is currently producing 120 kilowatts of their novel Silicon-Film PV modules to be installed at UPVG ventures with utility companies. This commercial success stems from many years of work with the DOE program. AstroPower's silicon cell technology was originally developed with funding and technical assistance from the PV research program. Their module-manufacturing processes were improved with funding support from PV/Mat. And their early Silicon-Film modules were installed as emerging technology products at PV for Utility-Scale Applications (PVUSA) in Davis, CA, a utility testing ground supported by DOE and others.

AstroPower's more mature technology will now be one of the first large PV arrays installed as part of UPVG ventures with utility companies. PV program support for UPVG continues as the laboratories perform technical assessments, provide module performance measurements for sizing the PV-array, and define current and voltage operating windows for the power-conditioning system. AstroPower's modules have been tested outdoors and their performance characterized over a wide range of solar irradiance and operating temperatures using standard reporting conditions.

By working with companies like AstroPower, from the research phase through to production and demonstration, the PV program accelerates the development cycle. The result is more PV product producing electricity today.

The National Rural Electric Cooperative Association sponsors co-ops to test new approaches like this one. One of a dozen prototype systems for pumping water, these panels supplied by Golden Photon, Inc., are made of cadmium telluride thin-film.
from DOE. ECD fabricated prototype products that were tested at NREL and Sandia. This year they installed their improved products on trial applications in conjunction with the National Association of Homebuilders and the Southface Energy & Environmental Resource Center.

Another product developed under PV:BONUS is the ac PowerWall module, which substitutes for plastic or glass in curtain wall or sloped glazing systems in buildings. The modules interface directly with 120-volt ac circuits at the electric distribution panel on each floor of a building and generate up to 250 watts of power per module. They can be manufactured in virtually any dimensions—up to a maximum of 53 inches by 87 inches—to meet building design specifications. The team that developed this product included Solar Design Associates, an architectural and engineering firm; Solarex, a PV module manufacturer; and ASE Americas, Inc, a PV module manufacturer.

PV Services Network (PSN), incorporated in 1994, came into its own this year. Their 54 member utilities have purchased and installed more than 300 systems, mostly in the western United States. Before the PV Services Network, each utility had to design its own systems in house. Through a bid process, PSN encouraged suppliers to design and offer package systems for a specific price and delivery schedule. PSN also requires suppliers to issue a 2-year warranty on their products. They select suppliers based on the predicted performance of their systems, reliability of their company, and price.

Documenting Performance for International Applications

The potential demand for a reliable source of electricity in the developing world is staggering and resulted in the export of about 75% of our domestic production of PV in 1996. More than 2 billion people, or 40% of the world’s population, lack a reliable source of electricity. As our production capacity grows to meet this demand, PV will become a larger component of our export economy.

For PV products to reach this market, however, structures for financing, installing, and maintaining systems must be developed within each country. Although international lending agencies are interested in renewable energy technologies, performance must be documented before loans are granted. And organizations within countries must be familiar with the technology and its requirements to successfully incorporate it into their energy planning.
This PV pumping system, installed as part of DOE’s efforts in Mexico, supplies the domestic water for a community of 31 families in a rural area of the state of Chihuahua.

The PV program carries out country-specific pilot projects in partnership with national or state institutions to document the performance of PV technology and U.S. industry. This year, projects in Brazil, India, China, and Mexico demonstrated the benefits of PV and PV/hybrid installations.

China—In 1995, the Secretary of Energy signed a protocol agreement with the State Science and Technology Commission of China. This protocol established the framework for Sino/American cooperation to develop renewable energy technologies and markets in China. NREL is conducting a series of case studies in Mongolia for household and village-power systems to develop technical and economic performance data. The NREL team published a report with the University of Delaware, Levelized Cost Analyses of Small-Scale, Off-Grid Photovoltaic, Wind, and PV/Wind Hybrid Systems for Inner Mongolia, China. The report concludes that from both a systems and users perspective, stand-alone renewable-energy home systems generate energy for less cost than diesel generators. Therefore, a large market for household-scale renewable-energy systems should exist in Inner Mongolia.

Brazil—Prompted by the Earth Summit in Rio de Janeiro in 1992, DOE, together with the state-owned electric utilities of Brazil, has organized the installation of more than 800 PV lighting systems from U.S. manufacturers. This year, two 50-kilowatt village-scale hybrid power systems went into operation to replace diesel generators. The two systems represent significantly different approaches to the problem of remote power supply using renewable energy. Deployment and assessment of the systems will give the Brazilian utilities experience and information about hybrid power for use in future projects. Data from these projects will then be available to the World Bank and others to support requests for financing additional projects.

India—As a direct result of a DOE trade visit to India in February 1995, Solar Cells, Inc., of Toledo, OH, signed up an India business partner to introduce and distribute SCI solar power modules into the growing Indian PV market. Applied Power Corporation of Lacy, WA, will supply 30 kilowatts of PV modules, charge controllers, and a surface water pump for the Ramakrishna Mission project in West Bengal, India.

Remote Power Associates of Ft. Collins, CO, will train people in India to install and maintain the systems. In all, 300 homes in seven villages will have electric lights, auxiliary power sockets, and street lights for the first time. The project cost will be equally shared between DOE and agencies within India.

Mexico—DOE and the U.S. Agency for International Development (USAID) are co-sponsoring a program to incorporate renewable energy technologies into established Mexican programs (totaling $245 million) aimed at increasing productivity in the countryside. The program is managed by Sandia, with NREL providing technical assistance through its wind program. Through training workshops and pilot projects sponsored by DOE and USAID, several Mexican rural development organizations are gaining the technical and institutional experience to incorporate PV into their ongoing programs.

Programs to promote pumping water with PV in Mexico are especially promising. Rural demand for water in Mexico represents a potential market of more than $2 billion for PV. To demonstrate the performance of PV for rural water pumping, the PV program has helped to initiate 36 PV water-pumping projects in the Mexican states of Chihuahua, Sonora, Baja California Sur, and Quintana Roo. More than 60 additional projects are planned for 1997. Most of these water-pumping projects are planned in partnership with the Mexican Trust for Shared Risk (FIRCO). As a result of these successful projects, Sandia will help FIRCO extend the program throughout Mexico. Work has already begun to duplicate the successful projects in five additional states.

Many Mexican states have large ecological reserves with demands for electric power. The PV program is working with the Nature Conservancy, Conservation International, and the World Wildlife Fund to install PV as a clean, quiet source for the electricity needed to manage the reserves. This year six installations were completed in projects funded jointly by DOE, USAID, and the conservation organizations.
These efforts help ensure that renewable technologies and American business will benefit from World Bank and Global Environment Facility funds. Sandia is keeping the U.S. renewable energy industry involved in the program through facilitating partnerships between U.S. and Mexican vendors, and through commercialization assistance with new technologies.

In addition, several activities generally promote export of PV. These projects, which cost relatively little, have the potential to greatly impact our domestic PV industry. For example, international standards-making bodies need input from the United States. DOE PV program personnel support Task V of the International Energy Agency's Implementing Agreement for a Cooperative "Grid Interconnection of Building Integrated and Other Dispersed Photovoltaic Power Systems." The task will develop technical guidelines for low-cost, safe connection to electric grids throughout the world. The United States will lead a subtask on non-technical barriers, which will evaluate economics and market potential, assess barriers to realizing that potential, and develop strategies for overcoming institutional barriers.

Engineering Certifiable Products

Utilities, building owners, and other potential purchasers of PV products look for assurance that these products will perform as advertised. The DOE PV program has worked with industry and various standards-making groups for years to develop standard ways of reporting and verifying PV module and system performance.

This year a certification program for modules sold in the United States came several steps closer to realization. Arizona State University, with DOE support, developed a guide for accrediting laboratories to set up a national PV module certification program. Their final report, *Photovoltaic Module Certification/Laboratory Accreditation Criteria Development: Implementation Handbook*, was used to establish PowerMark Corporation, which will use third-party testing performed by accredited laboratories to certify PV modules in the United States. Four U.S. module manufacturers actively support this effort because they view it as helpful in establishing buyer confidence in their products.

In addition, an Institute of Electrical and Electronics Engineers (IEEE) standards coordinating committee approved the first consensus standard of qualification practices for flat-plate PV modules. The tests specified in the document, many of which were developed and validated at DOE laboratories, cover crystalline-silicon and amorphous-silicon flat-plate modules and can be used for other thin-film modules.

Another useful tool for consumers will be a module energy-rating method being developed by the PV program. The methodology describes how to measure module characteristics under certain sets of weather and load conditions. When validated with data from actual systems operating in the field, the method will estimate module performance under specified conditions using a combination of models.

In other standards activities, the PV program supports efforts through IEEE to develop a standard for utility interconnection of PV systems. In addition, DOE supports the Solar Energy Industries Association to provide PV industry representation and feedback for changes to the National Electrical Code. Almost 50 PV-related proposals have been submitted for the 1999 cycle of the National Electrical Code.
Managing Program Resources

A National Center uses resources efficiently

The National Center for Photovoltaics

The National Center for Photovoltaics (NCPV) was created this year to strengthen communication and further unify national PV interests. The large number of participants—the PV industry, associations, consortia, utilities, and other end-users—involved in developing this technology grows each year. As we enter the present era in photovoltaics, the direct personal interaction once used to apply resources to problems must be augmented.

The NCPV will serve as a focal point for all the nation’s capabilities in photovoltaic research, development, deployment, and outreach. The National Center unites geographically dispersed researchers in a common purpose, with the sum greater than the individual pieces. Based at DOE’s National Renewable Energy Laboratory, the NCPV draws on the core expertise of NREL and Sandia National Laboratories to guide operations and coordinate support from other resources. These other national PV resources include Brookhaven National Laboratory and DOE’s Centers of Excellence in PV at the Georgia Institute of Technology and the Institute of Energy Conversion at the University of Delaware. In addition, dozens of university and industry research partners across the country are linked together to function in a more unified way. And the NCPV’s use of electronic communications and interlinked databases ensures all members of the PV community fast, easy access to the growing body of knowledge about photovoltaic systems and their applications.

Facilities Available

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

Material and Device Development—Competencies include solid-state spectroscopic analysis, experimentation with photoelectrochemical processes, and the application of advanced theoretical and computational tools for predicting the behavior of new PV materials.

Module and System Development—Facilities include laboratories for fabricating and evaluating thin-film technologies (amorphous silicon, cadmium telluride, and copper indium gallium diselenide), crystalline-silicon cells and modules, concentrator cells and PV arrays, and for developing and testing balance-of-systems components such as charge controllers and inverters.


Performance and Reliability Testing—PV technologies are tested using outdoor test beds, indoor laboratories, and field trials. Equipment can be tested under simulated and actual outdoor conditions, and under varying temperature, humidity, precipitation, and radiation levels.

Manufacturing and Deployment—Cost-shared development programs evaluate and resolve technical issues in the production of PV components and systems. DOE experts of the National Center work with large user groups such as utilities to address technical issues in deploying PV technologies in new applications.