Photovoltaic Energy Program Overview

Fiscal Year 1997

U.S. Department of Energy

Message from the Director

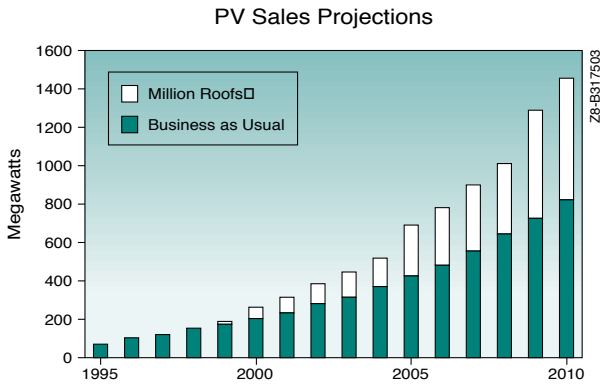
Warren Gretz, NREL/PIX03606

James E. Rannels

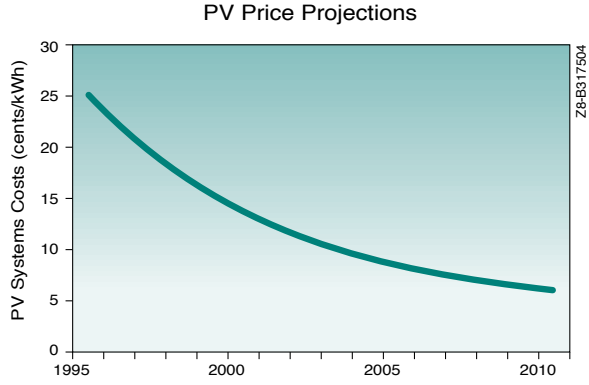
The photovoltaic (PV) industry in the United States is booming, claiming a growing share of an expanding worldwide market that grew 42% in 1997, from 89 megawatts (MW) to 126 MW. The U.S. share of this market amounted to almost 53 MW, which is a 35% increase in one year. And our market share is now 42%—markedly improved from 1991, when U.S. companies accounted for only 31% of total sales.

Operating at full capacity, with a backlog of orders and with manufacturing expansion in progress, the U.S. PV industry is poised to take advantage of a rapidly changing marketplace. This year saw new products introduced, manufacturing processes improved, capacity expanded, and new materials explored. Conversion efficiencies for cells and modules continued to improve steadily, and PV systems became more reliable.

A solid foundation for the Million Solar Roofs Initiative, announced by President Clinton on June 26, 1997, was laid by the combination of steady research progress in laboratories and universities, industry investment in new technology and capacity, and a burgeoning market. To help reduce production of harmful greenhouse gases, the President called on the Department of Energy (DOE) to lead the effort to place one-million solar energy systems on buildings and homes across the nation by 2010. Half of these installations are planned for photovoltaic systems.



Business-as-usual projections based on "PV Industry Overview: Domestic and International," Robert Johnson, Mountain View, CA: Strategies Unlimited, 1996. The additions to business-as-usual projections are based on Million Solar Roofs goals.



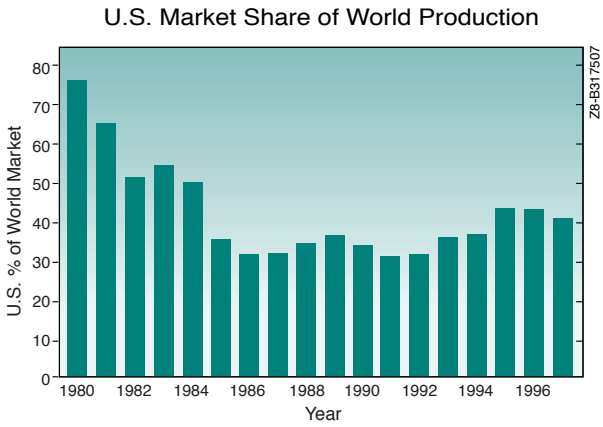
Cost goals derived from "PV: The Power of Choice, National PV Program Plan for 1996-2000," DOE, 1996.

The Million Solar Roofs Initiative will help the PV industry develop a most promising large-scale domestic market. As domestic sales increase and prices decline, the industry will further enhance its competitive advantage in the international market, where two-billion people have roofs but no electricity. Photovoltaics can generate electricity for these people, with less production of greenhouse gases than using fossil fuels.

Although one-million roofs is a dramatic advance from where we are today, it is a modest goal compared to PV's market and technical potential. I expect we will meet the Million Solar Roofs objective by 2010 and then far exceed it in the years after. The Initiative adds to the momentum that is building around the world for the use of solar power.

And it also complements the strong base of research and development that is the core of our PV Program.

The first step in the Initiative requires nearly doubling the sales of PV products made in the United States by 1999. By achieving 7,000 solar roofs by 1999 and reaching 1,000,000 in 2010, we will be one of the first programs to contribute to the President's goal of reducing U.S. greenhouse gas emissions below 1990 levels between 2010 and 2012. We will accomplish even more in developing countries, where greenhouse gas emissions are growing the fastest. Working in partnership, we have the opportunity to move PV to a new level of importance in the global energy mix.



Information is derived from Paul Maycock, PV News, *January 1998, v.17, n.1, and past issues.*

The DOE Office of PV and Wind Technologies will continue to support the domestic PV industry. At the beginning of FY 1997, DOE formed the National Center for Photovoltaics specifically to serve as a focal point for industry, end users, and the research community. Through the efforts of the PV community working together, I look forward to continued leadership by the United States in this technology.

James E. Rannels

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

Cover Photos:

From top left, clockwise:

A National Center for Photovoltaics engineer at Sandia National Laboratories uses a hail tester to determine the ability of a PV module to withstand the impact of hail stones. (Jim Yost Photography/PIX01820)

This home built by FIRST (Fully Integrated Residential Solar Technology) includes a 1.8-kW PV array of amorphous silicon modules. The house, which is near Princeton, NJ, is not connected to the utility grid. (Lyle Rawlings, FIRST/PIX04474)

A sheet of thin-film silicon emerges from the growth chamber of AstroPower, Inc.'s, manufacturing plant. The SiliconFilm™ product was developed through the DOE PV Program's PV Manufacturing Technology (PVMaT) project. (Rusty Ristin, AstroPower/PIX05668)

Using a physical vapor deposition system, an NCPV researcher at the National Renewable Energy Laboratory fabricates high-efficiency PV devices of thin films of copper indium diselenide. (Jim Yost Photography/PIX03524)

At the Salinas Missions National Monument, New Mexico, a 1.5-kW grid-tied PV system provides two-thirds of the power for the Visitor Center and comfort station. (National Park Service/PIX05664)

Background photo:

This house in coastal Maine generates its own electricity from a 4.25-kW PV system beautifully integrated into the rooftop. Surplus power is sent back into the utility grid. (Solar Design Associates/PIX04470)

1997 PV Program Highlights

Systems Engineering and Applications . . . . . page 2

■ The Department of Defense selected the 450-kW PV array at the U.S. Army Yuma Proving Grounds as a Federal Energy Management Program Showcase Facility.

■ The National Park Foundation awarded Sandia the 1997 National Park Partnership Leadership Award for promoting and expanding the use of renewable energy, reflecting the impact of the 1.5 MW of federal agency PV projects facilitated by the National Center for Photovoltaics.

■ The PV Program helped to complete 300 solar PV home-lighting systems in eight villages of the Sundarbans region in India.

■ To support safe installation of PV systems, the PV Program facilitated industry proposals of more than 50 changes, which have been accepted, to the 1999 National Electrical Code. The Program also facilitated a proposed standard for utility interconnection of PV systems.

■ The PV Program facilitated the development of criteria for laboratory accreditation and module certification. These criteria were applied to Arizona State University PV Test Facility—the first U.S. laboratory accredited by PowerMark Corporation to certify PV modules.

■ The PV Program designed and built a flexible test bed at the Outdoor Test Facility for short-term system performance characterization. The Program also sponsored the 1997 PV Systems and Performance Workshop, providing the primary forum for communication on system issues between industry suppliers and users of the technology.

■ The PV Program established baseline operation and maintenance costs for systems and identified the factors contributing to reliability.

Technology Development . . . . . page 9

■ The PV Program worked to extend the successes of the PV Manufacturing Technology (PVMaT) project, receiving 31 proposals for the new Phase 5A and supporting industrial manufacturing improvements that resulted in capacity growth.

■ United Solar Systems Corporation and Solarex opened large manufacturing lines for PV modules made of thin-film materials.

■ PV Program researchers gained new insights into failure mechanisms affecting the service lifetime of modules.

■ A patent application has been filed for a new encapsulant developed at NREL that has greater photothermal stability than current commercial formulations.

■ Cooperative R&D on balance of systems for PV produced a new, 97%-efficient, grid-tied inverter from Utility Power Group. Specifications were also developed for a new 30-kilowatt (kW) hybrid inverter.

Research and Development . . . . . page 17

■ United Solar made amorphous silicon triple-junction cells with a stable, total-area conversion efficiency of 12.1%, measured after 1000 hours of light-soaking.

■ The first PV Program Fulbright scholar proposed a theory to explain the Staebler-Wronski effect.

■ DOE's cadmium telluride team developed a new, high-performance transparent conducting oxide. The first cells produced with this material had an efficiency of 14%, and a patent application has been filed.

■ Siemens Solar Industries tested a 1-kW copper indium diselenide array having 9.2% efficiency.

■ AstroPower produced a 9.2%, 321-cm^2 monolithically interconnected Silicon-Film™ minimodule.

■ NREL received an R&D 100 Award for its new software tool, *PV Optics,* for cell and module design.

■ The PV Program received 63 proposals for participation in the next round of Thin Film PV Partnerships.

■ The Georgia Institute of Technology produced high-efficiency crystalline silicon cells (19.1% on float-zone material and 18.4% on Czochralski material) with rapid thermal processing.

Introduction

The U.S. Department of Energy (DOE) Photovoltaic Energy Program fosters the widespread acceptance of photovoltaic (PV) technology and accelerates commercial use of U.S. PV products. The Program is founded on a collaborative strategy involving industry, the research and development community, potential users, utilities, and state and federal agencies. There are three main Program elements: Systems Engineering and Applications, Technology Development, and Research and Development.

Systems engineering and applications activities make the essential connection between technology and markets. Systems engineering activities help commercialize PV systems by using the PV Program's engineering expertise to assist both industry and users in achieving the highest probability of success that PV systems will work as expected. Applications efforts deploy PV technologies to demonstrate and validate their performance in specific applications.

Technology development projects help new product ideas progress to manufacturing reality. Many PV manufacturing companies have improved their production processes and lowered manufacturing costs through a variety of DOE-supported and cost-shared programs.

Research and development projects generate new ideas, develop new theories, build laboratory-scale PV devices that push the limits of conversion efficiency, and address problems inherent in bringing processes from the laboratory to manufacturing.

As PV technology has matured, the number of people and organizations working in the field has grown tremendously. Recognizing the benefits of improved communication among these many people, DOE formed the National Center for Photovoltaics (NCPV) in November of 1996. The NCPV is working to help the U.S. PV industry maintain its global leadership in the face of intense foreign competition. The NCPV currently includes staff at the National Renewable Energy Laboratory (NREL), Sandia National Laboratories and several other organizations.

A strategic review held by the NCPV in July 1997 engaged the PV community in formulating plans for future activities. This success is highlighted in a letter from a major U.S. PV manufacturer to the NCPV. "The workshop played a valuable role in pulling together key representatives of all sectors of the U.S. PV community and getting their comments and suggestions in a documented report that could be used to help generate a national PV plan."

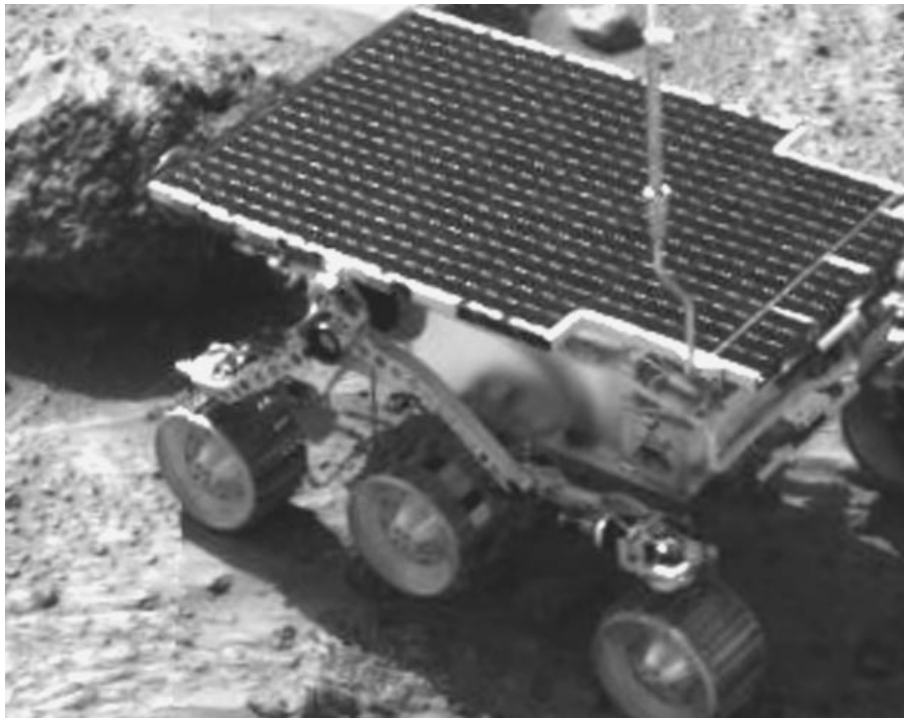


Photo from NASA Website

After decades of use on Earth and in space, PV saw its first use on another planet in 1997 when Sojourner began to explore Mars. These high-efficiency GaAs/Ge cells mounted on top of the vehicle provide 16 watts of power at noon on Mars, enough to perform the mission each day.

Systems Engineering and Applications

Expanding the global market for U.S. PV products

This year the PV Program's systems engineering and applications activities promoted wider use of photovoltaics at home and abroad. PV projects were installed in the national parks, on military bases, on public lands, on buildings, and in utility systems across the United States. Elsewhere, the Program's efforts placed U.S. PV products in some of the most populous countries of the world. Strategic alliances with end-use industries also fostered opportunities for the U.S. PV industry.

Byron Stafford, NREL/PIX05364

Sunrayce '97, a solar car race held for university students, was sponsored by General Motors, DOE, and Electronic Data Systems. The competition helps engineering students gain practical experience in photovoltaics and automotive technology. The race was held in June, starting in Indianapolis, Indiana, and finishing in Colorado Springs, Colorado. The top 3 finishers out of the 36 entries were California State University, Los Angeles, Massachusetts Institute of Technology, and Stanford University/University of California, Berkeley (shown here). Plans are under way for Sunrayce '99.

MILLION SOLAR ROOFS I

DOE Supports a New Presidential Initiative

The President's Million Solar Roofs Initiative, announced in June 1997, is designed to develop a large-scale domestic market for PV by increasing sales and reducing prices. By 2010, one million solar energy systems are proposed to be operating on the nation's roofs. The Initiative targets cost-effective applications of PV and reaches out to many groups within communities across the United States—groups that include city planners, housing developers and builders, utilities, PV manufacturers and suppliers, and home owners.

Market Conditioning

In the on-going effort to educate potential users of PV technology, DOE is working with the Solar Energy Industries Association and Photovoltaics for Utilities (PV4U) working groups. This year, an information/marketing package was designed for each of five target groups: embassies, organic farmers, the military, recreational vehicle clubs, and home improvement stores. DOE also developed and implemented Solar Finance, the first-ever national consumer finance program for PV and solar-thermal projects. The PV Program co-sponsored a project to develop a database of mortgage lenders willing to finance grid-independent homes and is negotiating with Bank of America to develop a national grid-independent home mortgage program. PV4U, managed by the Interstate Renewable Energy Council, continues its work with multiple stakeholder groups and consumer and environmental constituencies. PV4U state working groups now number 14.

Through the efforts of the PV Program's Markets and Applications team, as many as 750,000 people were introduced to the possibilities of PV in 1997. These efforts included such high-visibility events as the Pageant for Peace (a PV demonstration on the Mall in Washington, D.C.), the National Western Stock Show in Denver, and Sunrayce 97, as well as a growing number of international projects.

Utilities

The coming restructuring of the utility industry will catapult applications of PV technology into many new locales. PV offers an easy way for utilities to diversify into new, previously unserved remote markets. PV offers fast construction with an

MILLION SOLAR ROOFS II

Million Solar Roofs Initiative Is a Collaborative Effort

Million Solar Roofs will be implemented at the state and local level largely by groups that have been working with the DOE Program to promote PV. For example, the Utility PhotoVoltaic Group has already initiated several commercial and community efforts for the President's Million Solar Roofs Initiative. In another effort, the California PV Alliance, a PV4U working group, helped develop the California Solar Fund, which is a proposal to provide consumer incentives to purchase PV systems. The proposal, submitted to the $540 million California Renewables Trust Fund, is a model for state implementation of the Million Solar Roofs Initiative.

acceptable environmental impact. One NREL PV publication highlights the best U.S. locations for grid-connected PV systems. Another publication maps effective load-carrying capacity—a measure of how well PV can meet customer demand. A good example of high capacity for PV is in regions where midday air-conditioning demands are high. There, PV has a high tangible value to utilities in generating capacity to meet peak loads.

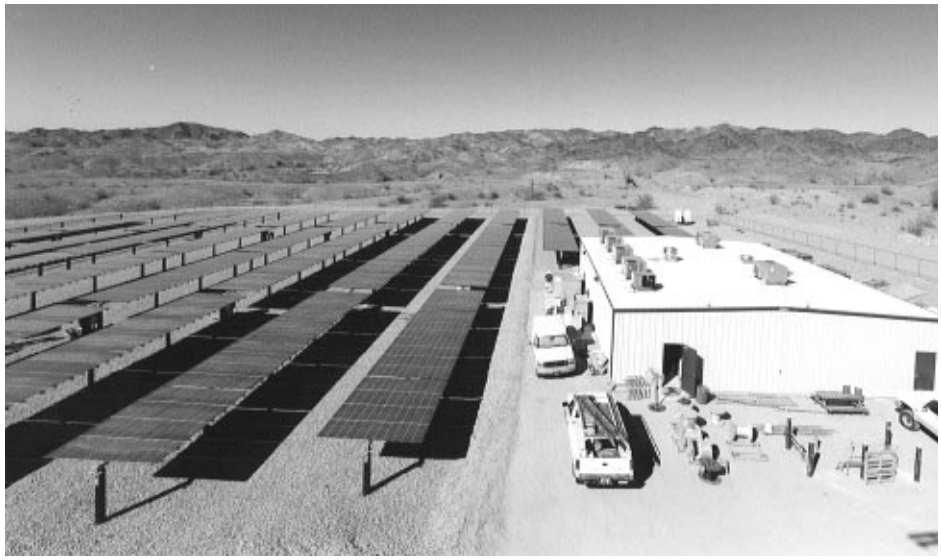
While PV can boost a utility's capacity at peak times, it can also serve homes and buildings directly. Such individual units, connected to the utility grid, are cost-effective now in regions such as Oahu, Hawaii, where conventional electric energy costs may exceed $0.12 per kilowatt hour. An NREL study shows that the best immediate markets for PV are in Hawaii, California, Arizona, New York, and Massachusetts. If other factors—tax credits, depreciation, financing, leasing, and giving full retail credit for PV-generated electricity (net-metering)—are added, PV becomes a cost-effective choice in many other areas.

The Utility PhotoVoltaic Group (UPVG), formed in 1992, is a group of more than 80 utilities and associations working to commercialize PV systems. UPVG, whose member utilities represent more than 40% of U.S. electricity sales, gets financial support from its members and from DOE. As of this year, there were 24 UPVG ventures under contract. As many as 35 utilities are directly involved in 25 states with commitments for more than 1300 PV installations. A total of 1.5 MW is installed and an additional 6.7 MW are planned. The NCPV provides technical assistance during the planning and installation of these ventures.

This year, DOE laid the groundwork for expansion in the restructured electricity market through educational activities on net metering and consumer incentive programs. Legislation was introduced in seven states this year and passed in three, bringing to 20 the number of states that have some form of net metering.

U.S. government agencies

Facilities operated by federal, state, and local governments present many opportunities for cost-effective installations of PV. With more than 500,000 rooftops, the federal government is the world's largest owner of buildings. The U.S. government spends more than $3 billion each year on electricity for buildings. State and local governments also own and operate many facilities that could save money by installing PV. The PV Program facilitated the installation of 1.5 MW of PV systems in government installations this year. These ranged widely in purpose, size, and location, but the majority were less than 1 kW, for uses such as providing power at remote recreational sites or pumping groundwater to reduce demands on surface waters.



Sandia National Laboratories/PIX05788

The 450-kW PV array at the U.S. Army Yuma Proving Grounds in southwestern Arizona is shown. Photovoltaics offered an excellent solution for Yuma because PV can generate the most electricity at the same time that Yuma experiences its peak demand—on summer afternoons when the sun is shining and all air conditioners are on. (Utility Power Group, ASE Americas, C&D Batteries, and Trace Engineering)

Department of Defense—The Department of Defense (DoD) consumes more energy than any other user in the world. Utility bills for DoD run more than $2 billion a year for about 35,000 billion kilowatt-hours of electricity. In addition to electricity purchased from utilities, DoD also generates about 3,000 gigawatt-hours of electricity at remote locations using fossil fuels. Costs for generating this electricity at remote locations may rise to $1 billion per year.

The PV Program has worked with DoD for more than a decade to make PV an option at military installations. Thanks to early studies that identified more than 50,000 cost-effective projects within DoD, standard military construction practice now includes considering PV. But for large installations (more than 100 kW), there were no suitable power-processing units on the market to convert direct current generated by PV into the alternating current most commonly used. To develop, test, and demonstrate the necessary new power-processing technologies, the PV Program worked with the military using funding from the Strategic Environmental Research and Development Program (SERDP).

Funding through SERDP and DOE has made several showcase military installations of PV possible. For example, this year, after five years of planning and testing, Sandia's researchers helped DoD install a unique grid-tied PV powerplant at the U.S. Army Yuma Proving Ground in 1997. The system, tied to the utility grid, can operate three different ways: it can supply the grid with up to 375 kW of ac power directly from the PV array; it can power a critical water-treatment plant during utility outages; and it can supplement the array power with battery power to supply up to 925 kW for maximum peak-shaving benefit.

In developing the Yuma project, systems integration and power-conditioning technologies have advanced significantly. Now that this technology base exists, more large-scale, PV powerplant applications can be identified and implemented within DoD. The Yuma facility and its power-processing and control technology were selected as one of DoD's Federal Energy Management Program Showcase Facilities. At the moment, the Yuma system is unique; but there are perhaps thousands of mini-grid, as well as remote and grid-connected, DoD facilities that could take advantage of the economical and environmental benefits demonstrated at Yuma.

PV in the Parks and on Public Land—The National Park Service, the U.S. Forest Service, and the Bureau of Land Management (BLM) all have large recreational areas without an electric power infrastructure. Such dispersed power needs can be met by PV systems designed to standardized specifications. For example, BLM took advantage of standardization with this year's installation of six 4-kW PV water pumpers in the Richfield District of Utah. Other PV installations completed by the BLM this year provide nearly 40 kW for lights and power for campgrounds, rest rooms, and host trailers in California, Colorado, Idaho, Oregon, Utah, and Wyoming.

In another project that took advantage of a standardized, packaged PV

MILLION SOLAR ROOFS III

Utilities Are Important Partners

One of the first successful models that could be followed for the Million Solar Roofs Initiative is the PV Pioneer project of the Sacramento Municipal Utility District. Participants pay less than $10 per month extra to "host" a 4-kilowatt rooftop PV system that feeds power back to the utility. In return, these customers are guaranteed that their electricity rates will not increase for 10 years.

Sandia National Laboratories/PIX05787

BLM campground hosts, as this one in Utah, rely on PV power to make their remote locations more comfortable. (Applied Power Corp., Solarex, Absolyte, and Trace Engineering)

Currin Corporation/PIX05667

This 11.2-kW PV array is part of the hybrid solar/diesel generator power system on North Manitou Island at Sleeping Bear Dunes National Lakeshore, Michigan. Three identical sub-arrays provide a total peak current of 75 amps for charging a 288-kW, 120-V battery bank. (Currin Corp., Solarex, Absolyte, and Advanced Energy Systems).

system made possible by the PV Program, the National Park Service installed a PV array at Salinas Pueblo Missions National Monument in New Mexico. This newest project in the PV Program's "Renew the Parks" partnership with the National Park Service benefited from Sandia's technical support and includes a 5-year, full-service agreement.

Sandia received the 1997 National Park Partnership Leadership Award from the National Park Foundation for promoting and expanding the use of renewable energy throughout the nation's parks with the on-going effort to define standardized PV packages. For example, a hybrid PV system installed at Pinnacles National Monument last year was the model for a 7.5-kW system being installed in North Cascades National Park this year, as well as for other units now being readied for Joshua Tree National Monument and Mohave National Preserve. Other "Renew the Parks" PV systems were completed and installed this year at the North Rim of the Grand Canyon, Navajo National Monument, the Channel Islands National Park, Yosemite National Park, and Sleeping Bear Dunes National Lakeshore.

PV Partnerships with the States—Working at the state level through the Interstate Renewable Energy Council (IREC), Sandia awarded 11 contracts in 1997 to state agencies, utilities, and other organizations across the United States that had not previously installed a PV project. For example, an IREC project in central Texas uses PV to pump water for livestock, with the utility charging farmers a special rate developed just for PV. Farther north, the Wisconsin Department of Natural Resources is identifying cost-effective applications for PV throughout its 60-facility system. How these first-time users of PV work their way through a project will be documented by Sandia and IREC.

Building-integrated photovoltaics

Residential, commercial, and institutional buildings consume about 67% of the electricity generated in the United States. To encourage the development of PV systems that work with building designs, DOE

Photovoltaics Systems Assistance Center

The Photovoltaics Systems Assistance Center (PVSAC) at Sandia promotes the use of PV technology through publications, technical assistance, and engineering evaluations. In 1997, the Center distributed more than 10,000 PVSAC publications, including the newly published *NEC Recommended Practices*, a manual of safety practices, and *Renew the Public Lands*, which identifies a large potential BLM market for the U.S. PV industry. In addition, PVSAC provided significant technical assistance to 106 requesters from the PV industry and 128 users of PV systems.

The PVSAC also manages DOE contracts for the Southwest Technology Development Institute at New Mexico State University in Las Cruces and the Florida Solar Energy Center at the University of Central Florida in Cocoa. The Florida Center focuses on building-integration issues at the component level. The Southwest Institute works with hybrid systems. Both groups conduct site surveys, "snapshot" one-day evaluations of the reliability of installed PV systems, and monitor other PV installations over a period of months to analyze their performance. PVSAC, through these contractors, performed technical evaluations at 24 utility and federal agency sites and prepared nearly 200 data reports for monitored sites.

initiated PV:BONUS (Building Opportunities in the United States for Photovoltaics) in 1993.

The PV:BONUS project funded the development of several commercial products for the building industry. For example, the award-winning flexible solar shingle and solar-electric metal roofing of Energy Conversion Devices, Inc., are now available as commercial products. The shingle modules are currently being produced at a rate of 40 kW per month.

Other PV:BONUS projects are moving toward the marketplace. The large-area ac PV module and micro-inverter developed by Solar Design Associates, Inc., received Underwriters Laboratories (UL) certification this year. In addition, four grid-connected, dispatchable PV peak-shaving systems developed under PV:BONUS contracts have been installed by Delmarva Power and Light Company, an investor-owned electric and gas utility headquartered in Wilmington, Delaware. Modular solar homes being developed by a consortium of builders, PV manufacturers, and utilities have been erected in the Washington area and in Philadelphia. The Philadelphia homes had substantially lower construction costs ($20 per square-foot less) than conventional homes in the community.

To expand on the success of the original PV:BONUS contracts, 17 new awards were made in 1997 under Phase I of PV:BONUS Two. The objective of PV:BONUS Two is to develop technologies and to foster business arrangements that integrate PV or hybrid products into buildings and demonstrate commercially viable products.

PV and agriculture

PV systems are reliable, require little maintenance, and put power right where it is needed—a primary asset for many agricultural uses such as electric fences, water pumping, and battery charging. Any small application where utility power is farther than several hundred feet away is a candidate for PV systems. The Photovoltaic Services Network, initially supported by the PV Program, publishes an annual catalog of "packaged" PV systems for remote residential use, water-pumping, and security lighting. In 1997, NREL published *Photovoltaics for Farms and Ranches*, a 24-page brochure detailing PV uses in remote agricultural applications. In addition, travelling exhibits spread information about PV at stock shows and agricultural equipment conventions across the nation's farm belt.

International markets growing for U.S. products

Some 40% of the world's population does not have access to electricity. Providing electricity is essential for raising health and living standards, so DOE is supporting the installation of renewable energy projects in emerging energy markets around the world. This year, DOE supported PV projects in the world's two most populous countries, China and India.

India—An agreement between DOE and the Ministry of Non-Conventional Energy Sources of India calls for sharing project costs 50-50 to demonstrate the economic viability of PV systems in India. This year, 300 solar PV home-lighting systems in eight villages in the Sundarbans region were completed by the Sustainable Rural Electrification Project with the Ramakrishna Mission in West Bengal, India.

China—A U.S./China summit held in Beijing in October 1997 proposed a Joint Program on Rural Electrification including village power, solar home systems, hybrid PV/wind/diesel systems, grid-connected wind-

United Solar Systems Corp./PIX05673

Embedded in these roof shingles are advanced, triple-junction amorphous silicon cells developed by United Solar Systems Corp., within the Thin Film PV Partnership.

farms, biomass gasification, and geothermal energy use. DOE and NREL cooperative work in China is expanding the work of the Solar Electric Light Fund (SELF). SELF established a system of credit for homeowners to finance PV systems in the Gansu province. The revolving credit accounts, managed by a local nonprofit group, were used to purchase equipment and services from local vendors. PV has now been installed in 300 households and 10 schools. The World Bank is also interested in developing renewable energy in China and, as applications expand, the potential market for U.S. PV products will also expand.

Brazil—A good example of how DOE's international projects help open markets to U.S. industry is the DOE effort in Brazil. More than 90% of the PV systems now in place were purchased from U.S. suppliers. This includes cooperative projects in five Brazilian states where DOE work is now integrating system designs and developing in-country installation and maintenance expertise.

South Africa—DOE and NREL are working with Renewable Energy for South Africa, the U.S. Agency for International Development, the National Rural Electric Cooperative Association, and Renewable Energy for African Development to bring stand-alone renewable power systems to 16,000 schools and 2,000 clinics. The first step is a pilot program using 2500 PV systems for off-grid rural electricity. DOE is also assisting the South African government in restructuring the electricity sector. U.S. analysts work with their counterparts in South Africa to analyze power generation, transmission, and distribution. In addition, NREL personnel will help train South Africans about the utility requirements for PV and other renewable energy sources.

Mexico—DOE's collaboration with the U.S. Agency for International Development on the development of pilot renewable energy projects in Mexico continues to demonstrate significant results. In 1997, the rate of project implementation doubled and there are now more than 120 PV systems installed in eight Mexican states. The applications are primarily water pumping for livestock and power for ranger stations. Sandia manages this program and NREL provides technical assistance. While the U.S. cost share for the pilot projects has been declining, the U.S. PV industry is gaining more access to Mexican markets. In FY 1997, one of Sandia's principal Mexican partners, the Mexican Trust for Shared Risk (FIRCO), began implementing parts of a $1.8 billion agricultural development program that explicitly includes renewable energy equipment.

Harin Ullal, NREL/PIX 05161

This PV module installed on a roof in an Indian village is part of the Ramakrishna Mission PV project in Sundarbans, West Bengal, India. (Solarex modules; Morningstar charge controllers; Applied Power Corporation, systems integration; Remote Power International, training).

Systems Engineering

Standards and codes

To be successful in global markets, PV products must not only work well, they must also meet internationally recognized standards performance and safety criteria. One effort to specify the performance and safety of PV systems is the PV Global Approval Program (PV GAP). This program an international effort to certify PV components and systems, includes representatives from the NCPV on its board of directors and working committees. To support these efforts, DOE provides funding to the International Energy Commission-Technical Committee 82 effort. Standards are especially important for PV products

designed to operate dependably in a variety of applications. Standards are now being developed for PV concentrator systems.

The DOE PV Program has long worked to develop both domestic and international standards, codes, and certification programs for PV products. This year the work paid off as PV products began to achieve the Underwriters Laboratories (UL) listings necessary for consumer confidence. In addition, DOE facilitated industry proposals of more than 50 changes to the 1999 National Electrical Code that would support the safe installation of PV systems. These changes have been adopted. The Program systems engineers also facilitated a proposed standard for utility interconnection of PV systems.

This year, the Arizona State University PV Test Facility became the first U.S. laboratory to be accredited by the PowerMark Corporation to certify PV modules. Using the recommended procedures and specifications for evaluating PV modules developed by the Institute of Electrical and Electronics Engineers— IEEE 1262— this certifying facility applies the DOE-facilitated criteria developed for laboratory accreditation and module certification. Industry involvement in this effort was key to its success.

The National PV Program operates test facilities to support research and validate performance of products for the PV industry. To adapt to different standardized tests of modules and systems, the Program added a flexible test bed to the Outdoor Test Facility at NREL. The flexible test bed, which can run a variety of standards tests, will be used to validate interface compatibility test methods for small PV systems.

Performance and reliability

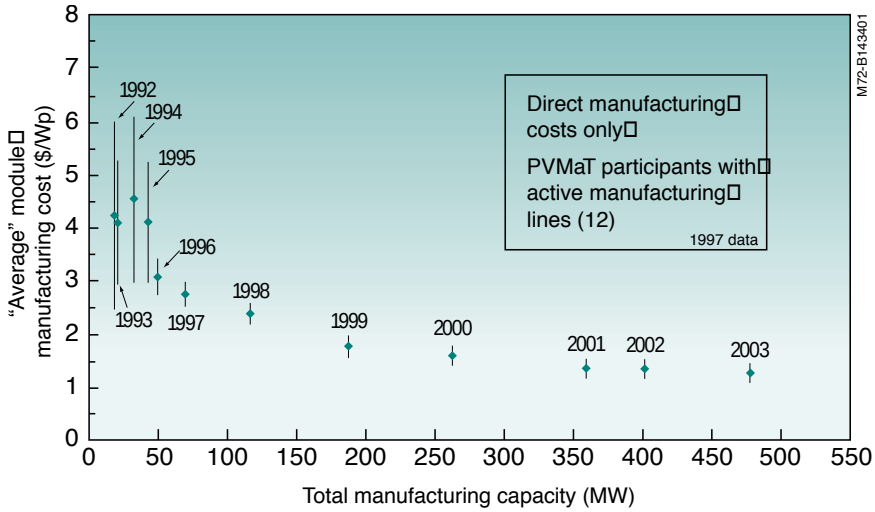
Industry and key users joined the national laboratories and the Southwest Technology Development Institute in August to discuss issues about PV performance and reliability. Nearly 100 people joined in discussions of PV systems issues, heard about lessons learned from field testing, and focused on real concerns for large, grid-tied PV systems. Specific topics included problems and resolutions with power conditioners, control systems, and maintenance of remote PV systems.

In FY 1997, in a partnership with the PV industry and PV system owners, NCPV researchers at Sandia quantified baseline operation and maintenance costs of systems. Factors contributing to reliability were identified and modeled, and these results will be used for future system improvements.

Technology Development

Modifying successful laboratory techniques for industrial production

This year the PV Program worked with PV companies in several ways to increase the conversion efficiency of potential new products and improve manufacturing techniques for current and future products. The Program conducted applied research and tested new concepts through the PV Manufacturing Technology (PVMaT) and Thin Film PV Partnership programs, cooperative research and development agreements (CRADAs), and in-house research at the DOE laboratories.



A PVMaT study shows that manufacturing costs have declined and are expected to decline further as manufacturing capacity increases over time.

PVMaT Repays Investments

To enhance the worldwide competitiveness of the U.S. PV industry, Congress approved funds for the PVMaT project in 1990. Sharing costs between the PV Program and the individual manufacturers, the total funding to date for PVMaT—including some 43% from industry—is about $146 million.

The PVMaT project is both helping the U.S. PV industry to extend its world leadership in manufacturing and stimulating commercial development of PV modules and systems. The objectives of PVMaT are to help industry:

- Improve manufacturing processes
- Accelerate manufacturing-cost reductions for PV modules
- Improve commercial product performance
- Lay the groundwork for substantial scale-up of U.S.-based PV manufacturing capabilities.

PVMaT's success in reducing the manufacturing cost of U.S. PV products repays both manufacturers and U.S. taxpayers for their investments. Since 1990, PVMaT has teamed the PV Program with industry in five separate staggered phases, to support the evolution of technology in the industry. This step-wise development process has been instrumental in the success of the U.S. PV industry.

Systems and components for PV products

In most cases, modules comprise less than half the cost of PV sys-

Solarex CRADA Supports Scale-Up of a-Si Module Manufacturing

Making larger modules is an important step to move prototype technologies toward manufactured products. To help scale up Solarex's multijunction amorphous silicon technology from 4-ft^2 prototypes to 8.6-ft^2 commercial modules, NREL and Solarex began a 24-month, $794,000 (roughly 50-50 cost-shared) CRADA. The new, larger modules can be used in building-integrated PV applications, solar farms, and more-traditional remote applications.

There are five major tasks in the CRADA:

- Characterize amorphous silicon multijunction modules.
- Characterize materials and devices.
- Study the stability of amorphous silicon alloys and devices.
- Test reliability.
- Identify and eliminate defects.

tems. 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 contracts under PVMaT may address either components or complete systems with optimized components or specialized components for PV generation.

Advanced Energy Systems, Inc. Wilton, N.H., developed a next-generation prototype 60-kW inverter for both grid-interactive uses and hybrid applications such as conditioning PV and/or wind-generated electricity for village power or remote military applications. The new design incorporates simpler manufacturing steps and remote monitoring. WPI Power Systems, Inc., of Warner, NH, built the inverter and assisted with the magnetics design. During Phase 4A1, Advanced Energy Systems, Inc., reduced the physical size of the inverter by 70%, simplified control circuits to reduce costs 5 cents per watt, and improved magnetics to reduce overall unit cost by $2000.

Ascension Technology, Inc., Waltham, MA, is working with ASE Americas Corp., Billerica, MA, to develop an Underwriters Laboratories-listed ac PV module rated at 240 to 300 watts. This unit combines ASE Americas' PV module, which produces dc electricity, with Ascension's ac inverter. In 1997, the module-sized inverter was fully integrated with ASE Americas' large-area PV module and the assembly was Underwriters Laboratories-listed and certified by the Federal Communications Commission. Innovations included a new mounting and quick-connector design and a "Zebra" anti-islanding circuit. The assembly was delivered to the NCPV for development tests. This PV unit is the first to be Underwriters Laboratories-listed. It is currently being shipped to several utilities for long-term performance tests.

Evergreen Solar, Inc., Waltham, MA, is developing new materials to facilitate continuous, in-line manufacturing of PV modules for high-volume mass production. 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 vacuum curing. Evergreen also developed a novel hard backskin material that serves as the frame, as well as the backskin for modules. It also can be processed continuously. A new innovative mounting design allows mounting brackets to be bonded directly to the backskin.

Omnion Power Engineering Corporation, East Troy, WI, working with Soft Switching Technologies,

Phases of the PVMaT Program

Phase 1: Problem Identification

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

Phase 2A: Process-Specific Problem Solutions

Seven companies carried out their recommendations from Phase 1 to perform manufacturing R&D intended to decrease PV module manufacturing costs and increase manufacturing capacities.

Phase 2B: Process-Specific Problem Solutions

Four companies carried out projects similar to those of Phase 2A. These 3-year subcontracts began in FY 1994.

Phase 3A: Generic Problem Solutions

Two companies addressed issues common to the entire PV industry. These subcontracts, begun in FY 1993, were completed in FY 1996.

Phase 4A: Process-Specific Problem Solutions

Phase 4A1—Eight companies began 2-year subcontracts in 1995 to develop system and component technology for PV products.

Phase 4A2—Five companies began 3-year subcontracts in 1995 to address company-specific manufacturing issues to reduce costs and increase the capacity of their production facilities. These subcontracts are similar to research carried out with other companies under phases 2A and 2B.

Phase 5A: Process-Specific Problem Solutions

Thirty-one proposals were received for Phase 5A, announced in June 1997. Phase 5A awards, similar to the 4A awards, will emphasize product-driven manufacturing R&D for improvements and cost reductions in manufacturing full-system PV products and are planned for early 1998.

Inc., is developing a 100-kW prototype 3-phase power conversion system for utility-interconnected PV applications using a resonant core inverter. In 1997, this system exhibited more than 97.5 % efficiency at peak power and more than 92% in the range from 10% to 100% of rated power. Audible noise was reduced to less than 50 decibels, and FCC standards for electromagnetic interference were met. Omnion goals include a cost of less than 50 cents per watt in high-volume production, 96%-97% efficiency, and Underwriters Laboratories listing for the product.

Solar Design Associates, Inc., Harvard, MA, leads a team in refining the design of a modular inverter developed under the PV:BONUS program. A digitally controlled, 250-watt micro-inverter has been developed by SDA's partner, Advanced Energy Systems, Inc., of Wilton, NH. The unit has microprocessor control and full communications capabilities. In 1997, AES completed Underwriters Laboratories listing for this digitally controlled micro-inverter, which is easier to manufacture than the previous analog design.

Solar Electric Specialties, Willits, CA, is a systems integrator. SES works with suppliers to enhance the suitability of currently available PV system components. They are working to design, fabricate, and test two PV power systems for off-grid applications. In 1997, SES obtained Underwriters Laboratories listing on the MAPPS (Modular Autonomous Photovoltaic Power Supply), a 12- and 24-V dc, 200-W PV power supply. This pole-mounted, stand-alone PV power supply minimizes weight and cost. The l-kW MAPPS was delivered to the NCPV for testing. A 1-kW photogenset, also nearing completion, combines a generator, inverter, and PV power supply in a containerized PV-hybrid system. The unit is expected to be completed in early FY 1998.

Trace Engineering, Arlington, WA, is developing, testing, and modifying its manufacturing methods to produce a lower-cost, higher-performance, 2-kW ac inverter for the PV industry. The inverter, which can be combined by 2-kW increments to serve larger systems, converts ac power to dc, or dc power to ac, as required. This standardized, unitized approach to manufacturing and the ability to incrementally add capacity is expected to reduce costs and improve reliability. In 1997, Trace Engineering improved the modes of operation and hardware modularity for their inverter. A prototype of the 2-kW inverter that can be used in parallel, in 3-phase systems, and expanded up to 30 kW, was delivered to Sandia for testing. Trace also completed development and achieved Underwriters Laboratories listing of a standardized containment system for inverters, controllers, and batteries.

Utility Power Group (UPG), Chatsworth, CA, has designed, built and tested a prefabricated, tracking PV array that includes a 20-kW inverter and power-conditioning unit called an Integrated Power Processing Unit (IPPU). During 1997, UPG received 60 orders (800 kW) from utilities for this system. 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. UPG teamed with Siemens to increase modular panel production of factory-assembled PV panels and reduced the overall system cost by 20% while increasing modular panel production from 20 kW to 5 MW. They also developed a high-efficiency (97%) inverter for the system which passed all tests at Sandia. UPG reported a total net cost reduction of more than 20% for a 15-kW PV system after changes in PV array assembly methods, field installation methods, and the IPPU.

Research and development for module manufacturing

Under Phase 2B of PVMaT, several contractors continued work in FY 1997.

Solar Cells, Inc. (SCI), Toledo, OH, is developing a high-speed manufacturing process for 60-cm by 120-cm, thin-film cadmium telluride modules. In FY 1997, SCI fine-tuned a system to increase production capacity by a factor of four, demonstrated module deposition in 30 seconds, and completed module qualification and multi-year outdoor testing for reliability. SCI also completed installation of key equipment for a multi-megawatt line and initiated marketing of manufacturing technology offering a variety of CdS/CdTe production lines and plate finishing lines. SCI, whose work was also supported by the Thin Film PV Partnership program, has reduced module manufacturing costs by 78% and expects to increase its production capacity to 20-30 MW per year in the near term.

Solarex, Frederick, MD, is reducing the cost and increasing the performance of its commercial products made 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 reduced module manufacturing costs during FY 1997 by modifying its production line to use wire-sawing techniques and has doubled its capacity in silicon ingot casting. Solarex expects to produce modules for about $1.20 per watt with a 15-megawatt-per-year production capacity.

Phase 4A2 of PVMaT, which began in FY 1995, continued in 1997.

ASE Americas, Inc. (formerly Mobil Solar), Billerica, MA, manufactures

Rusty Ristin, AstroPower/PIX05668

Thin-film silicon sheet emerges from the growth chamber at the AstroPower plant. The company's current commercial product is 15.5 cm wide, with sheets from prototype production measuring 30 cm wide.

PV wafers, cells, and modules using an edge-defined, film-fed growth (EFG) process developed at Mobil Solar. ASE's goal is to reduce wafer, cell, and 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 the wafers. In 1997, ASE increased EFG wafer production yield by 5%; demonstrated a new benign wafer-etching process; lowered cell add-on production cost by 7%; and reduced fluorine-ion effluent in the waste stream by 50%, hydrofluoric acid consumption by 20%, and deionized water consumption by 20%. With these changes and improvements in solar cell fabrication technology, ASE has reduced module manufacturing costs by 26% and doubled EFG module production capacity. Since PVMaT began, ASE has reduced module manufacturing costs by 75% and increased their production capacity by a factor of 10.

AstroPower, Inc., Newark, DE, is reducing the manufacturing cost of its commercial Silicon-Film™ material cells and modules. Their approach is to make the 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. In 1997, AstroPower fabricated the world's largest production silicon solar cell (240 cm^2), initiated production with a continuous Silicon-Film™ growth process that is 10 times faster than competing processes, and established a record efficiency of 16.6% for a 1 cm^2 solar cell. The latter accomplishment was one year ahead of the contract milestone. In Phase 4A2, AstroPower reduced module-manufacturing costs by 13% and increased production capacity by a factor of 4. Since PVMaT began, they have reduced module manufacturing costs 23%.

Iowa Thin Films Technologies, Inc. (ITF), Ames, IA, is increasing their throughput of a-Si deposition on continuous polymer substrates, and the subsequent metalization, laser-scribing, and welding processes to reduce costs. In FY 1997, ITF increased throughput in the printer and scriber by a factor of 6. Work on their submodule lamination process has increased throughput from 20 to 240 ft^2 per hour. Other areas of advancement included improving printing registration reproducibility from 100 to 10 microns. Under PVMaT Phase 4A2, ITF has reduced a-Si module manufacturing costs by 42% and increased production capacity by a factor of 4.

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 from larger, 225-cm^2 cells, which can reduce module costs per watt by 18% and increase manufacturing process yields by 15%.

Frank Jeffrey/PIX05674

Iowa Thin Films Technologies, Inc. supplied the solar array for the Indian Creek Nature Center outside of Cedar Rapids, Iowa. The panels provide about 200 watts of electricity, enough to run the low-wattage, energy-efficient lights. The Center, a project of the Iowa Department of Natural Resources, demonstrates the use of energy-efficiency and renewable-energy technology throughout its facilities as part of Iowa's commitment to environmental education.

Breakage can reduce yields by 20% to 40%, so Siemens is also investigating lowering costs through reduced breakage, while continuing to make thinner cells. In addition, a new prototype junction box combines low cost with improved design. In FY 1997, Siemens implemented statistical process controls on the manufacturing line, initiated production of a new PVMaT-developed, 150-mm thick round cell, and brought a semi-automated lamination process on line. Siemens has reduced module manufacturing costs under their PVMaT research by 16%, with 10% of this under Phase 4A2 alone. They have also doubled their module production capacity.

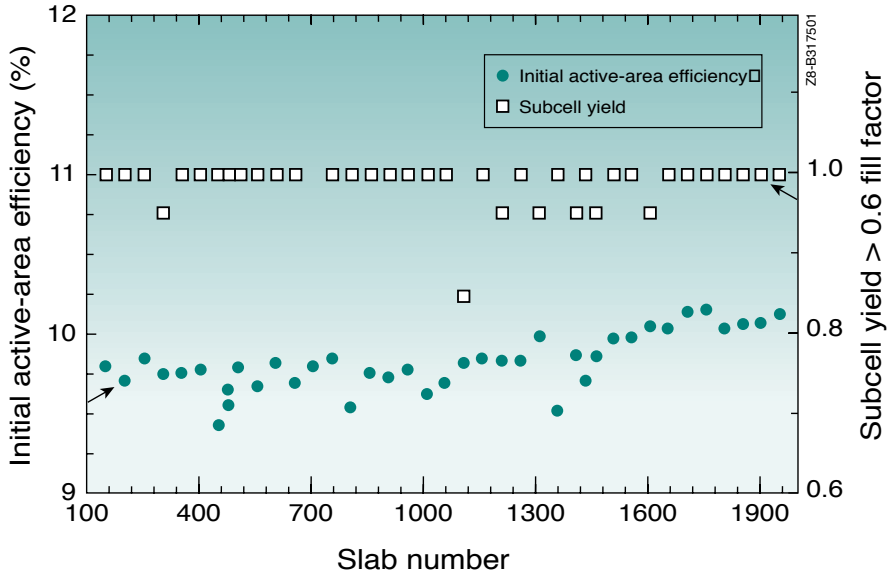
Photovoltaics International (formerly Solar Engineering Applications Corporation), Sunnyvale, CA, is reducing manufacturing costs for its linear concentrating PV modules by expanding the continuous processing of key components. In 1997, they developed an in-house capability to extrude Fresnel lenses which lowered product costs by 37%. They also increased lens manufacturing capability to 5 MW/year and completed the first half of an automated receiver-assembly station. They continue to investigate a new way to bond plastic collector components without using solvents. PVMaT 4A2 results have reduced module manufacturing costs by 41% and increased linear-concentrator production capacity by a factor of 5.

Progress in Technology Results in Industrial Expansion

In 1997, major U.S. crystalline and amorphous silicon manufacturers such as ASE Americas, Siemens Solar Industries, and United Solar Systems Corporation increased their production capacity and shipments by around 40% to help meet the rapidly expanding market for PV power systems. The PV Program contributed directly to such expansion through the successes of the Thin Film PV Partnership program, PVMaT, cooperative research and development agreements, and national laboratory work in measurements and characterization.

This year, two companies—United Solar Systems Corporation and Solarex—opened large manufacturing lines for modules made of thin-film materials. United Solar, a joint venture of Energy Conversion Devices and Canon, Inc. (Japan), began producing a-Si triple-junction alloys at their new 5-MW plant in Troy, Michigan. Around-the-clock operations began in May 1997, with products ranging from 3 to 64 watts. The United Solar a-Si devices are

United Solar makes its a-Si alloy triple-junction thin film using a roll of stainless steel half a mile long, 14 inches wide, and 5 mils thick. The roll passes through four machines, where it is washed and layers are deposited. The coated web is then processed to make a variety of products.



On the United Solar production line, samples are taken at regular intervals along the half-mile-long roll of a-Si alloy triple-junction thin-film cells to evaluate efficiency and yield. Yields of close to 100% are achieved over the entire length of the roll, as illustrated here.

MILLION SOLAR ROOFS IV

Expansion of PV Industry Supports Million Solar Roofs Initiative

The U.S. PV industry has more than doubled its manufacturing capacity in the last three years, while average manufacturing cost has fallen 32%. By 2000, industry projections are a production capacity exceeding 200 MW and manufacturing costs below $2/watt. This solid base of domestic production capacity makes possible an initiative like Million Solar Roofs. (from PVMaT progress report, 26th IEEE Specialists Conference, 1997.)

UL-approved and carry a 10-year warranty. These commercial products include PV shingles and metal roofing with 7.5% stable efficiencies.

The Solarex plant is designed to operate at 10-MW capacity. Solarex, a business unit of Amoco/Enron Solar, will use the results of its CRADA with DOE in its new thin-film manufacturing plant in Virginia. This plant is capable of producing 10 MW of tandem-junction thin-film modules each year.

Measurements in the Manufacturing Environment

To monitor and grade the quality of polycrystalline thin-film and silicon solar cells, a contactless, nondestructive, and real-time manufacturing-line method was developed at NREL. Known as Phase III radio-frequency photoconductivity decay lifetime spectrometry, the measurement system is being adjusted to meet some specific needs of the AstroPower Silicon-Film™ material, and a patent application has been made. The interaction between AstroPower and NCPV researchers has clarified the needs of the manufacturing environment. After beta-testing and error analysis, the collaboration with AstroPower will continue by comparing the quality of the measurements at the factory with those of the laboratory. More than 300 measurements of wafers produced by the AstroPower production facility were made in 1997 by NREL.

Warren Gretz, NREL/PIX01990

Tests of Solar Cells, Inc.'s 1-kW thin-film CdTe array at NREL's Outdoor Test Facility showed encouraging stability.

Module and Array Development

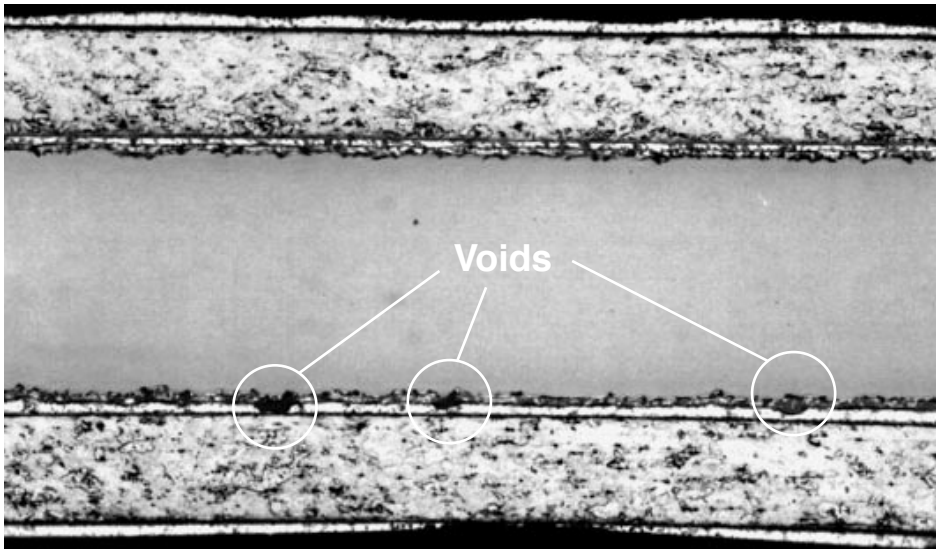
This year, tests and analyses point to improved techniques and validation of new technologies.

New products of thin-film materials test well

To provide important information to industry on evolving thin-film technologies, the PV Program's Outdoor Test Facility (OTF) continued ongoing studies of prototype thin-film modules. Concerns about the stability of thin-film modules were allayed by this year's trials at the OTF. Two dual-junction a-Si systems from United Solar demonstrated extremely good stability. Five years after stabilization, the 1.8-kW system has shown less than 5% degradation, while the 1-kW roofing system has shown less than 1% degradation over a 4-year period. Another thin-film system, a dual-junction 1-kW a-Si system from Solarex, has been operating for almost 2 years after stabilization with an average efficiency of 5.8%. And a cadmium telluride system from Solar Cells, Inc., rated at 1 kW, has maintained an average operating efficiency of 7%.

Extending PV module lifetimes with better solder bonds and encapsulants

To double the lifetimes of PV modules, the mechanisms that cause degradation must be understood and related to specific manufacturing processes and materials. Such fundamental understanding requires observing modules in actual field operations. Analysis of field-aged modules is required because accelerated-aging tests currently used in module qualification procedures do not generate all of the degradation



Sandia National Laboratories

This photo shows a microscopic cross-section used to evaluate the quality of solder bonds between solder-coated copper ribbons and solar cells. Layers of solder, copper, solder, and cell metalization sandwich the inner silicon cell. Dark sections in the lower solder layer reveal originating points of potential solder-bond failure ("voids").

mechanisms observed after actual outdoor exposure.
Tackling the difficult problem of identifying and minimizing degradation mechanisms that reduce performance and limit the ultimate lifetime of PV modules, the Program teamed with established module manufacturers, material suppliers, system users, Florida Solar Energy Center, and Southwest Technology Development Institute. In 1997, this Module Durability Research Cooperative (MDRC) led by Sandia emphasized two key issues of module durability: solder-bond processes and their fatigue lifetime, and the adhesion and chemical properties of encapsulant-to-solar-cell interfaces. In addition, the Cooperative has a well-monitored, long-term, outdoor exposure program for module manufacturers with commercial products that have already passed today's qualification test standards. Modules provided by manufacturers are being installed for long-term exposure and analysis in environmental conditions historically proven to be harsh on module lifetime: a hot and humid site in Florida (FSEC) and a hot and dry site in southern New Mexico (SWTDI). The results of these exhaustive analyses should lead to 30-year lifetimes for PV modules from U.S. manufacturers.

New ways to encapsulate PV devices into power-producing devices or minimodules are being explored. For example, this year, NREL identified formulations of the pottant material ethylene vinyl acetate (EVA) that show much greater photothermal stability than the two now in commercial use. The new EVAs will be patented soon, and NREL expects to make the formulations available for PV industry use in FY 1998. Although the new EVA formulas should improve module performance, lengthen service life, simplify processing procedures, and lower module cost, further work is needed to identify the ultimate module pottant materials for a 30-year service life.

Testing the Components of PV Systems

Reliable systems are a requirement for the successful implementation of PV. In electronic systems, reliability is directly related to manufacturing and usage experience. In the case of PV balance-of-system (BOS) components, manufacturing quantities vary from one to, at most, a few thousand. Thus, there is not adequate experience data to assure reliability. The NCPV's national laboratories are providing resources to help bridge this experience gap. These resources include the following:

- R&D contracts to provide funds for research that small companies cannot afford
- Contracts to develop quality, systems engineering and reliability programs in manufacturers' facilities
- Accelerated testing of new prototypes to identify problems before production
- Laboratory support to provide test capabilities that manufacturers do not have
- Laboratory evaluation programs that identify BOS problems, develop solutions, and coordinate industry approaches
- Codes and standards support.

The BOS laboratory also benchmarks equipment to provide users with information on how hardware can be used. For example, the Utility Power Group's grid-tied inverter, developed under PVMaT, was tested at 97% efficiency.

In 1997, the two largest U.S. manufacturers of inverters were awarded contracts to improve the reliability of their products. The Program also arranged and supported highly accelerated lifetime tests at a commercial test laboratory for four products important to PV systems.

In other work supporting demonstration projects, two large hybrid inverters were evaluated in the laboratory before field installation. When the inverters were connected to battery banks, a diesel generator, and realistic loads, several problems that could not be identified at the manufacturer's facility were identified and corrected.

Routine testing of inverters destined for demonstration projects continues. A 30-kW Abacus Tri-Mode hybrid inverter was evaluated in support of a Small Business Innovative Research contract. The inverter was then installed at the Channel Islands Naval Facility. A 60-kW AES Static Power Pack was evaluated for

MILLION SOLAR ROOFS V

Testing Supports Million Solar Roofs

The President's Million Solar Roofs Initiative relies on utilities to accept and promote the connection of PV systems to the grid. To demonstrate PV's compatibility, Sandia developed a test bed tied to the utility grid so that multiple inverters could be evaluated in a realistic, utility-connected configuration. The test bed has revealed problems with the way manufacturers design to prevent "islanding," the continued operation of the system even after the grid goes down. In particular, inverters from different manufacturers interfered with each other, and islanding times in excess of one minute were noted for disconnects on the customer side of the distribution transformer. It was observed that islands are not sustained when the island includes a distribution transformer. As a result, in FY 1998, Sandia will coordinate with U.S. inverter manufacturers to develop a single approach to anti-islanding and to modify existing U.S. standards accordingly. This addresses a key concern of utilities and is therefore critical to successfully implementing the Million Solar Roofs Initiative.

PVMaT. This inverter represents a new U.S. manufacturing capability.

Batteries are an important and costly component of stand-alone PV systems. To test battery reliability and lifetime in PV systems, a laboratory program is conducted at Sandia and FSEC. Researchers tested the lifetime of batteries, and they designed and built a PV hybrid and charge-controller system simulator for automated PV system level testing. In addition, they developed and tested a new hybrid battery charge algorithm using Digital Solar's microprocessor-based PV hybrid charge controller. Several publications were also added to the literature on batteries: a PV Battery Guide, and PV Battery Cycle Test Results.

Research and Development

Maintaining the U.S. PV industry's leadership in technology

Research continues on a variety of familiar and novel PV materials. Thin-film technology has the potential to achieve widespread use in grid-connected applications if this emerging technology can achieve performance goals approaching 15%-efficient modules that cost less than $0.50/W and offer a 30-year lifetime. A number of materials can be used to create thin-film solar cells. They include amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium diselenide (CIS), and polycrystalline silicon (Si). This year, research continued to support the development of thin films from the fundamental to pre-commercialization stages.

The crystalline silicon (c-Si) PV modules that dominate the market today have a long track record of proven reliability and steady cost reductions resulting from improved manufacturing efficiency and reduced material costs. This year, crystalline silicon efforts with industry focused on advanced manufacturing processes and simplified designs to further lower costs.

In high-efficiency (III-V) solar cells, two major efforts are under way: developing a novel 3-junction concentrator cell and investigating methods for growing high-efficiency III-V devices on low-cost substrates such as glass.

Thin Film PV Partnership

The U.S. PV industry is a world leader in thin-film technology. The Thin Film PV Partnership, like the other R&D partnerships of the PV Program, stimulates collaboration among researchers and test facilities at the national laboratories, colleagues in universities, the PV industry, and ancillary industries. The research teams address performance, reliability, cost, and manufacturability. The Thin Film PV Partnership has been particularly instrumental in identifying critical issues, an important step in scaling up successful laboratory results to a manufacturing environment. This focus on an agreed-upon set of research priorities is one of the clearest positive results of teaming, and the collaborative efforts are paying off in bringing thin-film technology to its full potential.

Amorphous silicon

As discussed in the Technology Development section, a-Si has successfully moved from the laboratory to the marketplace. Both United Solar and Solarex are now manufacturing thin-film a-Si for a variety of markets and applications. Manufacturing of a-Si for diverse applications is the fruition of nearly two decades of aggressive R&D in thin films, much of it supported in partnership with DOE and NREL through the National PV Program. Recent support for the successful commercialization of a-Si thin films has come from several sources: the PVMaT project for manufacturing development, the Building Opportunities in the United States for Photovoltaics (PV:BONUS) project for PV shingle product development, and the Thin Film PV Partnership for developing the advanced double- and triple-junction cells and modules.

Enhancing the stable efficiency of a-Si solar cells was identified as the highest-priority research area by the Amorphous Silicon National

Warren Gretz, NREL/PIX00652

One of the four a-Si systems tested at NREL that clearly showed a-Si to be a viable technology for use in future PV systems. All four small, grid-tied systems showed excellent stability after an initial degradation period (1.5-kW a-Si system by Advanced Photovoltaic Systems).

R&D Team. The 12.1% stable efficiency achieved by United Solar substantially improved the chances of a-Si in terms of both its transition to the marketplace and achieving the longer-term cost per watt reductions needed to make PV competitive on a global scale.

While partnered R&D fuels the steady development of thin-film manufacturing, research continues to explore the solid-state physics and other phenomena underlying advances in technology. For example, the Staebler-Wronski effect has long handicapped a-Si thin-film technology by initially decreasing cell efficiency by 20%-40%. A new model of the Staebler-Wronski effect was developed by the PV Program's first Fulbright scholar, Howard Branz, who spent a sabbatical at the University of Crete and the Foundations of Research and Technology Hellas (Greece). He created and explored the new model, which explains how the observed light-induced metastability in hydrogenated a-Si increases the number of atomic defects in the thin-film. The resulting paper will appear in *Solid State Communications*. NREL is conducting further theoretical and experimental studies to determine the implications of this new model for a-Si technology.

Cadmium telluride

Large-area CdTe technology saw initial commercialization this year when Solar Cells, Inc. (SCI) successfully demonstrated a low-cost, high-rate process that produces reliable modules. The SCI CdTe and cadmium sulfide deposition process produces these active semiconductor layers in under one minute. Manufacturing costs in full production could be less than $1 per peak watt. Development work is under way on a contactless, manufacturing-line method to monitor and grade the quality of polycrystalline CdTe thin films. This work is in the laboratory phase at NREL.

The NREL CdTe team focused on research addressing critical portions of the device. For example, a new, high-performance transparent conducting oxide (TCO) was developed to replace the conventional tin oxide layer in CdS/CdTe devices. Made of cadmium stannate, this new TCO has several significant advantages over conventional TCOs: it is more conductive, more transparent, has a lower surface roughness, is patternable, and is exceptionally stable. The first solar cells produced with this TCO had an efficiency of 14%, and a patent application has been filed.

The Institute of Energy Conversion at the University of Delaware is working to translate laboratory results into an effective engineering reactor design for use in large-scale module manufacturing using CdTe and CIS materials. The University of Delaware's Institute is a U.S. DOE Center of Excellence for PV Research and Development.

For the first time, NREL researchers succeeded in preparing cross-section samples of CIS and CdTe films deposited on glass substrates for transmission electron microscopy analysis. This development is important in determining the chemical and structural properties of CdS/CdTe interfaces.

Copper indium diselenide (CIS)

CIS technology continues to progress toward eventual commercialization by achieving milestones such as the Siemens Solar Industries' 1-kW array that demonstrated 9.2% efficiency this year.

In CIS thin-film technology, NREL focused in 1997 on process issues in scaling up CIS laboratory devices to larger-area samples with interconnected submodule efficiencies of 15%. Although this efficiency goal was not reached, the Program's emphasis on low-cost, scalable fabrication processes did make significant progress. Because reducing film thickness or increasing deposition rate are the primary means of increasing manufacturing throughput, NREL focused on evaluating three deposition techniques—sputtering, close-spaced sublimation, and electro-deposition.

Silicon film

AstroPower fabricated monolithically integrated silicon-film submodules as part of the Thin Film PV Partnership Program. These submodules provided the first convincing demonstration of interconnection and reasonable efficiency from this potentially low-cost silicon-film approach. The first module had an efficiency of 6.25%. The second module, which consisted of 36 cells connected in series, measured 9.2% efficient over a larger area (321 cm^2).

New PV partnerships to be formed

A recompetition of the Thin Film PV Partnerships began this year. The new solicitation covers the entire DOE Thin Film Program, including R&D and Technology Partners in CIS, CdTe, a-Si, film-Si, and Environmental Safety and Health (ES&H). Letters of interest for the second Thin Film PV Partnership were mailed to 131 requesters in May 1997, with 63 proposals received in response.

A significant aspect of this second round is that the Electric Power Research Institute is providing private funding of about $400,000, adding to the federal investment in thin-film PV. The DOE portion of the funding forms the backbone of the partnership and is expected to be about $11 to $13 million a year for 3 years. Corporate partners will cost share about 45% of the projects.

PV module recycling

The Thin Film PV Partnership ES&H team, co-chaired by Brookhaven National Laboratory and NREL representatives, addressed industry concerns about potentially toxic waste streams containing cadmium and selenium. The team created an SBIR (Small Business Innovative Research) category for PV recycling. The results not only produced an effective, low-cost recycling technology in advance of large-scale deployment of CdTe and CIGS thin-film modules, but also highlighted a way to recycle silicon cells from modules. Both Solar Cells, Inc., and Drinkard Metalox won first- and second-phase SBIRs to complete this innovative work. The resulting thin-film process results in recyclable, separated glass, metal, plastic, and metals-containing powders.

Research on Crystalline Silicon

The crystalline silicon program at the national laboratories coordinates three basic tasks: developing next-generation silicon crystal growth methods, increasing the fundamental understanding of crystalline silicon material science, and developing new or improved c-Si devices and processes. Test facilities at the national laboratories play a key role in all of these projects by verifying the performance changes that result from the research.

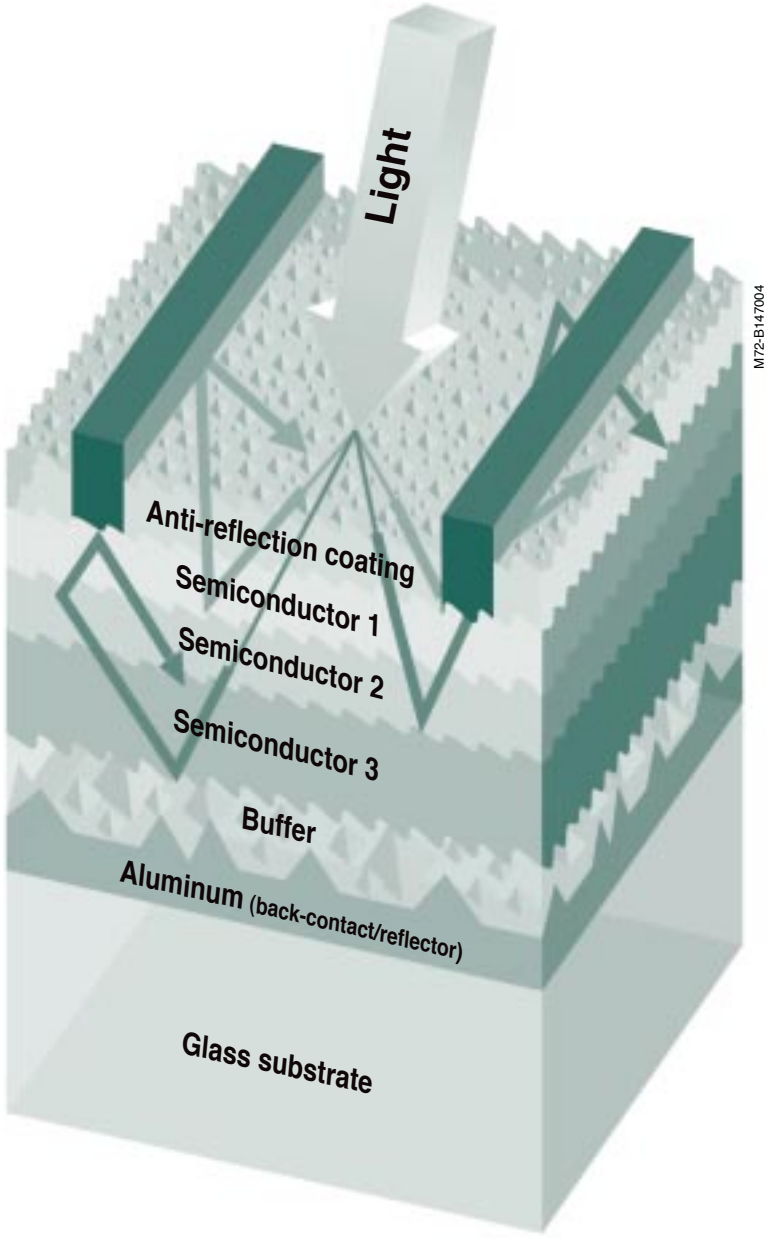
Next-generation crystal growth

The silicon substrate for the solar cell requires growing crystals and shaping them into slices. Because crystal growth and slicing represents one of the largest costs of c-Si PV modules, researchers have investigated alternative ways to grow crystals that significantly improve throughput, reduce cost, and reduce energy requirements. One way is to deposit a thin layer of silicon on a low-cost substrate. For thin-layer silicon to work, the structure of the layer must be designed to enhance optical absorption in the thin layer.

Process and device development

An NREL software tool for performing optical modeling of these sophisticated structures received an R&D 100 Award this year from R&D Magazine. Called *PV Optics,* the software quickly and accurately models the optics of any solar cell or module, whether crystalline, multicrystalline, or amorphous. Multijunction designs can also be modeled.

Fabricating c-Si solar cells and modules requires several steps or processes. Using plasma processing,



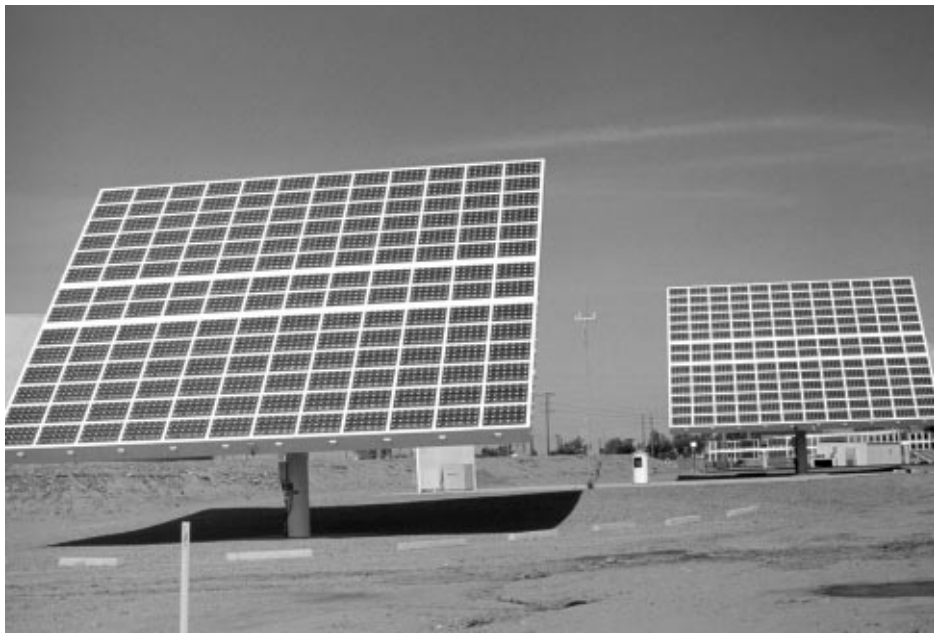
PV Optics, *a 1997 R&D 100 Award-winning computer software, is a complete, easy-to-use package that accurately models the optics of any solar cell or module.*

researchers at Sandia are optimizing processing techniques. Initial results show a statistically significant improvement of half an absolute percentage point in cell efficiency through the optimized use of hydrogenation in a commercial production line. These researchers have also investigated an alternative doping technique for reducing back-surface recombination. Aluminum-alloyed junctions are a popular technique for reducing back-surface recombination, and their performance can be considerably improved by doping the aluminum with boron.

A Crystalline-Silicon Research and Development Cooperative, made up of all major U.S. manufacturers of crystalline and multicrystalline modules, investigates c-Si device and processing issues that are of common interest to the members.

Researchers at the Georgia Institute of Technology are using rapid thermal processing (RTP) for crystalline-silicon solar cells, a process with potentially much greater throughput. Georgia Tech achieved a record efficiency of 19.1% on float-zone silicon and 18.4% on Czochralski (Cz) silicon using RTP. Also, improved understanding of aluminum-alloyed junctions led to the fabrication of 19.0% and 17.0%-efficient cells using laboratory and industrial-type processes, respectively. A new simultaneous boron and phosphorous diffusion process was developed and used to produce 20.3% float zone and 19.1% Cz solar cells in a single furnace step.

Researchers at Sandia are examining the entire PV module production process to optimize the cell and module design concurrently. This approach finds that considerable cost in the module assembly is due to the use of solar cells with contacts on both surfaces. Sandia is therefore developing solar cells with both contacts on the back surface and developing new module assembly concepts using back-contact solar cells. Some preliminary studies estimate that costs with this new approach may be reduced by 25%, compared to current designs. Preliminary work has demonstrated an 11%-efficient module using back-contact cells and the one-step assembly process.



Arizona Public Service Co./PIX05675

A high-concentration, point-focus concentrator is shown here being tested at Arizona Public Service Company's STAR test facility in Tempe. The arrays, made by Amonix, are two-axis systems that concentrate incoming solar energy by a factor of 265.

Concentrators: High-Efficiency Concepts

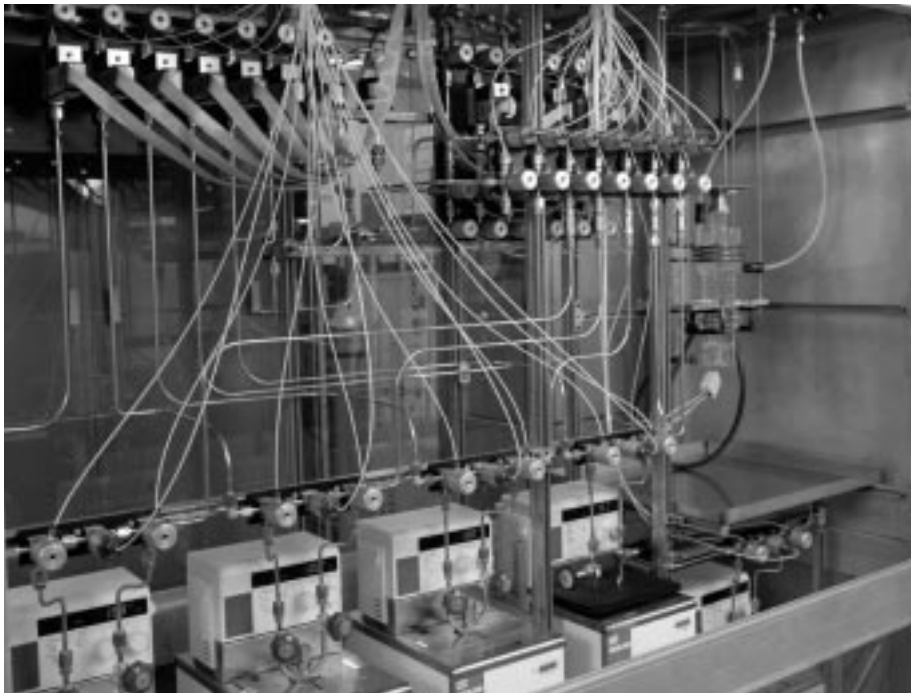
Research and development sponsored by DOE, Electric Power Research Institute, and industry has created a nascent concentrator industry ready to begin large-scale deployment of concentrator PV systems. The PV Concentrator Alliance was formed at a workshop for the PV concentrator industry. This group wrote a position paper for DOE to use in planning future support of the concentrator industry. The first problem identified by this paper—the need to develop standards for concentrators—is already being addressed.

The concentrator industry is in the process of changing from a group of very small companies to a group with representation of some large companies, including BP Solar and Honda. Future-generation concentrators are likely to use high-efficiency gallium arsenide cells.

III-V High-Efficiency Solar Cells

The PV Program is transferring its award-winning, high-efficiency cell technology to suppliers of solar cells for satellites, but this technology could also provide the necessary edge to make cost-effective concentrator systems for use on Earth.

Historically, high-efficiency solar cells have been two-junction GaInP-on-GaAs tandem cells. For example, a record-setting 25.7% (air-mass 0) and 30.2% (air-mass 1.5 direct, 150 suns) efficient cell won an award of excellence in technology transfer from the Federal Laboratory Consortium. This tandem solar cell



David Parsons, NREL/PIX05278

The III-V metal organic vapor-phase epitaxy system is used to synthesize single-crystal, thin films of a variety of III-V materials, primarily GaInAs and InP-based films for high-efficiency research cells.

uses two cells grown monolithically as one device: the top cell is gallium indium phosphide and the bottom cell is gallium arsenide.

The 30.2% efficiency can be increased by adding more junctions to the two-junction gallium indium phosphide/gallium arsenide cell. A study of related three- and four-junction concepts showed that, ideally, an efficiency over 50% is possible. Practically, it should be possible to reach an efficiency in the 35%-40% range, provided appropriate materials can be identified. There are a number of materials that may be suitable for the third and fourth junctions. These materials are known to have band gaps in the appropriate ranges and a lattice constant that can be matched to that of gallium arsenide. The possibility of using these new materials in high-efficiency solar cells is currently being investigated, with the goal of reaching a 35%-40% efficiency within the next 10 years.

Fundamental and Exploratory Research

Continued advances in PV technology depend on improving fundamental understanding of the synthesis and processing of the materials from which solar cells are made. Recognizing this national need, DOE's Office of Energy Research (OER) established the Center of Excellence for Synthesis and Processing of Advanced Materials (CSP).

The most recent project created within CSP is on High-Efficiency PV Projects. In FY 1997, project members held their first meeting to assess the progress and review various research activities. The overall approach is to effectively couple existing projects in the PV Program with some 20 relevant OER research projects involving national laboratories and universities.

Among other research results reported in FY 1997 were:

- With collaborative support from DOE's OER, a new photochemical device was fabricated and measured at NREL to have 10% solar-to-electric efficiency. This photovoltaic device is based on the dye sensitization of thin nanocrystalline films of titanium oxide.
- To further improve the efficiency and stability of CIGS cells, theoreticians performed first-principles calculations leading to several publications on the physics of Ga addition in CIS and its effect on the CIS electronic structure.
- Fundamental Raman spectroscopy studies provided strong evidence of Te precipitates in the microstructure on CdTe films. This understanding could lead to improved CdTe devices.

MILLION SOLAR ROOFS VI

NREL Resource Studies Pinpoint Best Million Roofs Locales

The NCPV characterizes solar resources using state-of-the-art measurement systems traceable to world standards. Electronic data sets and maps depict the global distribution of solar radiation and the quantity and variability of the resource at specific locations. For regions with limited sampling data, researchers are using satellite imagery, meteorological data, and models to estimate solar radiation. Such studies help to target houses best suited for participation in the Million Solar Roofs Initiative.

Some of today's successful thin-film PV technologies were once innovative ideas. The PV Program works especially with universities to keep these ideas coming in efforts such as the First Conference on Future-Generation Photovoltaic Technologies held in March of 1997. Sessions of the conference addressed the following topics: Criteria for New PV Concepts; Role of Government, Universities and Industries in Developing and Funding New Ideas; Dye-Sensitized Photochemical Cells; Single-Crystal-Like Films on Low-Cost Substrates; Innovative Concepts; and New Materials and Device Architectures for PV.

In addition to cutting-edge research in university laboratories, NREL also supports undergraduate education. For example, in 1997, NREL's Historically Black Colleges and Universities PV Research Associates Program provided significant PV education to students through seven subcontracts, giving tuition assistance and summer internships at NREL and the NASA Lewis Research Center in Cleveland, Ohio. Other participants visited Port Elizabeth, South Africa, to learn how Port Elizabeth Technikon trains young South Africans to start their own businesses installing and maintaining PV systems.

Measurements and Characterization

The PV Program's Measurements and Characterization laboratories perform thousands of measurements each year in teaming activities with industry, university, research laboratory, and internal researchers. The Measurements and Characterization team within the NCPV includes more than 40 experts who provide analytical support that covers the test-and-measurement range from atoms through PV arrays. With state-of-the-art equipment and facilities, these laboratories embody cell and module performance, electro-optical characterization, analytical microscopy, and surface analysis characterization capabilities.

These laboratories offer more than 40 techniques to measure electrical and optical properties of materials and devices, as well as the chemistry, composition, topography, structure, and physical nature of materials, surfaces, and interfaces. Through its Website, this NCPV operation offers its collaborators and clients a secure way to transfer data, thus enhancing customer interactions and measurement turnaround time.

The NCPV maintains technical leadership in the standard testing of solar cells and modules, and assists R&D and industry efforts by providing cost-effective measurement and characterization service, research, and technique development. In FY 1997, these laboratories performed more than 40,000 measurements on some 15,000 samples representing every photovoltaic technology. The technique development work addressed measurements specific to PV industry needs and the furthering of methods for the manufacturing environment.

New or improved offerings during this past year include a large-area, continuous solar simulator for evaluating cells and modules under standard conditions for flat-plate and concentrator technologies, a time-of-flight secondary-ion microprobe for high-resolution determination of impurities in cell materials, a large-area laser scanner for versatile module diagnostics, non-contact spectrometer for determining the minority-carrier lifetimes and diffusion lengths in semiconductors, a scanning micro-Fourier transform infrared system for examining insulators and conductors, and a novel near-field scanning optical microscope for nanoscale imaging and spectroscopic studies of semiconductors. With this arsenal of analytical capabilities, these laboratories offer a complete, one-stop site for diagnostic evaluation and correlation of events from the dimension of single atoms to the macroscale.

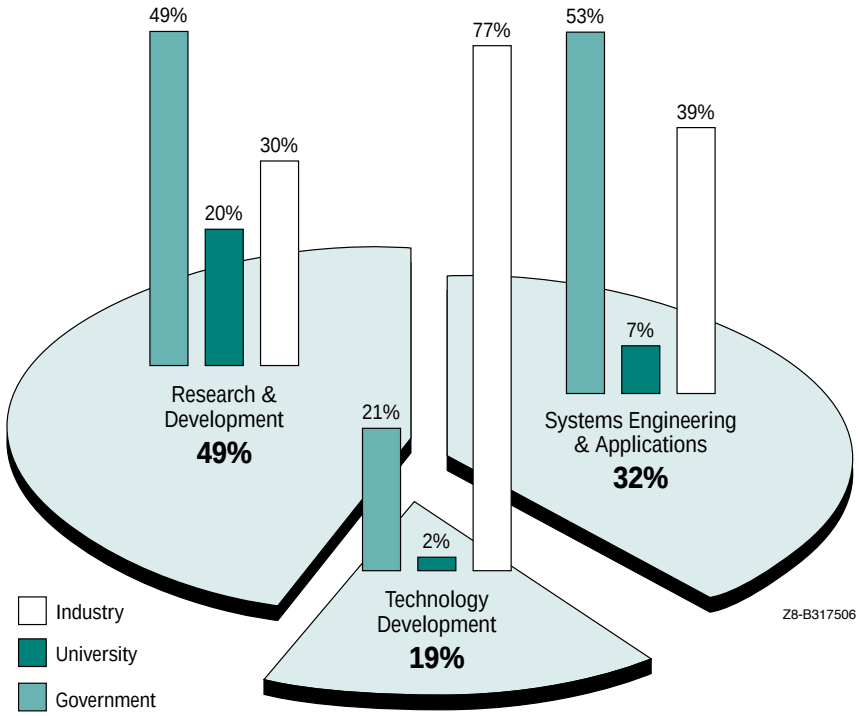
Program Resources

The National Center for Photovoltaics (NCPV) was created last year to improve the implementation of the National Photovoltaics Program by encouraging the most efficient use of the nation's PV resources. This year the NCPV conducted a series of discussion forums, a workshop, and a review to continue building unity in the national PV community. Specific efforts included an open house at the Solar Forum in April, a high-level industry summit in May, a workshop on PV Program Strategic Directions in July, and the Annual Operating Plan task review encompassing all elements of the DOE PV Program in August.

Headquartered at DOE's National Renewable Energy Laboratory, the NCPV draws on the core expertise of NREL and Sandia 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, the Institute of Energy Conversion at the University of Delaware, and the two Regional Experiment Stations—the Florida Solar Energy Center and the Southwest Technology Development Institute. In addition, dozens of university and industry research partners across the country are linked together to function in a more unified way.

Facilities Available

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



FY 1997 Budget Distribution.

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—includes laboratories for fabricating and evaluating thin-film technologies (a-Si, CdTe, and CIS), c-Si cells and modules, concentrator cells and PV arrays, and for developing and testing BOS components such as charge controllers and inverters.

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

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 producing PV components and systems. NCPV works with large user groups such as utilities to address technical issues in deploying PV technologies in new applications.

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

Solar resource characterization—State-of-the-art measurement systems traceable to world standards are used to characterize solar resources. Electronic data sets, maps, and models are available to quantify or estimate the distribution of solar radiation for specific locations.

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