## Contents

DOE/CH/10093--92

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# I. Executive Summary

This program plan describes the goals and philosophy of the Department of Energy's (DOE) National Photovoltaics Program and its major research and development activities for fiscal years (FY) 1991 through 1995. The plan represents a consensus among researchers and manufacturers, as well as current and potential users of photovoltaics (PV). It defines the activities that we believe are necessary to continue the rapid progress toward acceptance of photovoltaics as a serious candidate for cost-competitive electric power generation by the utility, transportation, buildings, and industrial sectors. A successful National Photovoltaics Program will help achieve many of our national priorities (Figure 1).

As we enter the 1990s, PV technology has evolved into a commercial and cost-effective energy source for many remote stand-alone and utility applications, such as water pumping, vaccine refrigeration, lighting, communications, switching, and rural electrification. Today's PV systems are successfully competing with primary batteries, small engine generators, and utility line extensions in markets estimated in 1990 to be growing at nearly 30% per year.

The previous National Photovoltaics Program Plan placed heavy emphasis on materials and cell research. This balanced new plan builds on the results achieved under the previous plan, emphasizing cost reduction and the transfer of technology to the private sector as well as continuing basic laboratory research.

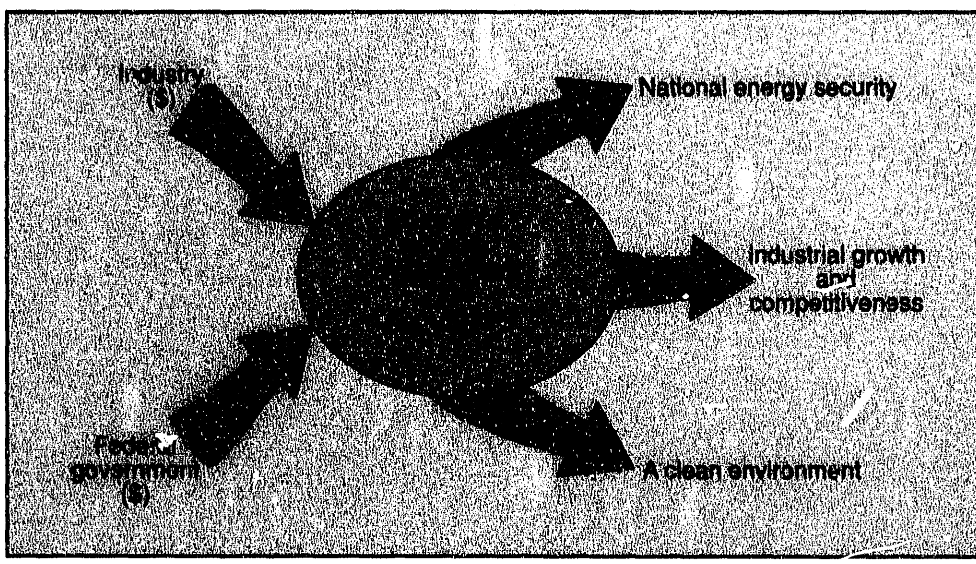
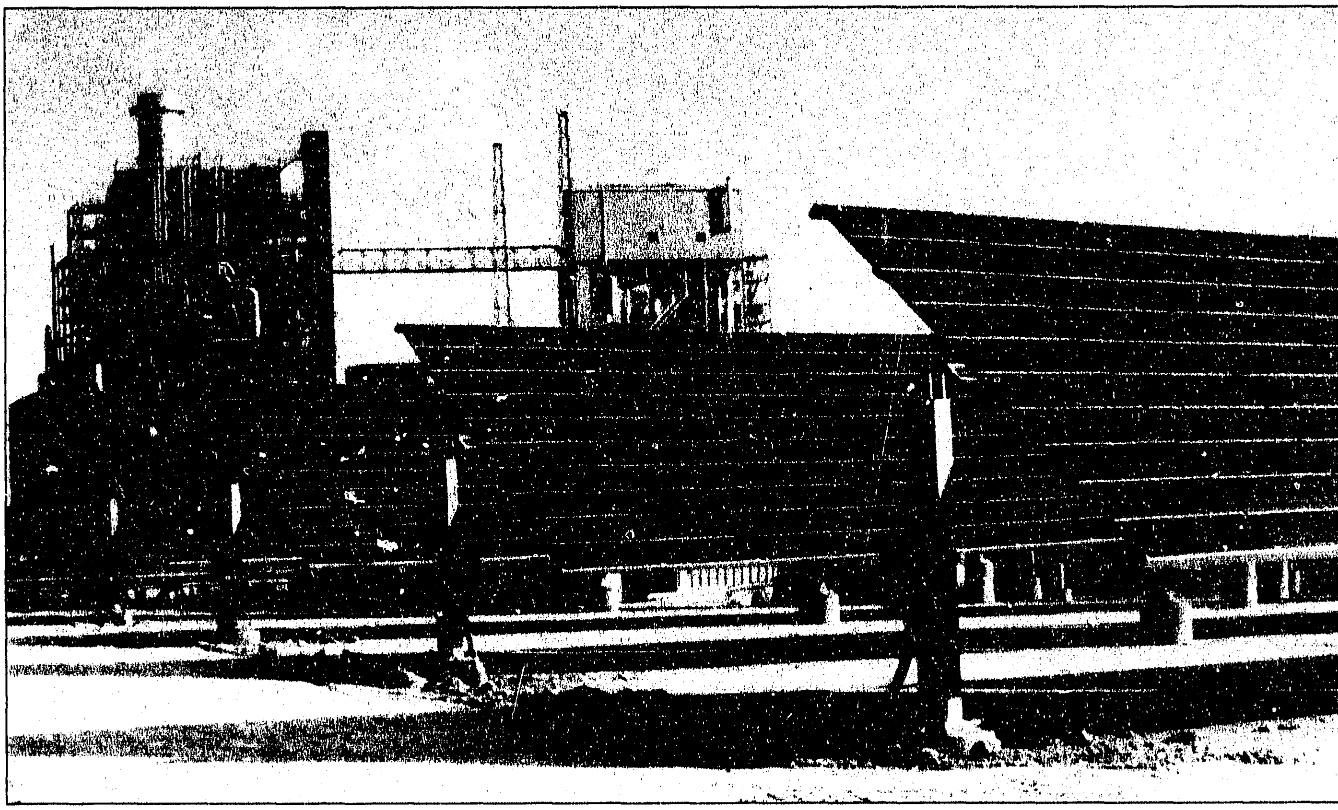



*Figure 1. The return on DOE's investment can be measured in terms of security, economics, and the environment.*

The mission of the National Photovoltaics Program is to help U.S. industry to develop photovoltaic technology for large-scale generation of economically competitive electric power in the United States, making PV a significant part of our national energy mix. To fully achieve this, we must continue to work toward the long-term goals established in our previous program plan: reducing the price of delivered electricity to 5 to 6 cents per kilowatt-hour (kWh), increasing lifetimes to 30 years, and increasing module efficiencies to 15% for flat-plate and 25% for concentrator technologies. If progress continues at its current pace, we expect that the PV industry will have installed at least 1000 megawatts (MW) of capacity in the United States and 500 MW internationally by the year 2000.

Toward these objectives, we have developed a technical plan for 1991 through 1995 and the cost and performance goals we expect to

*As we enter the 1990s, PV technology has evolved into a commercial and cost-effective energy source for many remote stand-alone and utility applications.*



*Large-scale, grid-connected power plants, such as this one at Austin, Texas, may ultimately be the largest market for PV systems.*

achieve. The technical plan has three major task areas that cover activities ranging from laboratory research to systems development. Each task area has well-defined objectives, consistent with technical needs and Congressional budget directives.

In addition to meeting the program's technical and cost goals, we intend to aggressively support the development of the industrial base needed for PV to penetrate the various energy end-use sectors. This is an incremental process, beginning with our continuing efforts to form partnerships with manufacturers and utilities (the ultimate benefactors and users), with universities, and with federal and state agencies.

Our program activities must also be oriented toward increasing the electric utilities' acceptance of PV systems as serious options. We must encourage utilities to install and operate systems under actual field conditions to gain both experience and confidence in PV's ability to perform reliably and cost-effectively. The ever-increasing number of small-load, cost-effective applications gives utilities ideal opportunities in which to obtain this experience. Pacific Gas and Electric Company (PG&E), for example, has installed more than 900 PV systems that are more cost-effective than other options for those specific applications.

We are also finding increasing interest among progressive utilities and public utility commissions in multimegawatt PV systems for selected grid-connected applications.

The Photovoltaics for Utility-Scale Applications (PVUSA) project in Davis, California, is successfully testing a variety of PV technologies under utility operating conditions.

Before the year 2000, we expect that grid-connected utility applications, using distributed PV systems, will be increasing rapidly. PV systems can provide substantial savings by providing end-of-line voltage augmentation and by allowing substation expansions and feeder line upgrades to be deferred. Progressive utilities, such as Public Service of Colorado and PG&E, have instituted planning processes to consider using PV arrays as alternatives to feeder upgrades.

Photovoltaic systems have applications in all energy sectors. The ultimate use of photovoltaics, however, will be for central power generation. Many scenarios have been suggested, and even the more conservative studies estimate that the potential electric market for central-station PV may run as high as several thousand megawatts by the year 2030. PV systems are environmentally acceptable and meet all known emission standards. They have the ability to generate fuels for storage, heating, and transportation. Low-cost electricity from PV could even generate hydrogen for use in a variety of applications.

Indeed, photovoltaics has a bright future. It offers the possibilities for a clean environment, energy security, and U.S. industrial competitiveness.

*The U.S. photovoltaic industry and the government are working to improve the manufacturability of PV modules. At Mobil Solar, silicon is grown into tubes 4 to 5 meters long and then laser-cut into 10-centimeter-square wafers.*

# II. The Photovoltaic Vision

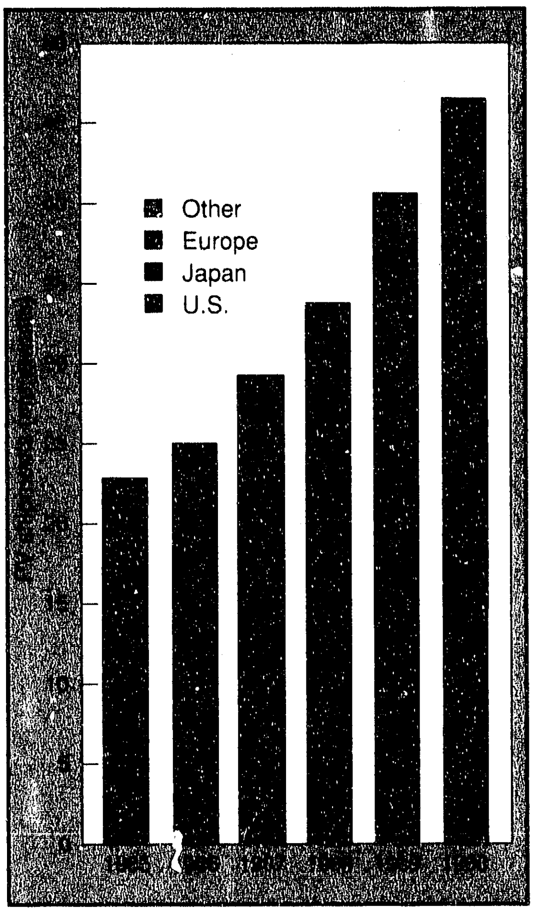



*Figure 2. The U.S. share of the photovoltaics market has climbed to about 32%. (Source:* PV News, *February 1991)*

*"It's not a question of whether photovoltaics will become a technology of choice—it's only a question of when."*

**Bernard Gillespie, President**
**Mobil Solar Energy Corporation**

Since the last program plan was published in 1987, the U.S. photovoltaic industry has made great strides. The price of electricity from PV has dropped by 30%, to about 25 to 30 cents per kWh. Worldwide PV sales have risen from 28.6 MW in 1987 to 46.5 MW in 1990. The United States has continued as a leading producer, with about 32% of the total sales worldwide (Figure 2); U.S.-manufactured modules capable of generating nearly 15 MW were shipped in 1990 alone.

World leadership has been gained through aggressive development of cells and manufacturing technology and substantial investment by both industry and the government. It is estimated that the U.S. government has put nearly $1 billion into PV research since the early 1970s, while private industry has invested more than $2 billion. The PV industry has been growing at a compounded rate of about 15% annually, a record that few high-technology industries have been able to equal or sustain. Since the start of the development of photovoltaics for terrestrial use in 1972, module prices have dropped to *less than 1/100 of their 1972 prices*, from $500 per watt to about $4.00 to $4.50 per watt in 1990, contributing to a twentyfold decrease in PV electricity prices (Figure 3). Modules with efficiencies ranging from 11% to 17% are commercially available; in the laboratory, experimental cells have demonstrated efficiencies as high as 34%.

A strong DOE role in partnership with industry has been and will be crucial in bringing PV into widespread use by the year 2000. Working closely with the private sector, we will aggressively pursue improvements in both cost and performance during the next five years. Annual investments in PV research, engineering, product development, and marketing by the private sector currently exceed $100 million. Our goal is a technology that is competitive with fossil-fueled power plants early in the next century.

## Increasing Competitiveness

PV systems have been cost-competitive choices for many applications since the first commercial cells were developed in the 1950s. Continual improvements in cost competitiveness have permitted PV systems to fulfill applications that we never dreamed of in the beginning. In the 1960s, PV power systems were found to be cost effective for satellites; in the 1970s, they found uses in remote, international, and military applications. PV power devices penetrated the consumer and commercial markets in the 1980s. Consumer and commercial markets accounted for more than 30% of total U.S. photovoltaic sales in 1990.

Now we are finding that photovoltaics can provide cost-competitive power for thousands of small utility applications. Several of the nation's largest public utilities, such as PG&E and the Southern Company, are installing hundreds of PV systems for selected applications throughout their service areas.

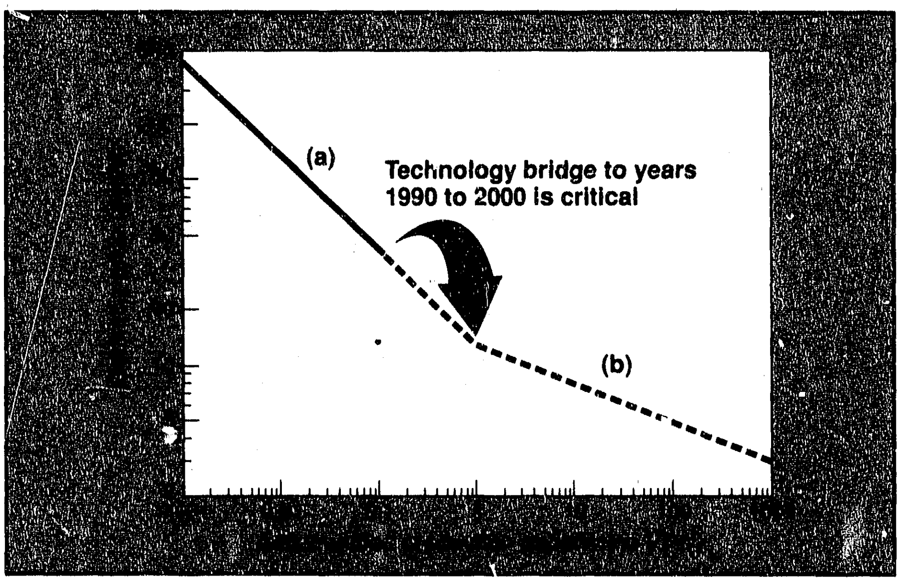



*Figure 3. Dramatic cost reductions should continue through the end of the century as production increases: (a) price reduction of 68% achieved per tenfold increase in production experience; (b) price reduction of 40% anticipated per tenfold increase in production.*

Because systems can be delivered in all sizes, photovoltaics can take advantage of niche markets as they develop. The phased entry of PV systems into ever-larger market segments allows potential users, such as utilities, to gain experience, develop standardized designs, and train service crews without massive capital investments.

As PV module prices drop and performance improves, we expect PV to gradually become more competitive in the peaking, intermediate, and baseload electric utility sectors (Figure 4). Figure 5 on page 6 shows the expected penetration of different market sectors by PV during the next decade.

As the environmental effects associated with more traditional sources of energy are recognized and increasingly factored into energy costs, PV may achieve cost competitiveness even earlier than planned.

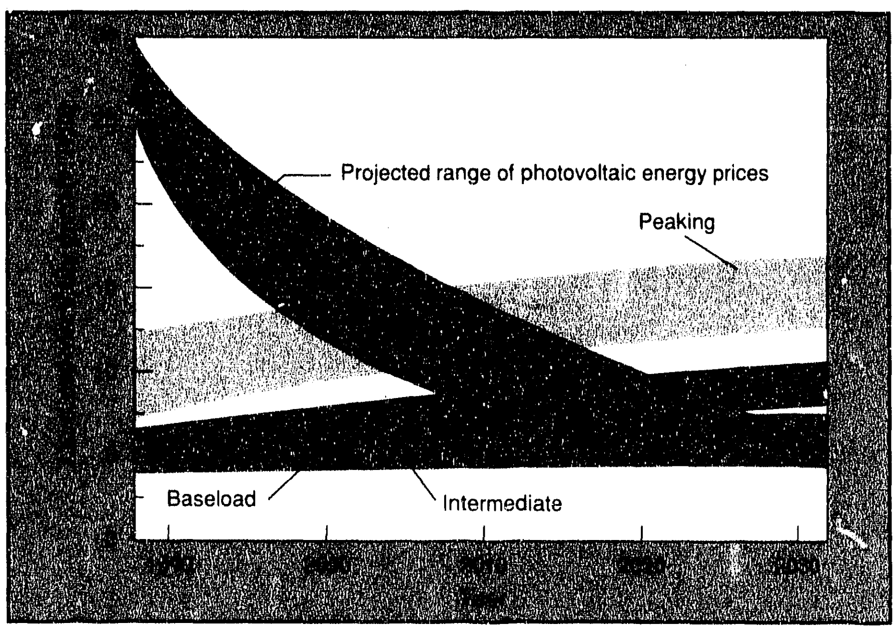



*Figure 4. PV will gradually become competitive in the peaking, intermediate, and baseload utility sectors (1990 $).*

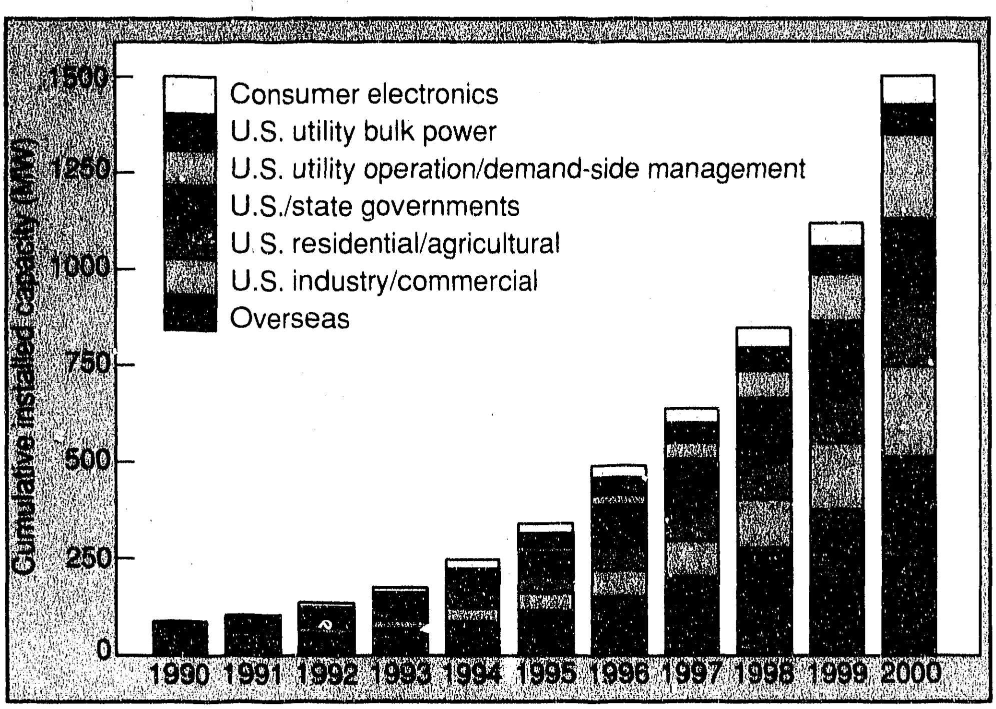



*Figure 5. Cumulative installed PV capacity by U.S. industry is expected to reach 1500 MW by the year 2000.*

## Technical and Economic Benefits

PV systems have several features that are attractive to potential users. First, they are modular, which means that systems can be optimized to meet the power requirements of the application, no matter how small or large the need. They can be installed in phased segments, which keeps construction lead times to a minimum.

The simplicity of PV systems provides for low operation and maintenance costs. Thus, the life-cycle cost of a photovoltaic system is frequently lower than that of other, more traditional options.

Since the life-cycle cost of a PV system is largely accrued in installation (Figure 6), this life-cycle cost is predictable, a factor that is not characteristic of most other energy sources. The user is sheltered from energy price fluctuations, interruptions in fuel availability, and subsequent changes in environmental regulations controlling emissions. Cost-related risks are taken up front where they can be calculated; long-range risks are substantially reduced.

These critical characteristics of modularity, reliability, and risk avoidance, combined with anticipated cost reductions, enable PV to be steadily phased into ever larger and more significant market sectors.

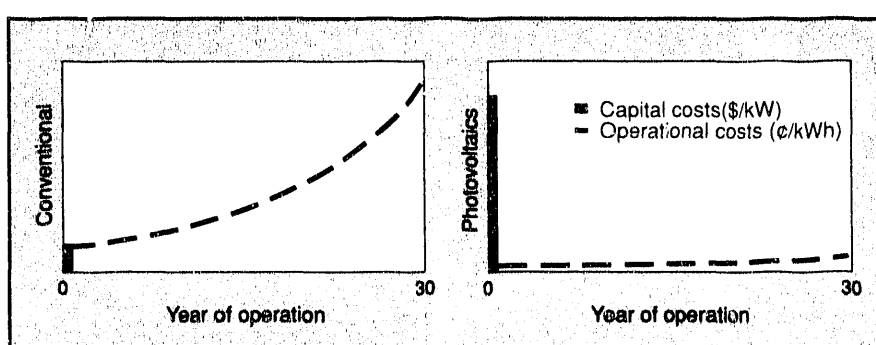



*Figure 6. PV's fuel independence and front-end cost ensure against unforeseen cost increases or supply disruptions that are characteristic of other energy options. (Source: Mobil Solar Energy Corporation)*

PV systems also match the load profiles of many of the nation's utilities, particularly those that have high air conditioning, commercial, and irrigation loads. Utilities' peak demand occurs during the middle of the day and tapers off toward evening, matching the energy available from the sun (Figure 7).

Small amounts of storage greatly extend the usefulness of PV systems by shifting the use of energy collected during the day into evening or morning periods where the value of energy is greater.

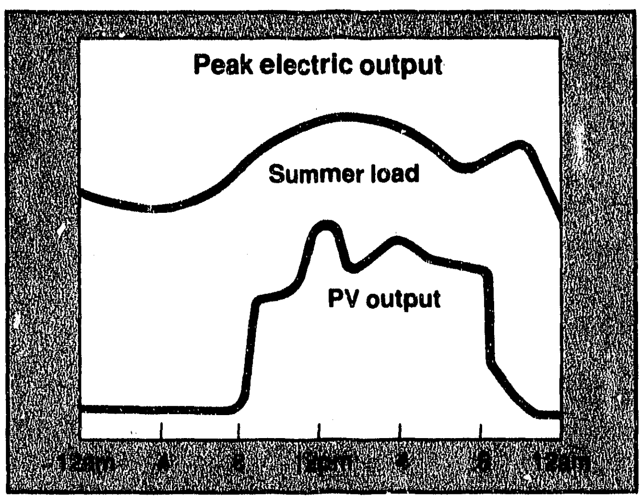



*Figure 7. For many utilities, photovoltaics' output closely tracks system load patterns.*

## Societal Benefits

The promise of photovoltaics includes many societal benefits as well. PV plants will add diversity to the nation's energy mix. For many applications, PV potentially offers lower energy costs than do fossil-fuel options.

While operating, PV plants produce no air pollution, no ashes or hazardous waste, and little or no noise. They require no transportable fuels. Each gigawatt-hour of electricity that is generated by PV rather than by burning coal prevents up to 1052 tons of carbon dioxide from being spewed into the atmosphere. The environmental effects of technologies are increasingly a matter of concern. Nineteen states now require that environmental issues be considered in resource selection, and an additional 10 states are now evaluating similar regulations.

Cooperative development of PV by the government and private sector will provide many other benefits to the nation, such as national energy security, industrial growth that creates new jobs, U.S. competitiveness, an expanded U.S. economy, and reduced trade deficits.

Conservative estimates show that, by the year 2030, we may have more than 100,000 MW of installed PV capacity. This would represent cumulative sales of more than $200 billion. Not including the money invested by the private sector, this reflects a seventyfold return on federal investments.

*Each gigawatt-hour of electricity that is generated by PV rather than by burning coal prevents up to 1052 tons of carbon dioxide from being spewed into the atmosphere.*

## Major Objective and Strategy

Our program's major objective is to stimulate the improvement of PV's cost effectiveness for electric power generation and fuel production for the utility, buildings, transportation, and industrial sectors. To accomplish this objective, we have formulated a strategy consisting of five critical steps:

- We will improve cost effectiveness by lowering production costs and improving the lifetime, efficiency, reliability, and safety of photovoltaic devices;

**Table 1.**
**Photovoltaic Program Achievements and Goals**

| Factor | Current Achievements (1991) | Mid-Term Goals (1995-2000) | Long-Term Goals (2010-2030) |
|---|---|---|---|
| Module Efficiency (%) | 5-15 | 10-20 | 15-25 |
| Electricity Price (¢/kWh, $ 1990) | 25-50 | 12-[illegible] | 5-6 |
| System Lifetime (years) | 10-15 | 20 | 30 |
| Installed Capacity (MW) | <50 | 200-1000 | 10,000-50,000 |

- we will characterize photovoltaic technologies in terms of societal benefits as well as competitiveness with conventional options;
- we will work closely with both manufacturers and potential users to expand the market and foster a viable PV industry;
- we will implement a program to hasten the acceptance of PV systems by utilities; and
- we will integrate program activities to be compatible with the National Energy Strategy.

In addition, taking advantage of other DOE-sponsored research in advanced concepts may lead to more efficient storage, transmission, and distribution of energy produced by photovoltaic systems and may also contribute to solutions to some critical environmental problems. These concepts include PV-generated hydrogen, superconducting magnetic energy storage, and the transmission of electricity through superconductors.

Table 1 quantifies our mid- and long-term utility goals as well as our current (1991) achievements. It is our expectation that industry will have installed at least 1000 MW of domestic photovoltaic capacity and 500 MW internationally by the year 2000.

# III. Implementing the Strategy

To fulfill the program's mission, the cost of energy from photovoltaic systems must be competitive with that of other sources of energy. This fact drives our research and development. But there is more than one way to make photovoltaic systems cost-competitive: by making more efficient devices, by making less expensive devices, by stimulating the market toward higher sales and production volumes, by employing combinations of these options, and by emphasizing values that have traditionally been ignored, such as environmental acceptability, modularity, and decentralization. For some technologies, module reliability must also be enhanced.

Device efficiency, the ratio of the electrical output power to the power of the incident sunlight, is limited by light absorption and loss mechanisms. The largest limiting factor is the inability of the device to effectively utilize all the wavelengths in the solar spectrum. Other limiting factors include the quality and type of material, reflection of light from the surface and interfaces, shading by the metallic grid, and series and contact resistances. The efficiencies of all types of photovoltaic cells have steadily increased as a result of research and development by both industry and government laboratories (Figure 8).

The price of a PV device is determined by several factors. These include the kind of materials used and the amount of materials required, the choice of substrates, the device design, and the fabrication processes. With the expectation of sufficient sales, manufacturing economies of scale and the degree of automation can also have a large impact on costs.

Crystalline devices are generally more efficient and reliable today. Thin-film devices are expected to show further cost reductions and become more efficient in the future. Concentrator technologies combine less expensive optical components in conjunction with small-area, highly efficient, and somewhat more expensive PV devices to achieve low cost.

There is no known reliable method that will tell us which materials, which device design, or which system potentially will be the most effective in fulfilling our mission. Therefore, the National Photovoltaics Program supports research and development in several different technologies being developed by industry.

*"PV-generated electricity is increasingly the option of choice for supplying power in the developing world. Over 75% of what Siemens makes here in the U.S. is exported."*

**Charles Gay, President**
**Siemens Solar Industries**

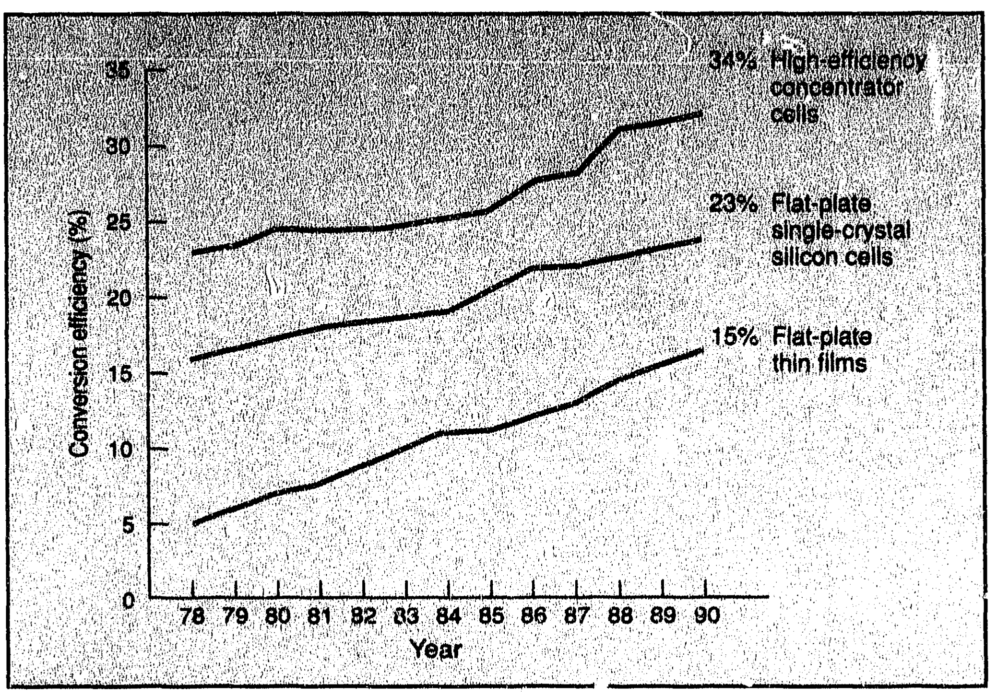
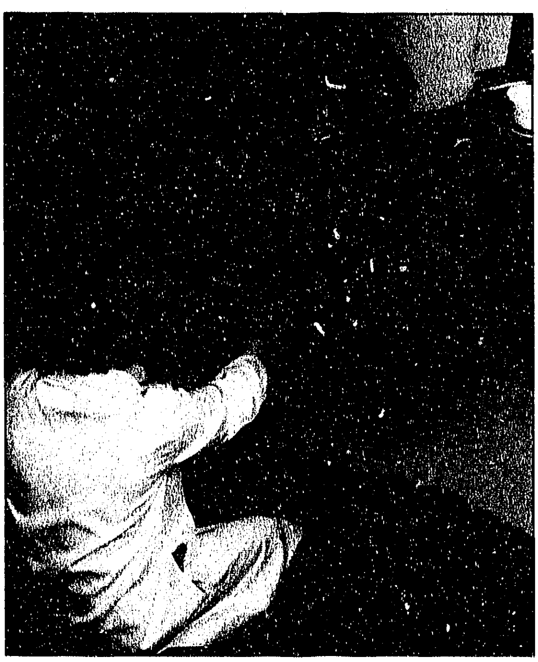



*Figure 8. The efficiencies of laboratory cells have increased steadily in all PV technologies.*

**Table 2.**
**PV Research and Development Tasks**

| Task Area | Objective |
|---|---|
| 1. Research and Development | Conduct basic and applied research on promising new materials, processes, devices, and encapsulation schemes through the development of prototype modules; provide supporting measurements and modelling capabilities |
| 2. Manufacturing Technology Development | Develop the technology and manufacturing processes with industry for cost-effective PV modules and transfer them to the private sector |
| 3. Systems and Market Development | Assist industry in the development of system technologies for cost-effective applications and condition markets; transfer technological development to the private sector |



*Scannin‑ transmission electron microscopy allows researchers to characterize photovoltaic materials and cells using a variety of techniques, including imaging and x-ray diffraction.*

Our strategy for the next five years will be organized around three major R&D tasks, as shown in Table 2. PV Research and Development addresses scientific and engineering questions pertaining to photovoltaic materials, cells, and devices. PV Manufacturing Technology Development surveys the problems involved in developing, testing, and manufacturing PV modules. PV Systems and Market Development assesses the performance of PV systems today and recommends ways to develop PV technology for both near-term and long-term markets.

## PV Research and Development

### *Fundamental and Supporting Research*

The primary goal of Fundamental and Supporting Research is to provide a strong foundation to the scientific and technical knowledge base for photovoltaic materials, devices, and processes. Several scientific and engineering disciplines support this task, including theoretical solid-state physics, device physics, chemistry, materials and surface sciences, and optics. Universities, industry, utilities, and government laboratories work together on many subcontracted or collaborative research projects in these areas.

*New Ideas.* The New Ideas for Photovoltaic Conversion Project identifies innovative approaches to existing technology, new materials, new device configurations, and new photovoltaic concepts. We periodically issue requests for letters of interest to identify new concepts. The most promising ones receive research funding for one year. If a concept shows significant potential, it is supported for an additional year, with the possibility of transferring the project to the appropriate major photovoltaic program for extended support. To date, more than 50% of the initial research conducted under this program has been worthy of further research funding, patents, or commercial product development.

*University Participation.* The University Participation Project attracts highly qualified university research teams to the National Photovoltaics Program. Since the project began in 1985, we have made 12 subcontract research awards. The project provides continuous funding over a three-year period, allowing universities to build and support multidisciplinary teams. It also helps train graduate students for careers in the photovoltaic community.

During the next five years, work will continue on current projects in the New Ideas and University Participation Programs. There will

## The Basic PV Technology

Photovoltaics directly and continuously converts sunlight into DC electricity through semiconductor electronic processes. PV power elements, being solid-state devices, are highly amenable to mass production.

The basic power element of a photovoltaic system is the solar cell (Figure 9). Each cell has two or more specially prepared layers of semiconductor material whose atoms absorb light, freeing electrons and creating "holes" to carry current. Each cell has a junction between two dissimilar semiconductor materials that creates a voltage to drive electrons through a circuit.

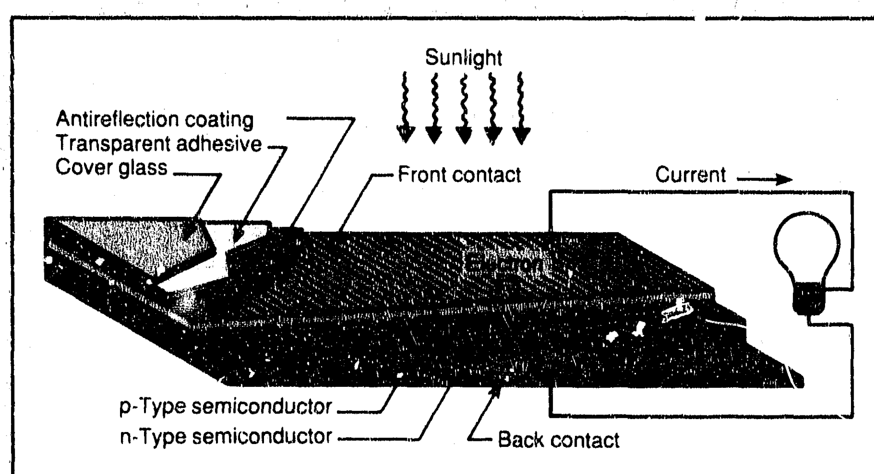



*Figure 9. Solar cells have a built-in voltage produced by layers of dissimilar semiconductor materials.*

Solar cells can be made from several different semiconductor materials, and these materials are available in a variety of physical states: single crystal, polycrystalline (many small crystals), or amorphous (noncrystalline or glasslike).

Multijunction cells, produced by stacking layers of semiconductor materials on top of each other, capture a larger portion of the solar spectrum than do single-junction cells. This enables higher device efficiencies to be obtained for the same amount of sunlight.

Connecting many cells together into a module, the building block of photovoltaic systems, produces more power output and provides protective packaging for the cells. Modules can also be made by depositing amorphous or polycrystalline semiconductor layers over a large area and then encapsulating the layers in protective coatings. Today's power module consists of a complete, enclosed package of solar cells, interconnects, power leads, and a transparent cover or optical concentrator, depending on the type of module. Modules fall into two broad categories: flat-plate modules, which are used under ordinary sunlight, and concentrator modules, which include lenses or reflectors to focus sunlight onto the solar cells (Figure 10). For large power needs, modules are grouped together to form arrays.

Few PV systems require only a module to operate. Many require other systems hardware such as batteries for energy storage, charge controllers, inverters to change from direct current to alternating current, or trackers that automatically follow the sun. Collectively this type of equipment is referred to as balance-of-systems hardware.

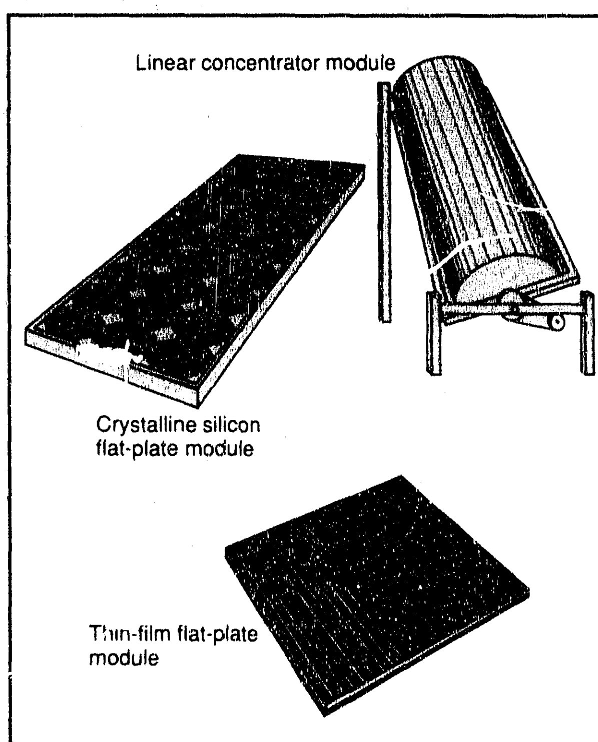
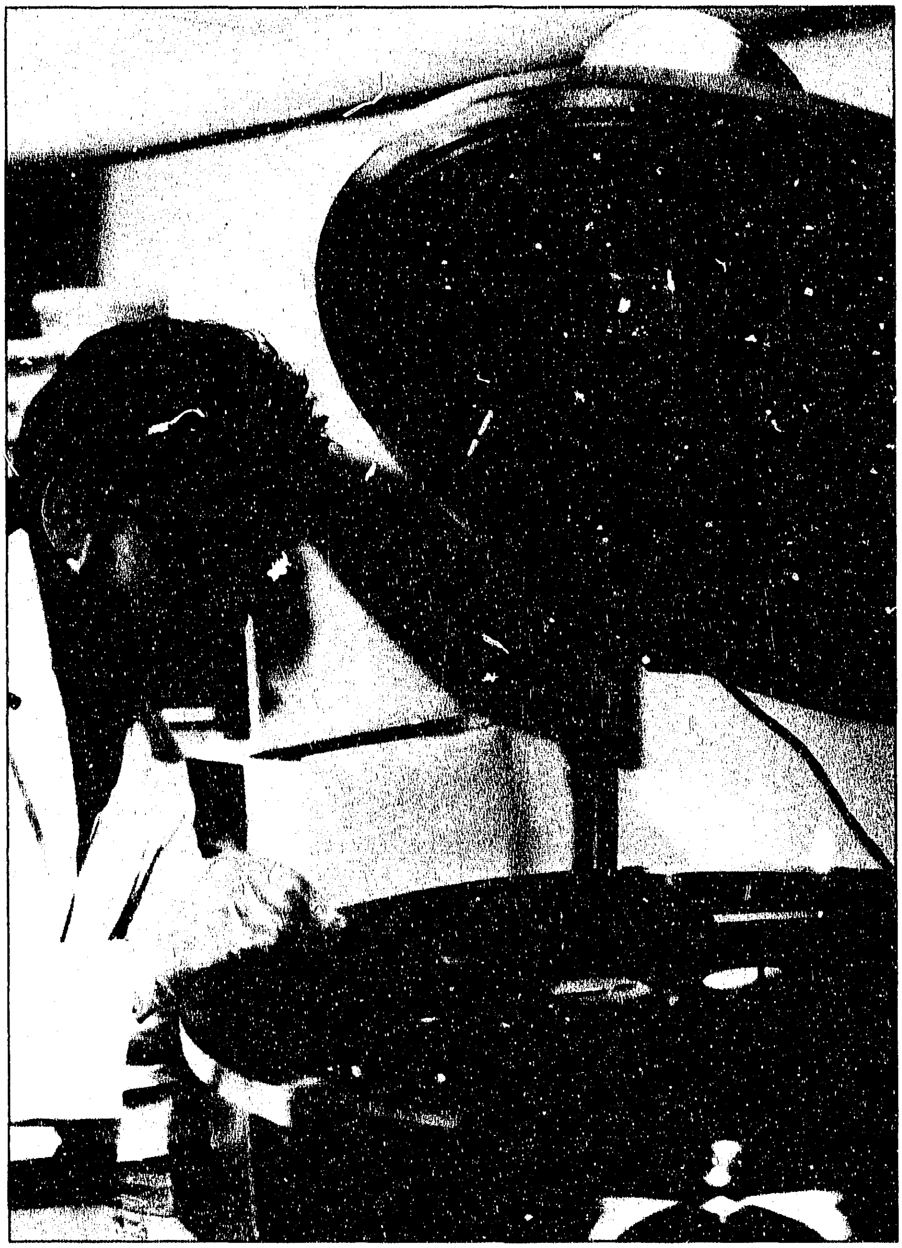



*Figure 10. Modules are of two basic types: flat plates (crystalline silicon or thin-film) and concentrators.*



*A laboratory sputtering system deposits transparent conducting oxide layers, the top electrode on polycrystalline thin-film cells.*

also be new solicitations approximately every two years.

*Solid-State Theory.* Solid-state theory research brings state-of-the-art condensed matter theory into the realm of photovoltaic materials. The performance of solar cells depends on a very large number of material characteristics and interactions that are difficult to isolate. Solid-state theory helps us to develop a fundamental understanding of solar cell performance by modelling the electronic structure of prototype materials that characterize these complex relationships. Knowledge gained through these studies can be applied to the discovery of novel photovoltaic materials. It also allows us to analyze the properties of existing materials. During the next five years, we expect to develop new techniques for theoretical research, integrating these techniques with experiments to predict new materials and devices.

*Characterization and Testing.* Measuring and testing materials, cells, and modules are vitally important not only to the research done at the DOE laboratories but also to the R&D done throughout the photovoltaic community. We examine tens of thousands of samples from government laboratories, universities, and industry each year. Characterization methods extend from the macroscopic evaluation of modules to the imaging of atoms. In addition to routine diagnostic information, the laboratories have special capabilities to link events observed on the atomic scale with the macroscopic performance of cells and components.

As part of our commitment to providing these analytical services, we have developed many new characterization techniques, some of which have won such honors as the R&D 100 Award. Some of these characterization techniques have been transferred to the private sector. We also provide recognized standards for measuring efficiency, allowing the

## Multiple Paths—Putting Our Eggs in Several Baskets

Because of the difficulties associated with predicting the success of any specific technology during its formative period, R&D is conducted on a selection of the most promising concepts. The R&D path is balanced; the state of the art of well-known technologies like crystalline silicon is being steadily improved, while continuing progress is being made with new and promising photovoltaic materials.

*Crystalline Silicon.* Crystalline silicon technology is the most mature and best understood of the photovoltaic technologies. Researchers have identified the major barriers that limit efficiency and cost effectiveness; consequently, laboratory cells have now passed the 23%-efficiency mark. This is a particularly impressive achievement, since crystalline silicon was accepted as a very mature technology in the early 1980s with efficiencies in the 17% range. Working with industry, we have reduced the cost of producing high-purity silicon and have developed new methods for growing silicon material, including growing crystalline silicon in flat sheets. An industry has developed and grown that is now competing successfully in today's remote-power market.

*Amorphous Silicon.* Thin-film devices made of hydrogenated amorphous silicon are a leading alternative to crystalline silicon. The first amorphous silicon cell was made in 1974 and had an efficiency of less than 1%; single-junction cells now demonstrate initial efficiencies around 12%. Multijunction cells have reached initial efficiencies of more than 13%, and submodules, 10%. Very large modules (10 square feet or more) are now available at 4%-5% efficiency. Deposited as a low-cost, thin film of silicon on a low-cost substrate such as glass, amorphous silicon cells were the first thin-film cells to achieve real commercial status. From almost zero in 1980, amorphous silicon cells now comprise about 30% of the world market in photovoltaic devices. They are most commonly used in consumer products.

*Copper Indium Diselenide.* Polycrystalline thin films of copper indium diselenide (CIS) have made impressive strides. Since the beginning of their development in the late 1970s, cell efficiencies have risen to nearly 14% and submodule efficiencies to 11%. Experimental cells combining CIS with amorphous silicon have reached efficiencies as high as 14.6%. Many advances have been made recently in manufacturing methods for CIS devices. Most are now made by selenization, where copper and indium are deposited on glass and then annealed in the presence of selenium. Several companies are in the process of producing the first commercial modules.

*Cadmium Telluride.* Cadmium telluride (CdTe) is another promising polycrystalline thin-film material. Recent technical results have been impressive. Under the National Photovoltaics Program, cells have reached 12% efficiency and submodules, 7%. CdTe technology is particularly attractive because of its potential for very low-cost manufacturing techniques, including electrodeposition, spraying, and screen-printing. Several U.S. companies are working to identify the best fabrication methods for commercial production.

*Thin-Film Crystalline Silicon.* Crystalline silicon remains a highly promising approach. Conventional crystalline silicon cells are 200 to 300 microns thick. Thin-film crystalline silicon cells approximately 100 microns thick have exceeded 15% efficiency. These cells are made by depositing crystalline silicon on low-cost substrates. This approach offers the potential for thinner cells of high efficiency with very low manufacturing costs.

*Gallium Arsenide.* With their high efficiencies (more than 25% under one-sun conditions and more than 30% under concentrated light), gallium arsenide (GaAs) cells are extremely stable and resist radiation damage in space. Single-crystal GaAs cells can be made on a GaAs substrate (25% efficient) or on a germanium or silicon substrate (20% efficient), or a thin film can be removed altogether from a GaAs substrate after fabrication (22% efficient). Alloy materials based upon GaAs are easily tailored to produce very high efficiency multijunction devices. Terrestrial GaAs cells are being developed for both concentrator and flat-plate power systems.

*Concentrator Cells and Systems.* Concentrator systems use lenses and other optical components to concentrate light onto high-efficiency cells. Concentration allows more power to be produced from a given amount of photosensitive material. Smaller cells thus become possible, reducing costs.

Concentrator systems need to track the sun and are cost effective primarily in areas of high direct insolation (such as the southwestern United States). We are developing three types of concentrator systems to operate at low-level sunlight concentrations (less than 30 times), mid-level concentrations (100 to 400 times), and high-level concentrations (greater than 400 times).

Advanced silicon concentrator cells from university laboratories, incorporated into modules, have already achieved efficiencies greater than 25% in comparison to their expected practical limit of 30%. Very sophisticated, multi-junction solar cells, with expected practical limits of about 40%, have recently exceeded 34% efficiency in laboratory research.

*Researchers study solar radiation to better predict the performance of solar cells and modules.*

confirmation of cell and module measurements made by others.

During the next five years, we will continue to provide analytical services to DOE researchers and the photovoltaic community and to develop new analytical techniques. We also expect to upgrade some of our critical equipment that is becoming technically obsolete. It is essential for us to maintain or re-establish state-of-the-art equipment for characterization and testing and for material and device fabrication.

*Solar Radiation Research.* Research on the solar radiation resource is the foundation of cell, module, and system evaluation. Because of atmospheric effects such as clouds and aerosols, neither the amount of solar radiation nor its spectral (color) content are constant. Designers and users of PV cells and modules need to know how these solar radiation variations affect the energy produced by existing devices, as well as new materials and designs. Measurements of solar radiation

## Environment, Safety, and Health

An electronic bulletin board service is available through the Biomedical and Environmental Assessment Division of Brookhaven National Laboratory. The Photovoltaic Environmental, Health and Safety Bulletin Board (516-282-2489), which is accessible 24 hours a day, Monday through Thursday, provides a forum for exchanging environmental, health, and safety information relating to photovoltaic cell fabrication. The bulletin board is available at no cost to both commercial and federally funded organizations engaged in PV cell research, development, and production.

The National Renewable Energy Laboratory (NREL) and Sandia National Laboratories are also involved in the development of process safety standards for all levels of PV manufacturing, from solar cells through complete systems. They have been active in the development of PV-related guidelines for the National Electrical Code and both national and international consensus standards.

See Appendix A for contacts at NREL and Sandia.

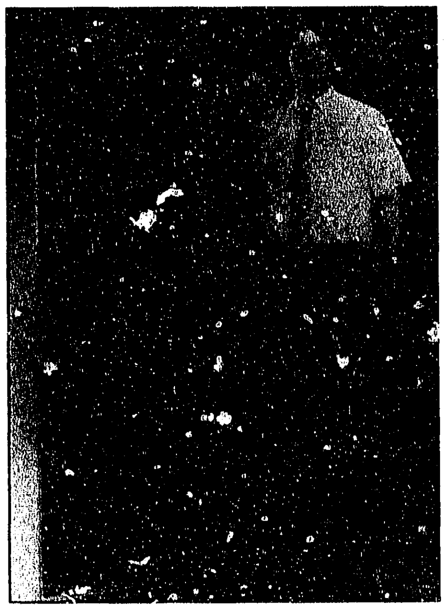
are also critical for testing and evaluating modules outdoors. During the next five years, we will continue to work closely with the PV community to gather and distribute data on the characteristics of solar radiation for use in quantifying its impact on system performance.

*Environment, Safety, and Health.* The goal of the Environment, Safety, and Health research is to ensure that these issues are carefully considered during the development and commercialization of photovoltaic technology. We work actively with industry and other federal organizations (such as the Environmental Protection Agency and the Occupational Safety and Health Administration) to evaluate possible manufacturing hazards presented by various PV technologies and to advise on alternative ways to manage these hazards. Industry is a very important partner in this effort. We expect to continue this work during the next five years, including sponsoring a third photovoltaics safety conference.

We also maintain an electronic bulletin board that provides a forum for exchanging environmental, health, and safety information to anyone involved in the program. Standards and codes relating specifically to photovoltaics are continually being developed at both the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories.

### *Advanced Thin-Film Materials*

Thin films are semiconductor layers that are much thinner than the silicon used in conventional cells (typically less than 10 microns, compared with 100 to 300 microns). Thin-film modules are expected to



*U.S. industry can produce large amorphous silicon modules like the one shown here.*

be lower in cost than conventional modules because they use less material; they have potential for high-throughput, continuous manufacturing processes; and they may have lower handling costs.

The main thrust of Advanced Thin-Film Materials research is to reach module efficiencies of 15% while maintaining the advantages that tend to lower costs. Achieving 20- to 30-year reliability is also a critical goal. During the next five years we will be developing four materials: amorphous silicon, copper indium diselenide, cadmium telluride, and thin-film silicon (Table 3).

*Amorphous Silicon.* One of the major strengths of the amorphous silicon technology is its manufacturability. Relatively well-defined manufacturing processes having high yields and low cost have been developed. Additional strengths include a large U.S. and international industry/university infrastructure, a

*Improving our understanding of solar cell theory is allowing us to understand the effects of different materials and cell designs.*

**Table 3.**
**Key Research Issues: Advanced Thin-Film Materials**

**General**
- Transparent conductors: Improved transmission, conductivity; lower cost processes
- Module design: Laser scribing and monolithic interconnection
- Encapsulation and edge-sealing: Resolution of durability and stability issues associated with module packaging

**Amorphous silicon**
- Fundamental studies to reduce or avoid initi[illegible] light-induced instability
- Development of stabilized high-efficiency multijunction cells, submodules, and modules
- Development of amorphous silicon-based alloys and microcrystalline thin films
- Investigation of higher rate deposition processes

**Copper indium diselenide (CIS)**
- Improved junction properties to raise voltage and fill factor
- Transfer of cell results to submodules and modules
- Investigation of alternative processes for making thin layers (CIS, ZnO, Mo, CdS)
- Replacement of hydrogen selenide feedstock

**Cadmium telluride (CdTe)**
- Resolution of contact stability issues
- Improved ultraviolet response (thin CdS)
- Improved junction properties to enhance voltage and fill factor
- Transfer of cell results to submodules and modules

**Thin-film silicon**
- Development of thin, high-efficiency cells
- Achievement of proof-of-concept, low-cost substrates
- Fabrication of large-area submodules (1000 $cm^2$ or more)
- Monolithic submodule integration

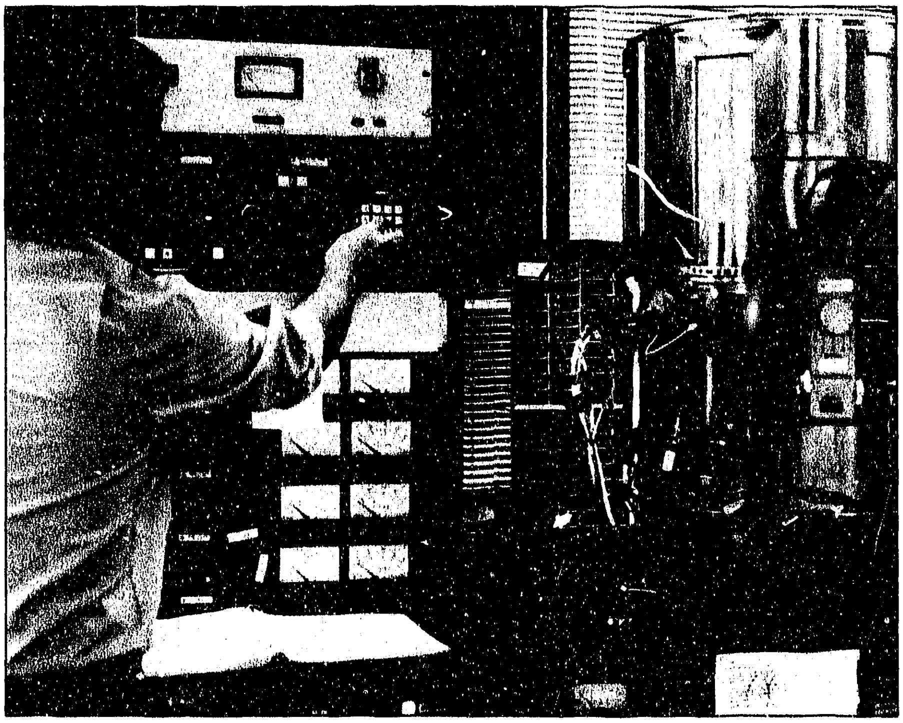
large investment base for the U.S. industry, a wide applications base (including profitable electronic applications), and flexibility in module design choices.

A key challenge for amorphous silicon technology is increasing the performance of production modules in terms of stabilized efficiencies. A technical issue that needs to be addressed is the light-induced instability of amorphous silicon devices. Light-induced instability, an intrinsic effect in amorphous silicon materials, appears to be self-limiting and can be minimized by using an engineering approach — making the devices thinner. Other reliability issues for a 20- to 30-year lifetime are similar to those for other PV materials.

The goal of increasing efficiencies has led to an innovative multijunction structure for amorphous silicon devices. Multijunction devices contain a stack of two or three PV cells in which light that is unused in top cells can be used effectively in the lower cells. Amorphous silicon films alloyed with germanium or carbon increase multijunction device efficiencies in the red or blue portions of the solar spectrum, respectively. Combining different amorphous silicon alloys to achieve high efficiencies and improved stability will result in a thin-film amorphous silicon module that meets the long-term DOE goal of 15% efficiency. Research will continue to improve various types of amorphous silicon materials and devices and then transfer these improvements into production modules.

*Copper Indium Diselenide (CIS).* One of the major strengths of CIS technology is that it appears to be extremely stable. Outdoor testing of prototype modules for more than 500 days showed almost no change in efficiency. A focus of our R&D efforts will be to establish whether CIS modules can achieve the high stability of crystalline silicon modules.

Single-junction CIS cells have the practical potential of achieving 18%-20% efficiency, allowing modules more than 15% efficient to be fabricated. Research in CIS will address cell design and materials issues to optimize cell efficiencies. For example, we will investigate various

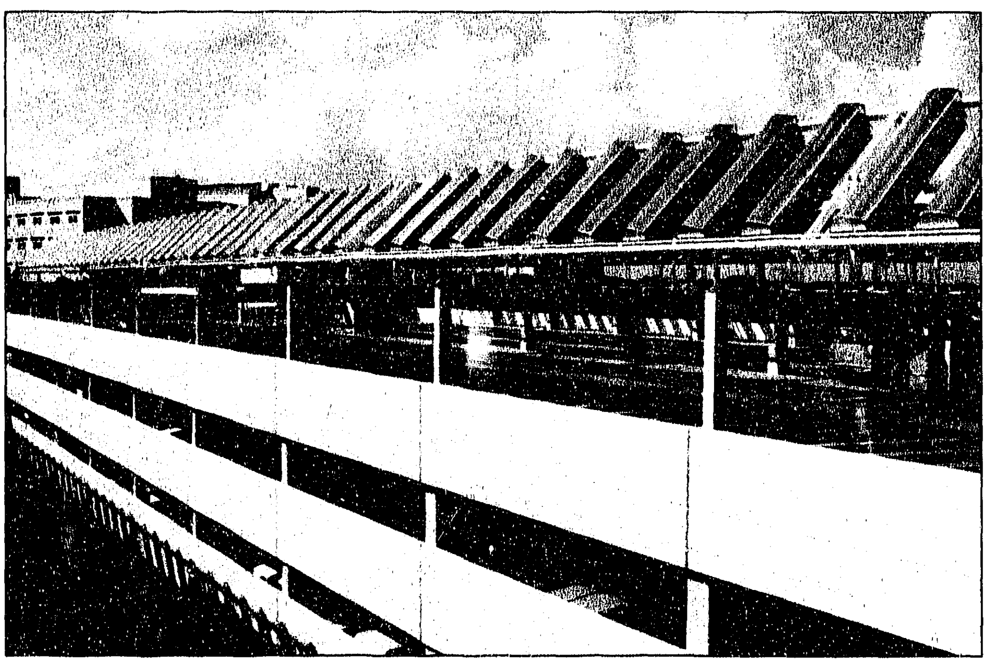


*Controlling deposition parameters is one of the keys to producing high-quality thin films for photovoltaic cells.*

other alloys, such as those incorporating gallium or sulfur, to determine whether they increase efficiencies. Successful modifications will be incorporated into larger devices. The critical issue in manufacturing larger modules will be uniformity over large areas and high process yields.

During the next five years we will address a number of critical technical tasks. Our goal is to have a prototype module capable of competing for remote and peak power applications at the end of 1995 that is 13% efficient, 4000 square centimeters (or more) in size, and susceptible to less than 5% degradation over a 10-year period.

*Cadmium Telluride (CdTe).* Recent work in innovative CdTe designs has been very promising. At the module level, the effect of humidity on performance is being



*In Austin, Texas, 3M Company has installed a 300-kW concentrator PV system manufactured by Entech to supply part of the power to its new research center.*

evaluated. Preliminary outdoor test results are promising; CdTe modules show about the same durability as CIS modules during their initial half-year outdoors.

Our research efforts will focus on increasing the efficiencies of cells toward their practical maximum of 20% as well as increasing the efficiencies of CdTe modules.

*Thin-Film Crystalline Silicon.* Another thin film that shows promise is thin crystalline silicon. Qualities that make silicon an attractive material for many types of PV cells include silicon's abundance and its stability. Important work is being done to develop thinner crystalline silicon cells because, with proper design, such cells can be more efficient than thicker ones.

Optimizing crystalline silicon as a low-cost, thin-film option entails growing thin layers on low-cost substrates. The cells must be efficient, and the processes and designs amenable to producing large-area, monolithic modules.

Processes for depositing silicon on substrates have been developed and experimental cells produced. Our goals are to make larger area cells and to interconnect the cells without numerous handling steps.

*Institutional Issues.* Some thin-film technologies use small amounts of hazardous materials as well as materials that may not be available in the quantities needed for large-scale use. With the help of staff at Brookhaven National Laboratory, we will look for ways to understand and manage these problems, such as avoiding feedstock losses during manufacture, making thinner layers, and finding substitutes where possible for critical elements.

### *High-Efficiency Materials*

High-efficiency crystalline semiconductor materials include silicon, gallium arsenide, and related compounds. The intrinsic stability of a wide variety of crystalline materials has been well established by long-term outdoor operation. With efficiency, stability, and an extensive research infrastructure established, we will focus our efforts predominantly on developing lower cost cell designs and developing manufacturing processes that exploit the current level of scientific understanding of these materials (Table 4).

*Crystalline Silicon.* The low-cost production materials available today do not provide the purity or crystalline perfection of the float-zone silicon used for laboratory device research. But we can increase the efficiencies of commercial cells using our knowledge of the limitations of device design and the interactions

**Table 4.**
**Key Research Issues: High-Efficiency Materials**

**General**
- Lower cost cell designs and manufacturing processes

**Crystalline silicon**
- Improved efficiencies through improved processing
- Better understanding of electrically active defects
- Evaluation of specific processing steps

**Gallium arsenide**
- Reduced substrate costs
- More uniform, larger area epitaxial growth
- In-line monitoring for better process control
- Simpler cell designs with fewer process steps
- Novel manufacturing technologies

**Advanced materials**
- Improved quality in commercial crystalline silicon
- Application of knowledge of high-quality materials to commercial-quality materials

**Concentrator cells**
- Lower series resistance without increased shading
- Application of advanced cell technology to commercial manufacture

of processing steps with defects and impurities in the material. To do this, we will assist industry in three specific research areas during the next five years.

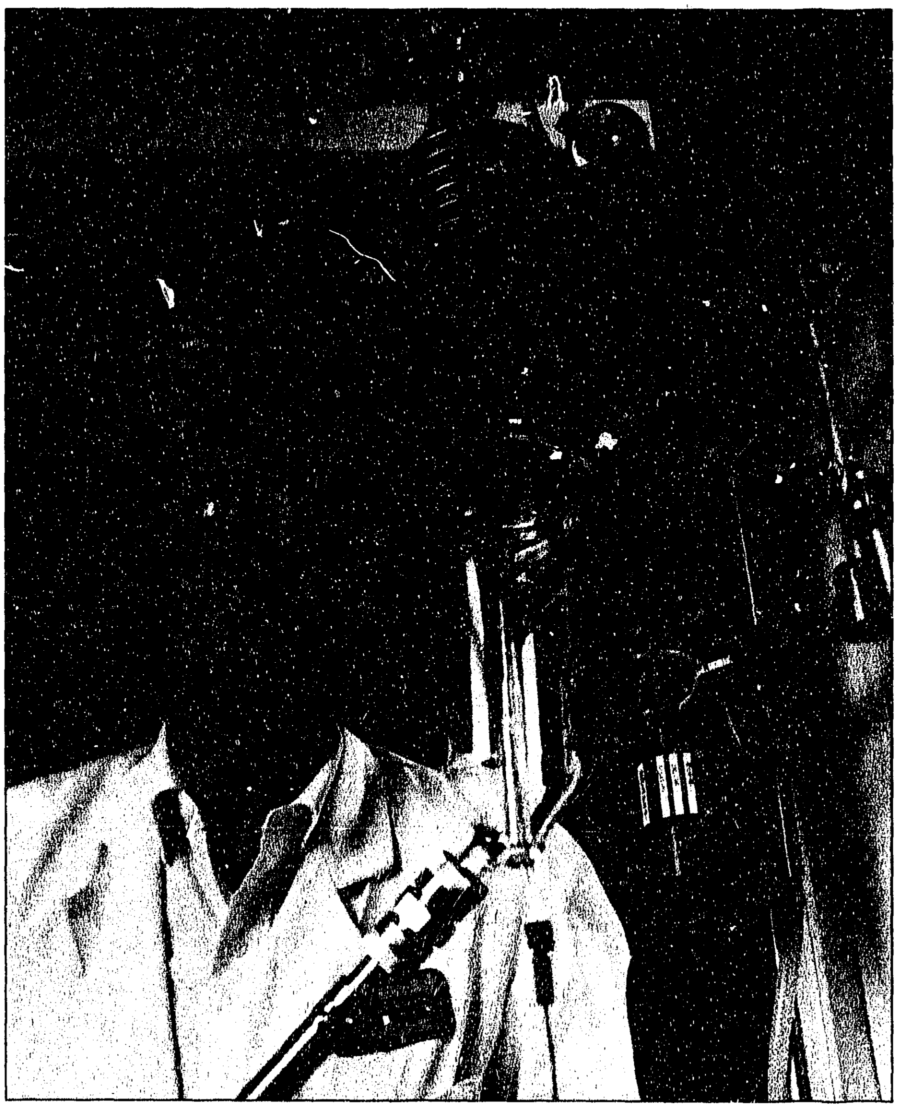
In the first area, we will extend our understanding of the nature and magnitude of the effects of defects in crystalline silicon. This knowledge will be essential in analyzing the performance trade-offs inherent in designing fabrication sequences.

In the second area, we will study the interaction between specific processing steps (such as cleaning, texturing, and diffusion) and various grades of silicon under controlled conditions. The analytical capabilities at NREL and Sandia will be used to characterize materials processed by industry. This collaborative research will guide the improvement of the solar cell fabrication sequence.

In the third area, we will build on the previous two areas, along with ongoing high-efficiency device research, to improve overall fabrication procedures on a company-specific basis.

*Gallium Arsenide.* The cost of terrestrial gallium arsenide photovoltaic devices is currently too high to make GaAs a strong contender in the PV marketplace. Our research over the next five years will focus on conventional and new methods of crystal growth. Improved crystal growth will allow us to reduce or eliminate the costs associated with GaAs substrates, improve the safety and reduce the cost of growing the GaAs cells, and develop new crystallographic structures that will improve cell performance.

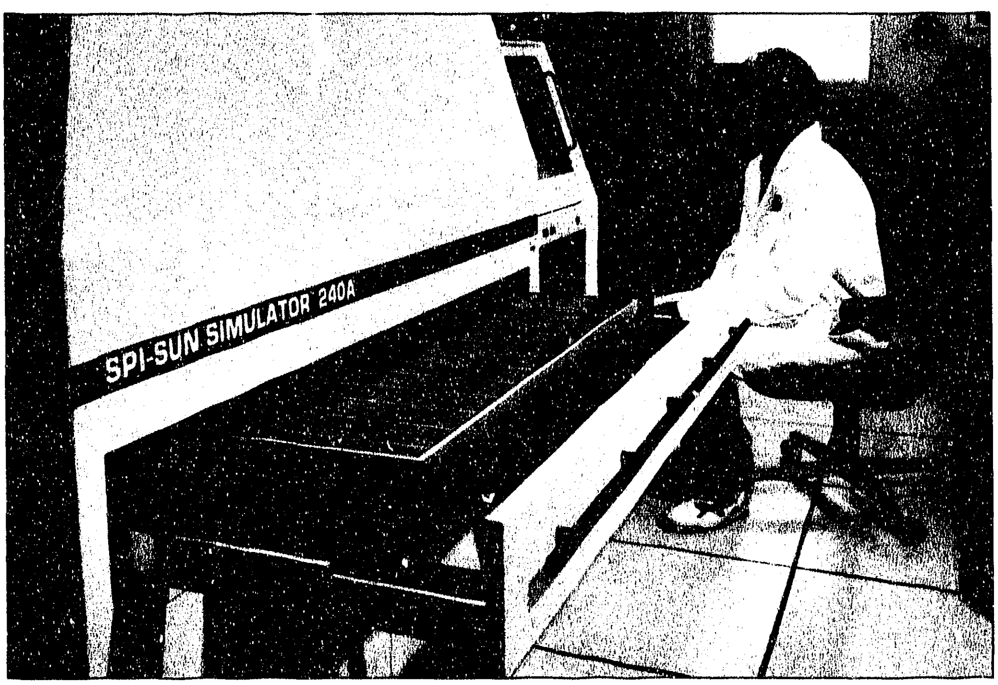
We will also be addressing processing issues so that GaAs devices will be able to take advantage of the expected market growth in photovoltaics. We will strive to improve the uniformity and lower the cost of current manufacturing techniques (commonly, metal-organic chemical vapor deposition), simplify the cell design and hence the number of processing steps, and develop in-line monitoring methods to better control processing variables.



*Using metal-organic chemical vapor deposition techniques, researchers study the epitaxial growth of materials for high-efficiency solar cells.*

*Advanced Materials and Devices.* To help improve the quality of today's commercial materials, we will explore the fundamentals of growing silicon crystals at high growth rates while yielding very pure, high-quality material. This will require characterizing the thermal and mechanical properties of silicon near its melting point. Several promising techniques will be evaluated for their performance and cost effectiveness.

In high-efficiency cell research, we will investigate the application of new fabrication processes to thin photovoltaic cells. These processes, such as lateral epitaxy and seeded recrystallization, have produced high-quality crystalline thin films. And while the cell materials researched to date (silicon, gallium arsenide, and related compounds) show great promise for thin cells, we will explore other materials as well.



*A sun simulator allows researchers to measure the performance of photovoltaic devices under controlled conditions.*

High-efficiency device research enables us to better understand the electronic processes that occur in these devices and to better control the efficiency loss mechanisms. Improving our understanding of solar cell theory is allowing us to help improve the design of cells made from less-than-ideal materials and to understand the effects of different processing options.

*Concentrator Cells.* The research issues pertinent to high-efficiency, one-sun cells also apply to concentrator cells. We will continue to address problems specific to concentrator cells, such as how to reduce series resistance to accommodate the higher current generated by concentrated sunlight, without increasing the shading caused by larger grid lines. Another issue we will study is how to apply advanced cell technology to the commercial manufacture of module-ready cells. The Photovoltaic Concentrator Initiative, begun in 1990, will help speed the commercialization of concentrator systems.

## PV Manufacturing Technology Development

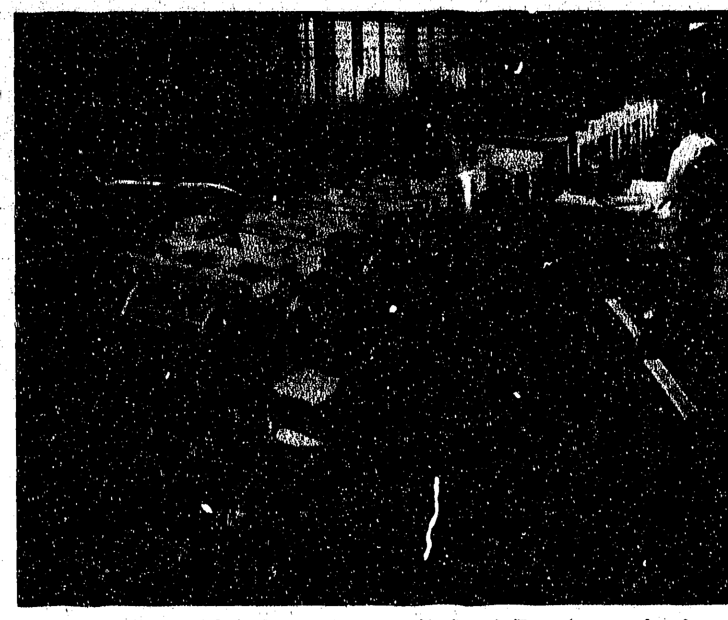
Improving the way that PV devices are manufactured is vital to achieving our goals. We intend to take two complementary approaches to improving PV manufacturing technology. One approach, the PV Manufacturing Technology (PVMaT) project, calls on the PV industry and DOE to work together to advance PV manufacturing technology. The other approach involves module development research and uses the resources of the DOE laboratories to evaluate modules and module

## Photovoltaic Manufacturing Technology Project (PVMaT)

PVMaT is a joint U.S. PV industry/DOE effort to significantly reduce module manufacturing costs and to lay the groundwork for large-scale increases in module production through improvements in PV manufacturing technology. The goal is to enhance U.S. industry's share of the world PV market.

In 1980 worldwide PV module sales were about 4 MW, and the U.S. industry dominated with a 60% share. In 1990 worldwide sales were more than 46 MW; the United States had about a 32% share. To enhance the U.S. position in the marketplace, improvements in the laboratory must quickly become improvements on the production line.

In this project DOE will act as an investment partner with industry. By supporting the development of better manufacturing technology, which will lead to larger commercial production capacities, we intend to improve the U.S. industry's competitive position by reducing module production costs. These cost reductions and production increases are necessary if DOE PV Program goals are to be met.



*DOE is working with industry through the PVMaT project to develop better manufacturing technology for photovoltaic modules.*

PVMaT will proceed in two phases. In Phase I (1990) we will have identified current problems, assessed current manufacturing capabilities and technology, suggested ways to increase capacity and reduce cost, and anticipated future problems. In Phase II (1991-1995) we will work with industry to solve the problems. Individual companies will address their specific issues in cost-shared programs; researchers in industry, university, or government laboratories will work on generic research issues with industry's advice. PVMaT will be open to all PV technologies and will lead to a variety of working relationships, consortia, and cooperative research and development agreements.

performance and suggest solutions to common module problems.

### *Photovoltaic Manufacturing Technology Project*

The goals of this DOE/industry partnership are to advance PV manufacturing technologies, substantially reduce module production costs, increase module performance, and expand U.S. commercial production capacities. DOE will act as an R&D investment partner with industry to improve the U.S. industry's competitive position. This five-year project is proceeding in two phases. Phase I is focusing on problem identification; Phase II, also cost-shared with industry, will focus on problem solving.

DOE intends to encourage cooperative activities with industry and provide tangible assistance in identifying and overcoming major technical obstacles to improving manufacturing technology. These obstacles, for example, could involve process rates, process control, encapsulation, yield, throughput, scaling to larger areas, material utilization

*Through PVMaT, DOE assists the industry in advancing PV manufacturing technologies.*

efficiency, substitution of more cost-effective materials, or the introduction or increased use of automation and robotics. These issues will be coordinated with the module development activities described below.

### *Module Development*

The primary goal of module development is to develop the collector manufacturing technology for producing cost-effective photovoltaic modules. Improvements in encapsulation and sealing technology will be sought. New module designs must be producible through automated, low-cost manufacturing with high yields and excellent product quality (Table 5).

*Flat-Plate Crystalline Silicon Modules.* Although this is the most developed and widely used of the three PV module technologies, module prices must be substantially reduced to compete with other electric power technologies. Besides lowering the cost of the cells that go into the modules, there are also opportunities for lowering module costs by automating and integrating cell processing with module manufacturing. Through cost-shared research with industry, we will work toward this goal. We will also continue to evaluate modules for their durability and reliability and address issues in those areas as the need arises.

*Flat-Plate Thin-Film Modules.* Because of the way cells are produced (by depositing thin films), cell and module manufacturing is inherently integrated in thin-film technology. We will concentrate on module development activities that include mechanical and electrical design, encapsulation, evaluation, and reliability testing. In the area of manufacturing technology, we will emphasize the design and development of large-area deposition and processing equipment and material handling systems.

*Concentrator Modules.* Concentrator modules are significantly more complex than flat-plate modules. They need further development to ensure the optimum performance and packaging of the cells, cell assemblies, and concentrator optics. They also require that we develop low-cost, sun-tracking array support structures.

The Photovoltaic Concentrator Initiative is a cost-shared project with the concentrator industry (cell and collector manufacturers) to advance concentrator technology toward a competitive, commercial product for utility bulk-power generation. Integration of module design with manufacturing technology, module

**Table 5.**
**Key Research Issues: Module Development**

**General**
- Testing and evaluation
- Integrated module design and manufacturing
- Encapsulation and edge-sealing
- Degradation mechanisms and lifetime prediction

**Flat-plate crystalline silicon**
- Automation and integration of cell processing

**Flat-plate thin-films**
- Mechanical and electrical design
- Attachment of electrical interconnects
- Large-area deposition and processing equipment
- Materials handling systems

**Concentrators**
- Development of low-cost components (lenses, cell assemblies, module housings)
- Design and development of complete modules
- Automation and integration of cell processing with module manufacturing

evaluation, and reliability engineering are included. Advanced concentrator module research will support these activities.

*Module Testing, Evaluation, and Development.* We also test and evaluate modules and study general problems that affect all types of modules. During the next five years, we will continue measuring electrical performance characteristics, testing durability, analyzing the failures of modules (see Figure 11), collecting pc formance data, working with industry and standards groups to set electrical and performance measures, and other general activities. These activities will help develop modules that meet performance, safety, and reliability requirements.

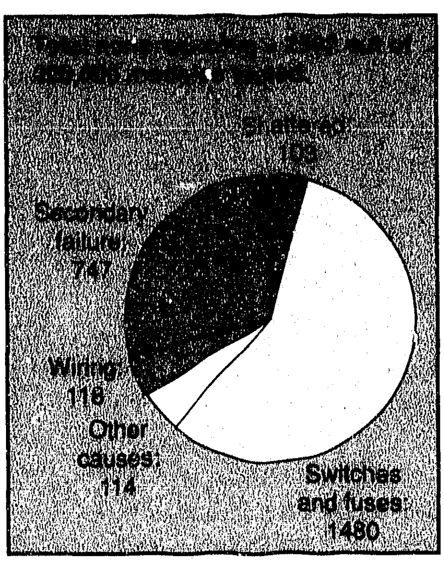
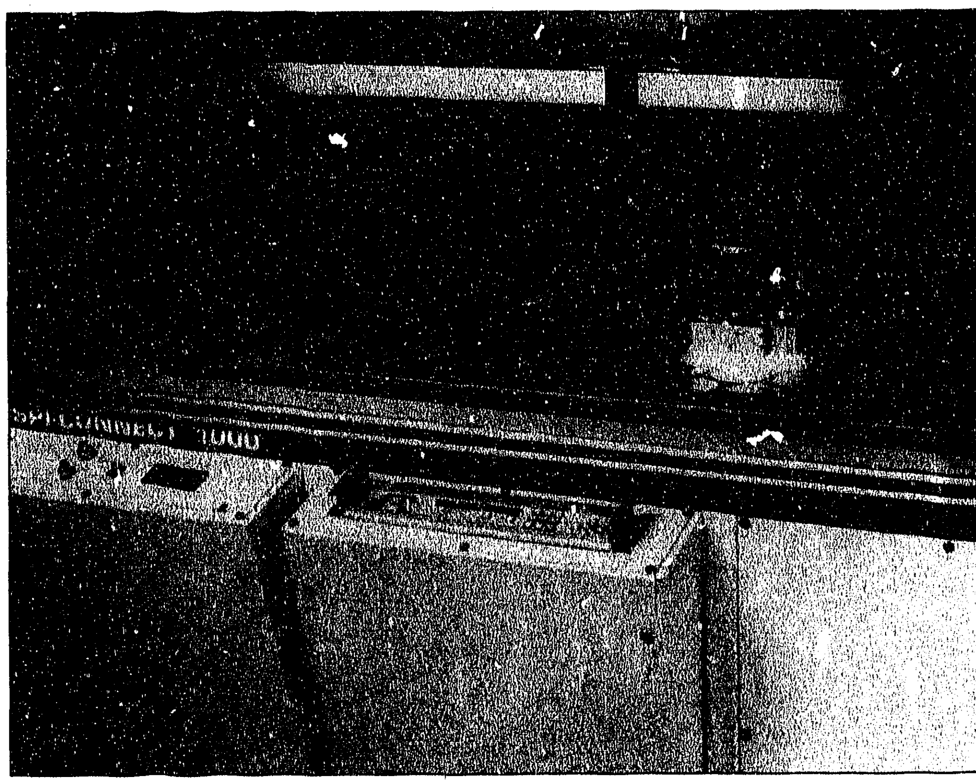


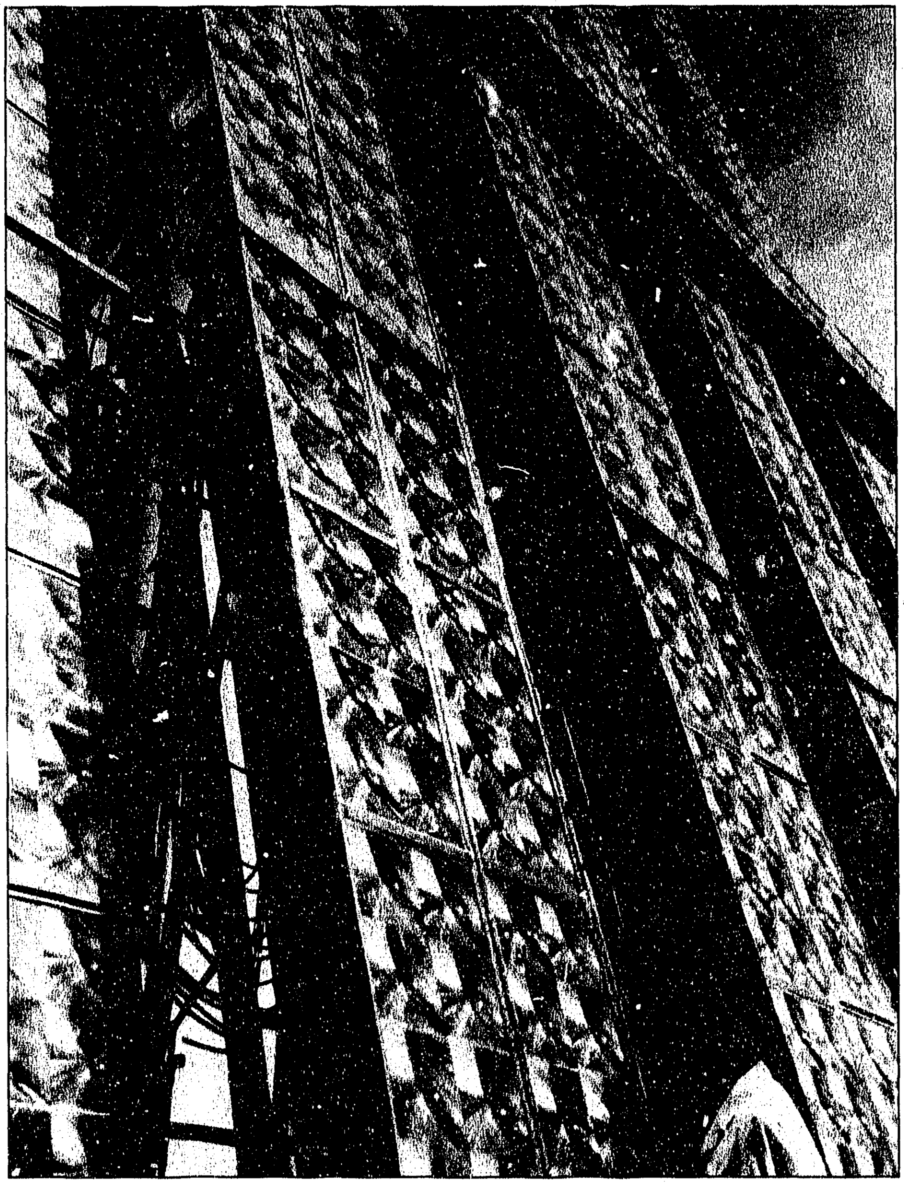

*Figure 11. Only about 1% of in-service modules fielded between 1985 and 1989 were nonproducing. Most of the failures were due to electrical components in the array, not the photovoltaic modules themselves. (Source: Southwest Regional Energy Service)*



*An automated module assembly machine produced by Spire Corporation solders electrical connections between cells.*

## PV Systems and Market Development

The objective of PV Systems and Market Development during the next five years is to create the environment whereby system technology, user acceptance, and the PV industry can accommodate the continued expansion of photovoltaics into larger applications and markets. These are needed to achieve our goal of 1000 MW installed by the year 2000. To achieve this goal, we will focus on four key activities: assessment of the field performance of systems and components; development of the system and balance-of-system technologies needed for cost-effective applications; support of industry in the definition and development of near-term and



*Concentrator modules are usually mounted on a tracking array to follow the motion of the sun.*

long-term markets; and acceleration of the acceptance of PV by disseminating information and transferring technology to industry and potential users. The unprecedented market growth represented by our 2000 goal requires that we pursue these activities for the broadest possible set of potential markets.

*System Field Performance.* Since the late 1970s, we have maintained comprehensive performance information from systems throughout the country. Remotely monitored, on-site instrumentation and periodic system field surveys have provided valuable data on performance, reliability, and operational costs. Evaluations of the performance of systems will continue throughout the country, focusing on new collector, power-processing, and balance-of-system technologies. We will also expand our evaluation activities on stand-alone systems and components.

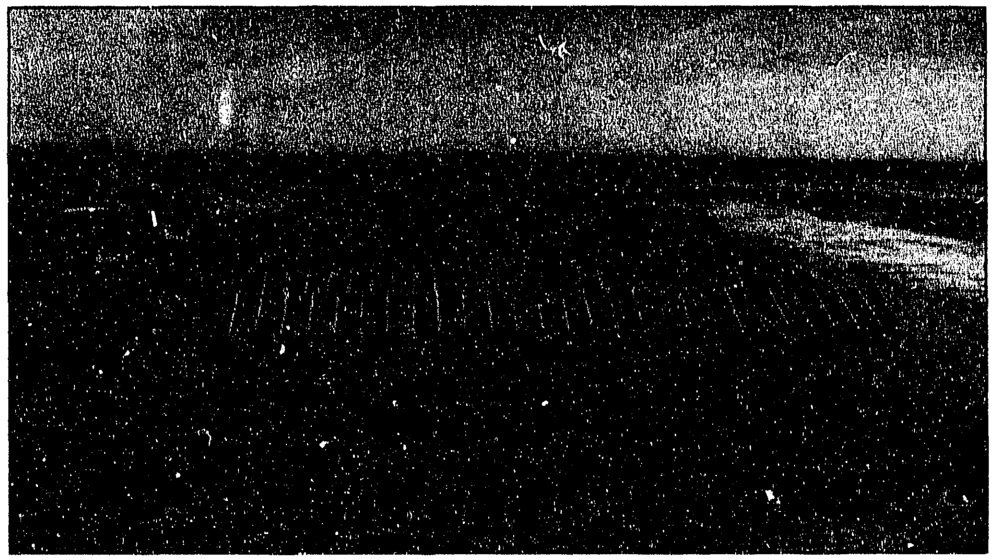
We will continue to be actively involved in the PVUSA project, which has proven to be a very successful test bed for the evaluation of new collector technologies in a utility operating environment. The nearly 1 MW of arrays and systems to be installed at the PVUSA test site at Davis, California, by mid-1991 represents a tremendous program resource for the comparative performance assessment of various technologies.

*Advanced Storage Technologies.* PV devices generate electricity only when light falls on them. While PV output has significant intrinsic value to a utility, energy storage devices are necessary for PV to be useful as an on-demand power generator for utilities. Pumped hydro is one storage technique available to utilities today; batteries, hydrogen, and fuel cells are advanced storage technologies that DOE is studying for the future. PV could also be used to generate hydrogen for use as a utility or transportation fuel.

*Power Processing Hardware.* As the size of grid-connected PV systems extends into the multimegawatt range, larger, more advanced power processing equipment will be required to meet the needs of utilities. We are continuing a cooperative effort with the power-processing industry to expand and improve the usability of existing hardware as well as to investigate new designs. Issues include control circuitry, product quality control, increased efficiency, reduced cost, and development of equipment for remote village power applications.

*Marketing Photovoltaics to the Utility Sector.* While progress toward the greater use of photovoltaics has been steady, primarily in the remote stand-alone market, we realize that utility use is required for photovoltaics to meet its full potential as a significant national energy source. It is not realistic to assume that utilities will begin using photovoltaics the instant the economics reach a particular threshold; rather, this use will follow an evolutionary path that will allow the utility industry to become acquainted with the characteristics and benefits of photovoltaic power generation.

During the next several years, we intend to pursue a strategy oriented toward accelerating the acceptance of photovoltaic technology within the utility industry. This plan, which is closely coordinated with the Electric Power Research Institute, involves a cooperative effort with government, the PV industry, and the utility community. The objective is to establish an educational process that makes utility companies aware that the technology is not simply an energy source to be compared with other competing alternatives, but that photovoltaics has unique characteristics that need to be understood and may enhance its value beyond energy alone in particular applications.



*These arrays in Davis, California, are part of PVUSA, a joint utility/government/industry project undertaken to assess the potential of photovoltaics for large-scale utility applications.*

One aspect of the plan is based on phasing the introduction of the technology into utilities by first emphasizing currently cost-effective systems (Figure 12 on page 26). The experience we have gained from these systems helps build acceptance which, in turn, spurs industry investments and the price reductions needed for the next phase of applications. The process is iterative, eventually extending to multimegawatt applications. The development of high-value photovoltaic opportunities within utilities—applications that can provide significant market support to the U.S. industry during the next decade—coupled with carefully selected demonstration projects aimed at these opportunities should create the healthy utility market necessary to achieve our long-term goals.

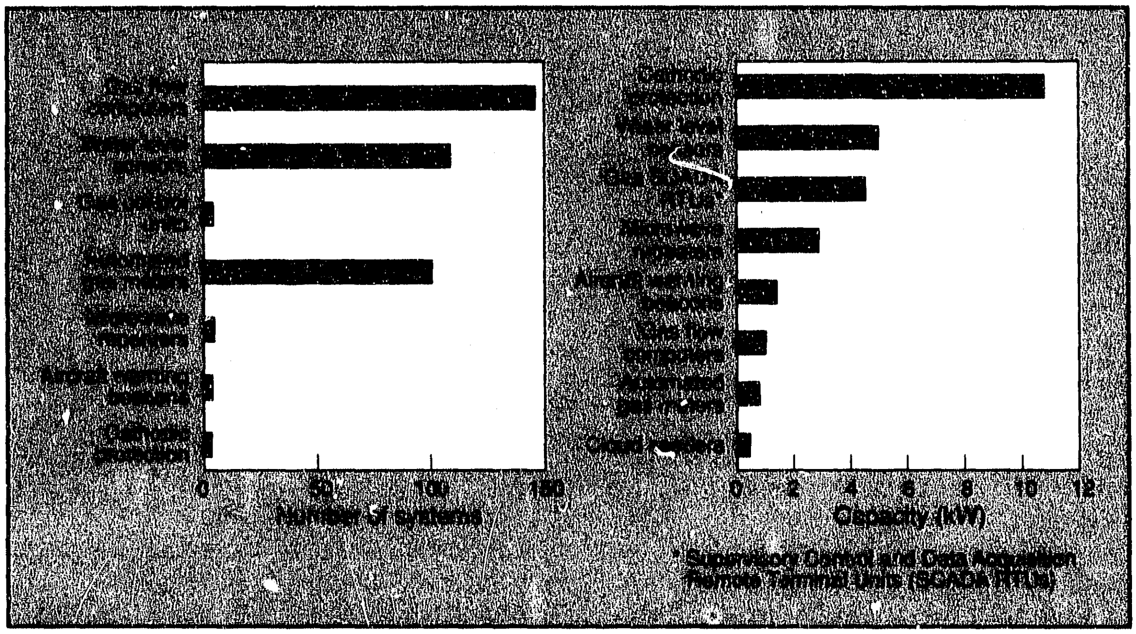



*Figure 12. PG&E had 420 cost-effective PV systems in operation in December 1989. The application with the largest installed capacity at that time was cathodic protection.*

*This PV-diesel hybrid from Integrated Power provides electricity for a telecommunications system in Egypt, one of the largest commercial applications of PV today.*

Another aspect of the plan encourages the near-term application of PV by utilities to systems in the multimegawatt range for voltage support or peaking power. Many niche applications are emerging where these larger systems are economically attractive.

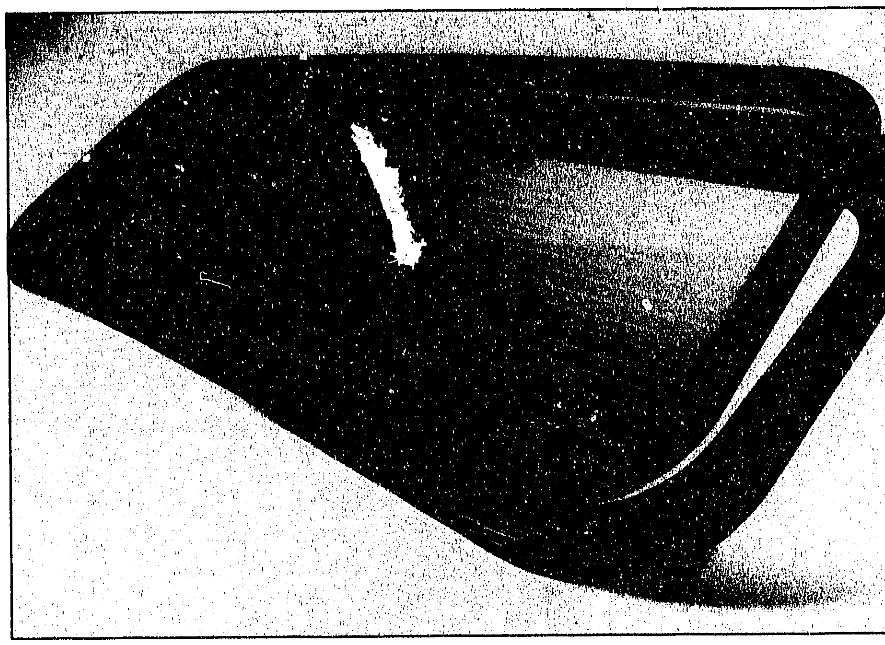
One important demonstration project is PVUSA. Pacific Gas & Electric, the Electric Power Research Institute, the California Energy Commission, and DOE are the founding cosponsors of PVUSA. Some of PVUSA's specific objectives include comparing and evaluating PV systems for performance and reliability, assessing operating and maintenance costs in a utility setting, and documenting the data and lessons learned.

As part of the first phase, the primary PVUSA test site in Davis, California, includes 20-kW, emerging technology arrays from seven different U.S. manufacturers using eight different, relatively untried technologies. Also included are two 200-kW arrays and a 400-kW utility-scalable one from each of three U.S. manufacturers; these arrays are being installed at the test site. By mid-1991 we expect that nearly 1 MW of arrays and systems will be installed at Davis.

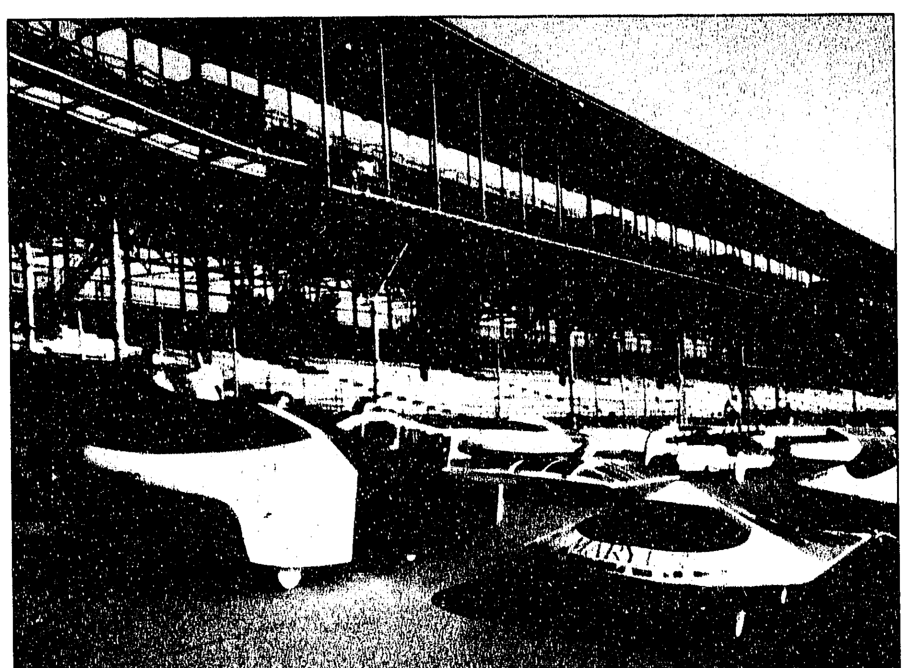
We are also participating in a second phase of PVUSA. Phase II is expected to give priority to the field testing of technologies for a diverse array of utility applications, both multikilowatt and multimegawatt.

We plan to conduct workshops and hands-on training sessions to alert utility engineers to the benefits of photovoltaic systems. And we will work directly with public utility commissions and other regulatory agencies, providing them the technical information needed to include photovoltaics in the integrated resource planning process. This, in turn, will hasten the adoption of policies that will permit photovoltaics to be considered on an equal basis with other options.

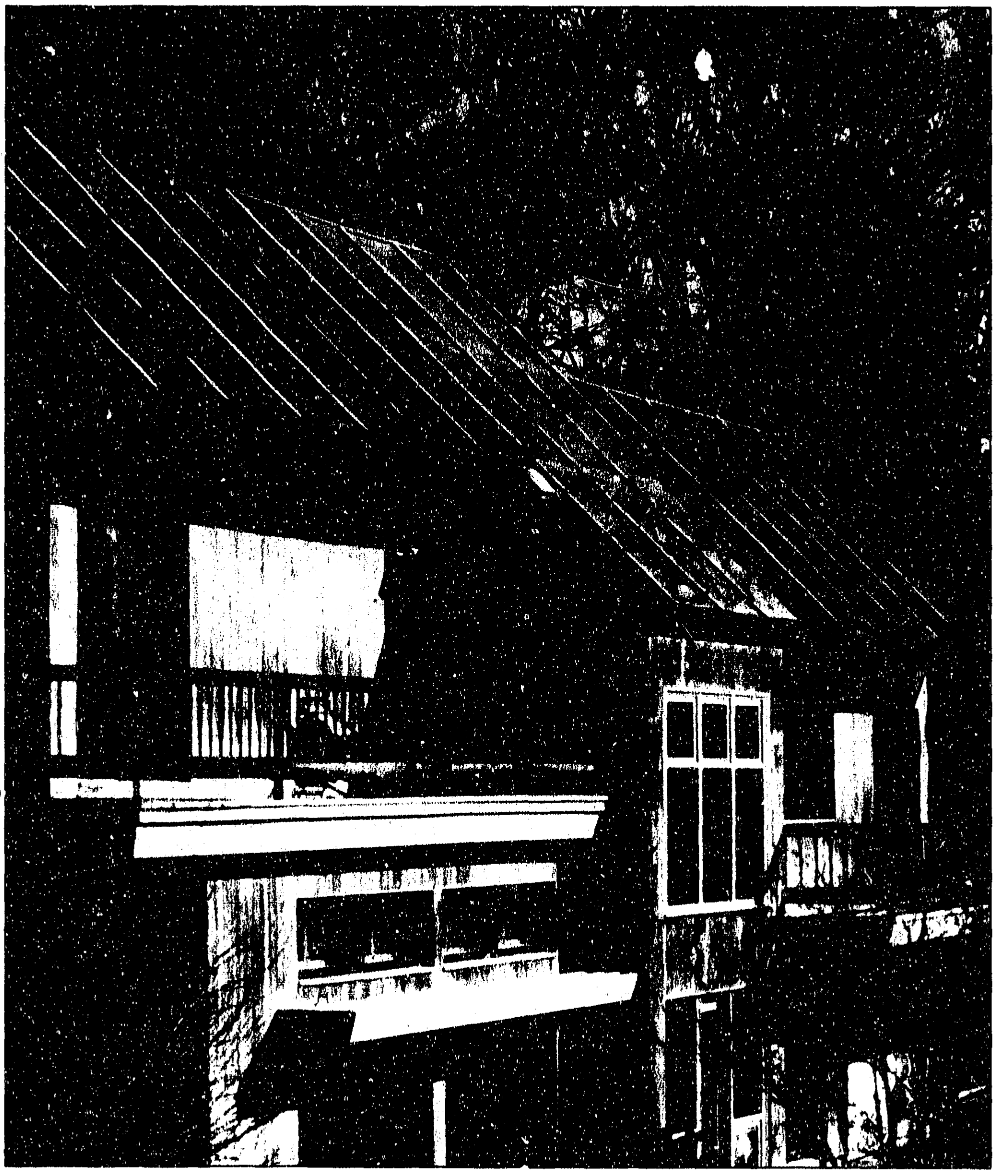
*Marketing Photovoltaics to the Transportation Sector.* Photovoltaic technology can be used in many ways in support of the transportation sector. Cars with sunroofs made of photovoltaic materials are just beginning to enter the marketplace. The photovoltaic sunroofs provide a trickle charge to the battery to offset the drain of ventilation fans and other small loads. Battery chargers that sit on the dashboard are also on the market. PV-powered cars make the headlines today in solar car races around the world. In the future, PV may be the most desirable method to recharge batteries to power electric cars.



*Sunroofs for cars are just one of many PV applications in the transportation sector.*



*PV-powered cars designed by university students line up at the Indianapolis Motor Speedway in GM's Sunrayce USA. Such student competitions help bring new ideas to the forefront and encourage young scientists and engineers to pursue careers in alternative energy.*


The Boston Edison "Impact 2000" home uses a 4-kW photovoltaic system.

Today photovoltaics also supports the transportation industry by providing power for highway lighting, traffic signals, lighted barricades, emergency call boxes, and highway maintenance facilities in remote areas. PV panels currently supply power to railroad signals, runway lighting, aircraft warning lights, range instrumentation, buoys, lighthouses, and supplementary power for recreational vehicles, pleasure boats, and aircraft. As the cost of PV modules decreases, there will be even more applications in which PV can supply power more cheaply than batteries, diesel generators, or utility tie-ins.

*Marketing Photovoltaics to the Buildings Sector.* In areas of the country where air-conditioning is a significant utility load, PV may be a cost-effective way to reduce loads in commercial and residential buildings, especially when used in conjunction with new, high-efficiency, variable-speed heat pumps. PV already powers window-shading devices, and we are investigating the use of PV to power electrochromic windows and other advanced building features. As the cost of PV has dropped, remote buildings (vacation cabins, Forest Service and National Park facilities, etc.) are increasingly powered by PV.

*Marketing Photovoltaics to the Industrial Sector.* PV has two basic uses in the industrial sector—to reduce load in areas where demands are high during daylight hours, and where small amounts of power are needed in remote areas. PV is now a widely accepted power source for telecommunications facilities, for cathodic protection of pipelines and underground storage tanks, for well monitoring, and for remote sensors of many types.

*Marketing Photovoltaics to the International Sector.* The international markets for PV are growing, in particular in developing countries. Over the last ten years, several village electrification projects have been successfully completed using PV. Since as early as the mid-1970s, hundreds of PV-powered water pumps have been installed around the world. Many health clinics now use PV-powered vaccine refrigerators and lighting. We work closely with the multi-agency Committee on Renewable Energy Commerce and Trade (CORECT) to promote the cost-effective use of photovoltaic technology in other countries.

*Design Assistance Center.* The goal of the Design Assistance Center is to accelerate the acceptance of photovoltaics worldwide by helping to educate potential users about the benefits and use of the technology. The Design Assistance Center is actively involved in helping the industry market to many sectors. Nearly 100 different public and private, domestic and international organizations have received substantial assistance during the past three years, and requests for assistance are increasing. We will continue to expand our technology transfer activities by developing new user-oriented publications and by consulting directly on projects for an increasing number of technology users.

*DOE's Design Assistance Center is helping the government of Samoa with a PV-powered translator on the island of Ofu that brings educational television to 2200 people.*

# IV. Meeting the Challenge

*The mission of the National Photovoltaics Program is to develop photovoltaic technology for large-scale generation of economically competitive electric power in the United States.*

The major challenge in fulfilling our program's mission during the next five years will be to assist the photovoltaic industry in laying the foundation for the installation of at least 1000 MW of electrical capacity by the year 2000.

This mission grows out of our enabling legislation. On November 4, 1978, the Solar Photovoltaic Energy Research, Development, and Demonstration Act (Public Law 95-590) declared the policy of the United States: to "establish during the next decade an aggressive research, development, and demonstration program involving solar photovoltaic energy systems and in the long term to have as an objective the production of electricity from photovoltaic systems [that is] cost competitive with utility-generated electricity from conventional sources."

The technical advances and cost reductions we have achieved are noteworthy, but the cost of photovoltaic systems is still not competitive enough for large-scale utility power generation. Opportunities remain for technical improvements that will help to improve conversion efficiencies, lower the cost of modules and systems, and improve system design and integration. These are also challenges we face and must meet to fulfill the program's mission.

Our tools will be continued R&D at NREL, Sandia, and universities in cooperation with industry, education of potential users about PV applications, characterization of industry products, and technology transfer through cost-shared programs.

## Planning for the Future

Table 6 compares the status of PV technology today, the PV industry in the United States, and PV markets with near-term (1995) and long-term (2010-2030) prospects. Several critical research activities are needed to move closer to these future prospects and to achieve our goal of utility cost competitiveness. These activities are broken into three task areas, as described in Section III. Research activities cover the full cycle of photovoltaic technology, from basic scientific understanding, to improved photovoltaic devices, to better manufacturing processes, to advanced system development and commercialization. Environmental and safety issues are included as well.

Recent legislation has encouraged us to more strongly address issues of international development and deployment. On July 18, 1984, the Renewable Energy Industries Development Act was signed into law. Established to enhance the export potential of the U.S. renewable energy industry, it required the formation of a working group (CORECT) of industry representatives and key federal agency officials to explore ways of promoting the industry overseas. The Department of Energy chairs this working group. CORECT has been instrumental in helping the photovoltaic industry to educate potential users and to expand its markets.

## Transferring the Technology

In the 1980s Congress passed legislation that opened new doors for DOE laboratories to license technology and to work cooperatively with

**Table 6.**
**Technology Status and Future Prospects for U.S. Photovoltaics**

| | Today (1991) | Mid-1990s (1995) | Future (2010-2030) |
|---|---|---|---|
| **PV Technology** | | | |
| Flat-Plate Crystalline Silicon | 22-23% laboratory cells<br>11-13% commercial modules | 25% laboratory cells<br>14-15% commercial modules | >26% laboratory cells<br>>18% commercial modules |
| Flat-Plate Thin Films | 12-14% laboratory cells<br>4-6% commercial modules | 15-18% laboratory cells<br>8-10% commercial modules | >20% laboratory cells<br>>15% commercial modules |
| Concentrators | 27-32% laboratory cells<br>14-17% commercial modules | 35% laboratory cells<br>18-20% commercial modules | >40% laboratory cells<br>>25% commercial modules |
| Balance-of-Systems (BOS) Components | In engineering development;<br>$0.40/W power-related costs | Fully engineered:<br>$0.20-0.30/W power-related costs | Large-scale production;<br>~$0.15/W power-related costs |
| Component Reliability | 5-15 years for modules<br>5 years for BOS components | 15-20 years for modules<br>>15 years for BOS components | >30 years |
| **PV Industry** | | | |
| Module Manufacturing Capacity (MW/year) | 15-20 | 50-100 | >1000 |
| Manufacturing Characteristics | 0.5-5 MW lines<br>Batch; labor-intensive | 5-20 MW lines<br>Partly automated | 100-500 MW plants<br>Fully automated |
| **PV Systems and Markets** | | | |
| Utility Power Systems (MW total) | 10-15 | 50-100 | 10,000-50,000 |
| Typical Systems/Electricity Price (¢/kWh, 1990 $) | Consumer; remote, stand-alone<br>25-50 | Distributed; high-value utility applications<br>12-20 | Central utility power<br>5-6 |

the private sector (the Stevenson-Wydler Technology Innovation Act of 1980, the Federal Technology Transfer Act of 1986, and the National Competitiveness Technology Transfer Act of 1989). Technology transfer has always been a cornerstone of the National Photovoltaics Program, but this legislation permits a greater variety of interactions with the private sector with less red tape than ever before.

Attaining our mid- and long-term program goals cannot be achieved solely by our laboratories at NREL and Sandia. Both the U.S. PV industry and the potential users, such as utilities, are vital collaborators. The DOE Photovoltaics Program must continue to complement the programs being pursued in the private sector for maximum effectiveness. The exciting advances in cell technology that are taking place almost daily are useful only if they are effectively incorporated into modules and systems for the benefit of the public.

Our program has pioneered and used many different technology transfer mechanisms. One of the most important mechanisms is competitive, subcontracted research in the form of government/industry partnerships. The industry partner frequently shares the cost of research with DOE.

Government/industry partnerships involving crystalline silicon and amorphous silicon are paying off in continuing advances in technology today. (The Amorphous Silicon Research Program won a technology transfer award from the Federal Laboratory Consortium in 1989.) An expanded government/industry effort in polycrystalline thin films was added in 1990 (Table 7). During the next five years, we also plan expanded government/industry partnerships in concentrator technology and in manufacturing processes for all PV technologies.

We offer five formal program services to the private sector. Through these program services, DOE laboratories work with the private sector on problems as diverse as measuring the solar resource; testing cells, modules, and other hardware; and educating potential users. Many of the laboratory facilities at NREL and Sandia are available for use by the private sector.

Personal involvement is another vital technology transfer mechanism in the program. Scientists and engineers from the private sector can work side by side with DOE researchers at DOE laboratories through site visits, temporary work arrangements, and personnel exchange programs. We sponsor and participate in many photovoltaic conferences, workshops, and project review meetings each year. Our researchers are also heavily involved in various standards-setting organizations.

Technology transfer is also a means to help ensure that a future workforce is available in the photovoltaic community. One of our subcontracted research programs, the University Participation Program, is specifically designed to encourage and train graduate students in photovoltaic technology. Student programs such as DOE's Sunrayce also contribute to this effort.

Publications are another important technology transfer tool. Researchers at DOE laboratories and at DOE subcontractors publish

**Table 7.**
**Major Government/PV Industry Partnerships**

| Project | Years | DOE Funding ($ million) | Industry Funding ($ million) |
|---|---|---|---|
| Flat-plate Solar Array Project | 1978-1986 | 235.0 | N/A |
| Amorphous Silicon Research Project I | 1985-1987 | 13.3 | 5.7 |
| Amorphous Silicon Research Project II | 1988-1990 | 15.6 | 17.0 |
| Amorphous Silicon Research Project III | 1990-1992 | 10 (est.) | 10 (est.) |
| Polycrystalline Thin-Film Initiative | 1990-1992 | 12 (est.) | 5 (est.) |
| Photovoltaic Concentrator Initiative | 1990-1993 | 12 (est.) | 5 (est.) |
| Photovoltaic Manufacturing Initiative | 1990-1995 | 55 (est.) | 55 (est.) |
| Technical Validation | 1986-1995 | 30 (est.) | 30 (est.) |

## Program Services

The National Renewable Energy Laboratory and Sandia National Laboratories have unique facilities and expertise that support the private sector.

*Measurements and Performance.* Both NREL and Sandia perform thousands of state-of-the-art measurements and analyses each year for the photovoltaic community. These include analyzing materials, characterizing devices, evaluating fabrication problems, and computer modeling. Both laboratories often provide semi-official, impartial confirmation of cell performance and calibrations of photovoltaic reference cells.

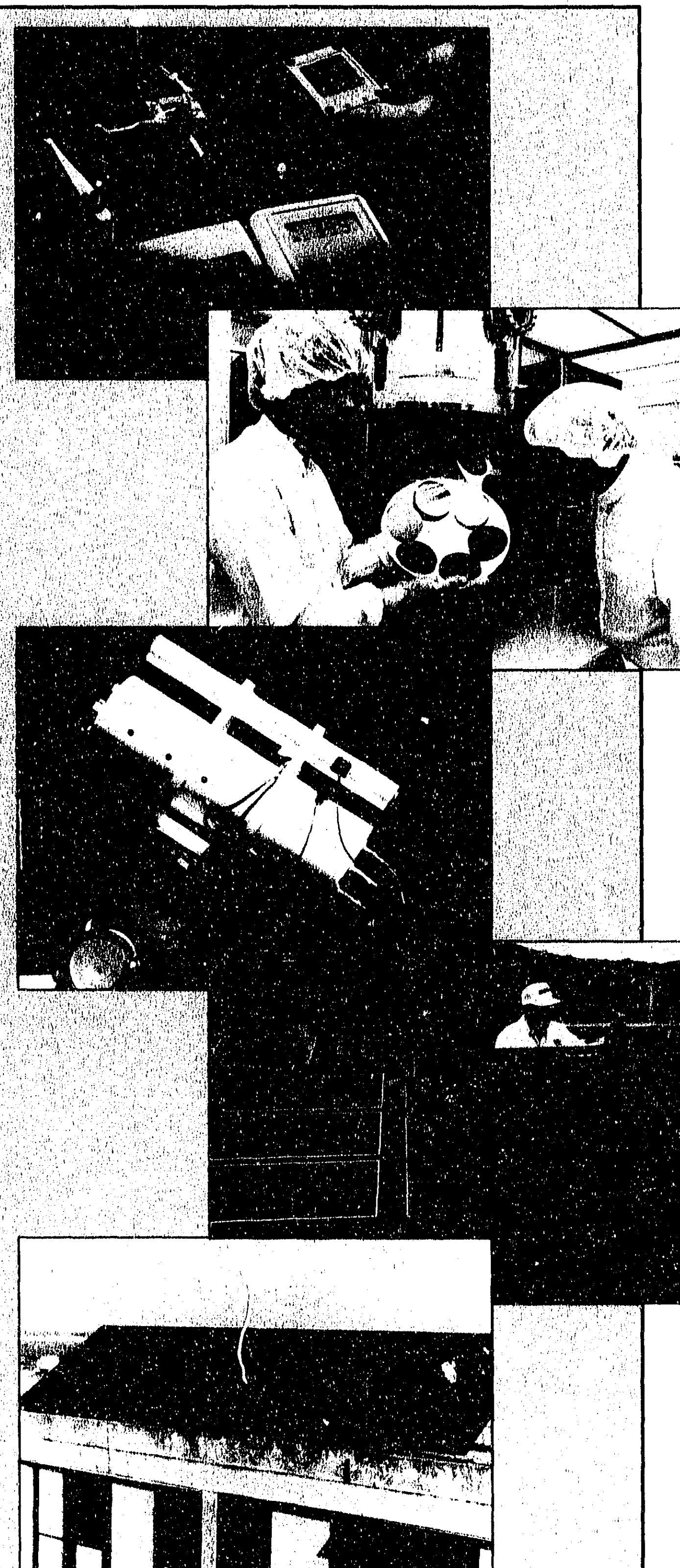
*Photovoltaic Device Fabrication Laboratory.* This laboratory at Sandia is available to assess new solar cell designs and fabrication processes. Small-scale versions of the most commonly employed cell fabrication equipment are available with computer-controlled data collection. Industry can test new ideas without having to shut down production lines or build a new laboratory. Proprietary processes are protected from disclosure.

*Solar Radiation Research.* The response of different types of solar cells depends on the intensity and spectral distribution (color) of sunlight striking them. NREL provides researchers in the photovoltaic community with solar radiation data, models, and algorithms to help predict device performance, optimize designs of devices, and improve instrumentation that measures solar radiation, as well as other services.

*Module Performance Testing.* Both laboratories maintain facilities to test the reliability and performance of modules under simulated and outdoor conditions. Working with the private sector, we maintain a data base to track advances in design and performance, develop evaluation criteria and test methods, and design new test and measurement techniques.

*Photovoltaic Design Assistance Center.* The Design Assistance Center at Sandia is a resource for technical information about photovoltaic systems. The staff helps prepare requests for proposals, reviews system designs, evaluates new and fielded systems, leads workshops and seminars, identifies applications for photovoltaics, and performs feasibility studies. The Center has been involved with most major photovoltaic systems in the United States over the past several years and has participated in several major international projects.

See Appendix A for contacts at both laboratories.



*This balanced plan emphasizes cost reduction and the transfer of technology as well as fundamental research.*

hundreds of technical reports, peer-reviewed journal articles, and conference papers each year. The Technical Information Program produces publications that explain our technology and its advances in terms that the lay person can readily understand. Appendix A contains names and addresses for more information.

## Establishing Policies

In the executive branch of the government, the Secretary of Energy develops the federal energy policy that guides the direction, management, and operation of the National Photovoltaics Program. This energy policy, which incorporates recommendations from the Executive Office and energy advisory boards, provides general directives to ensure that the program reflects national objectives for energy research and development and technology transfer.

Congress also influences the activities and the direction of the program, not only through legislation but also through budget appropriations. Technical review committees, made up of experts from the private sector, also make recommendations to program managers on the scope, objectives, and activities of the program.

The program's managers then develop comprehensive operating plans that respond to the requirements of federal policy, Congress, and the program's constituents. Organization and management mechanisms ensure that the program's direction, components, and budgets reflect the directives of its framers.

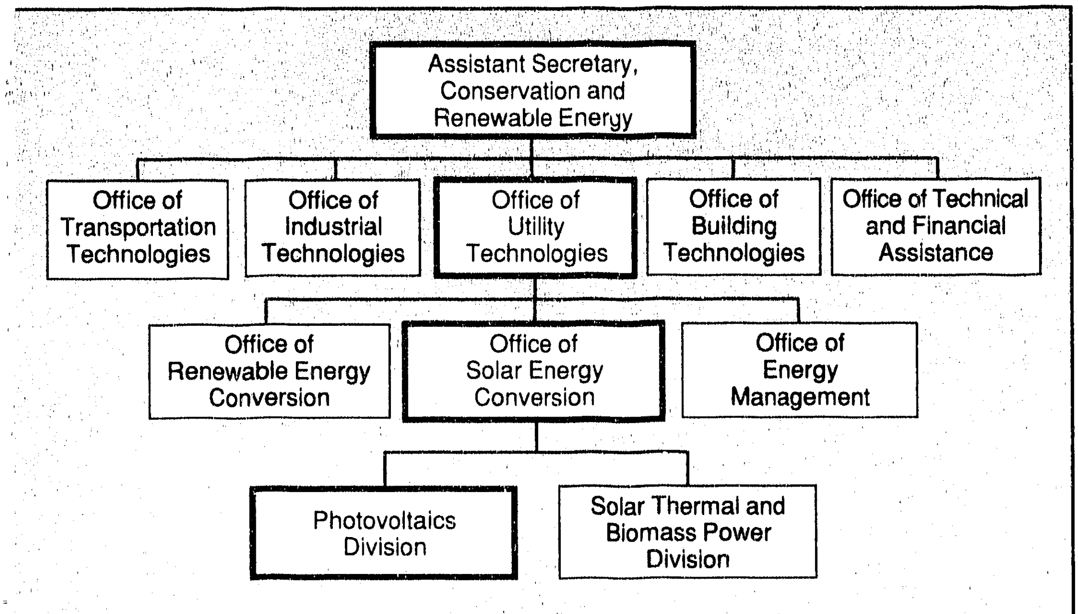



*Figure 13. The Photovoltaics Division is part of the Department of Energy's Office of Conservation and Renewable Energy.*

## Organizing the Program

In 1990, DOE's Assistant Secretary for Conservation and Renewable Energy (CE) established five new offices to implement energy strategies established by the executive branch and Congress in response to the nation's energy needs. The Photovoltaics Division is now under the Office of Solar Energy Conversion, which is part of CE's Office of Utility Technologies (Figure 13).

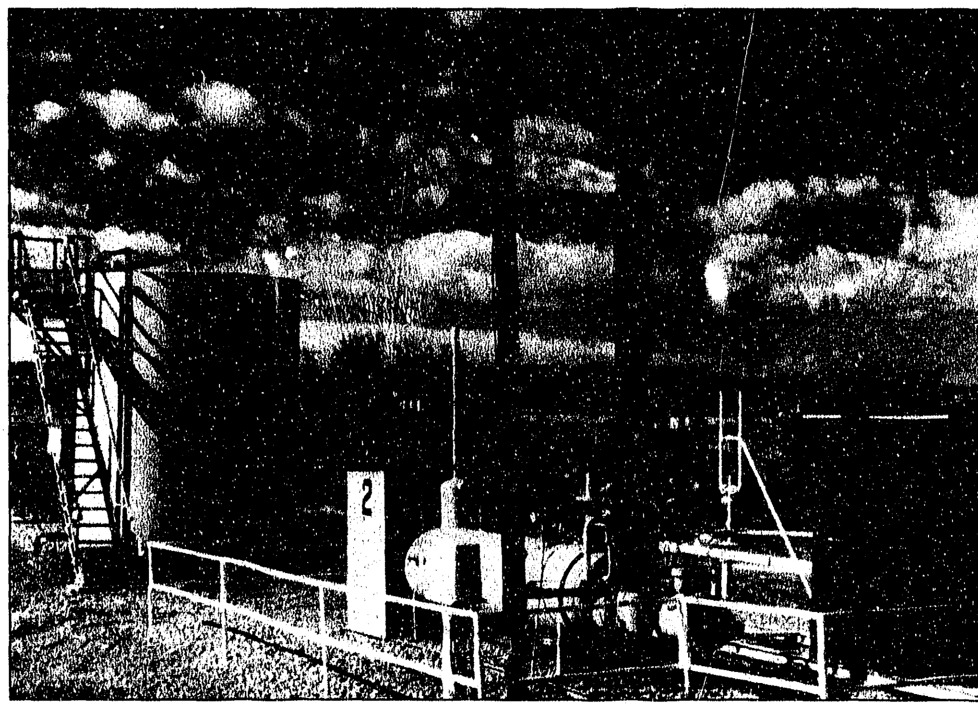
*The Photovoltaics Division.* The director of CE's Photovoltaics Division provides the leadership needed to ensure that the National Photovoltaics Program conforms to national energy policy, priorities, and directives. The director also develops and implements program concepts and plans, provides guidance for priorities, conducts regular program reviews and evaluations, distributes resources, and responds to requests from DOE staff, other federal agencies, and Congress for information about the program and project activities. Division personnel with specific technical expertise manage the program's technical activities.

*The Research Centers.* Two research centers, the National Renewable Energy Laboratory in Golden, Colorado, and Sandia National Laboratories in Albuquerque, New Mexico, provide management and technical support to the national program. These research centers are responsible for the day-to-day management of photovoltaic research and development and for meeting the technical goals of the national program. They manage program activities, in-house research projects, and subcontracted work in areas assigned to them by the director of CE's Photovoltaics Division.

The research centers allocate a significant portion (about one-half) of their resources to projects that are performed by universities, private companies, and other research organizations. The remaining resources are allotted to activities performed at the research centers themselves.

## Managing the Program

The National Photovoltaics Program employs management controls at two levels: at division headquarters and at the research centers. Controls at division headquarters provide mechanisms that ensure adherence to national policy and foster the overall success of the program; controls at the research centers ensure that operations in their assigned areas of responsibility are consistent with division directives and technical goals. Integration is accomplished by means of planning documents, technical progress reports, periodic program reviews, and frequent personal communications.



*Small-scale, high-value applications for photovoltaics include providing power for monitors at natural gas wells.*

The general technical direction of the program is outlined in this program plan. Specific technical emphases and modifications are determined each year, when CE's Photovoltaics Division director approves planned research activities and project milestones based on technical progress and available resources. The research centers regularly provide written reports of progress and activities to division headquarters. Each center submits a quarterly report on resource expenditures, technical activities, and progress in each task area. Brief monthly and weekly highlights supplement the quarterly reports.

## Sandia National Laboratories

Sandia National Laboratories is a multiprogram DOE R&D laboratory with overall responsibility for addressing the technical aspects of national security issues, including energy-supply security and weapons research and engineering. Sandia's energy programs represent the broadest energy R&D activity in the nation; more than 800 researchers work on solar, wind, fossil, geothermal, and nuclear energy technologies.

Within the photovoltaic program, Sandia has principal responsibility for crystalline cell research, concentrating collector development, and systems and balance-of-systems technology development. Although these activities vary greatly in scope, the emphasis in each is to work with industry and users to accelerate the development and acceptance of photovoltaic technology.

Sandia's researchers recently demonstrated a 20%-efficient, prototype concentrator module, and they are defining a new baseline module design concept. The higher conversion efficiencies achievable with concentrator collectors (estimated to be about 30% or more) reduce the amount of collector and land area needed for photovoltaic systems. Advanced, module-ready silicon concentrator cells now have efficiencies greater than 25% at concentrations as high as 500 suns. The practical limit of two-junction concentrator cells is currently estimated to be about 40%.

These efforts and initiatives are designed to help industry more rapidly develop cost-effective commercial products. Cell research activities continue to support promising new concepts and provide valuable services through the Photovoltaic Device Fabrication Laboratory. Indoor and outdoor measurement and evaluation facilities provide support to industry for cell, module, and systems measurement, evaluation, and analysis. Systems-level work concentrates on application engineering, data-base development, and technology transfer to overcome remaining technical and institutional barriers to the acceptance of photovoltaic technology. The Design Assistance Center in Albuquerque, New Mexico, has become a model for a government-sponsored, industry-supportive, technology transfer mechanism.

## National Renewable Energy Laboratory

The National Renewable Energy Laboratory (NREL) was established by Congress as the nation's primary center for renewable energy R&D. More than 400 staff members are engaged in R&D and supporting activities at NREL's facilities in Golden, Colorado. NREL's Materials Science and Engineering Division supports DOE's National Photovoltaics Program and is responsible for most of the fundamental, supporting, and materials research, as well as some of the module and systems development, performed under the program, which includes both in-house and contracted R&D.

Staff members direct and manage contracted research performed at universities, other research centers, small businesses, and large industries. These activities include cost-shared, multiyear, government-industry partnerships and technology initiatives.

Basic research teams investigate a variety of photovoltaic materials. Researchers and technicians study amorphous silicon, polycrystalline thin films, high-efficiency materials and concepts, and high-purity silicon and compound semiconductors. A team also conducts basic research in theoretical solid-state physics.

NREL's scientists recently developed a record-breaking monolithic tandem PV cell. Consisting of layers of InP and InGaAs, this device measured almost 32% efficient in the laboratory. It is being developed for both terrestrial and space applications.

NREL's scientists also support the national photovoltaic program with device measurements, cell modeling and fabrication, performance evaluation, and material and device characterization. Sophisticated measurement equipment and techniques are used to better understand the behavior of photovoltaic materials and devices.

NREL conducts both simulated and actual outdoor tests on cells, modules, and arrays. The test results are used in developing standards and performance criteria for the photovoltaic industry. Data on solar radiation are compiled and evaluated to create computer models that simulate solar radiation under various conditions. NREL staff members also provide instrument calibration support in accordance with national and international standards.

*"The photovoltaics R&D work funded by DOE for over a decade is giving promising preliminary results toward reaching the ambitious goal of generating commercially competitive solar electricity by the mid-1990s."*

**DOE Office of Energy Research, February 1990**

Program reviews are conducted periodically to inform program participants and the public of recent activities and developments. Each year, a major program review is held in which the research centers and other program participants describe their activities. Each research center also conducts annual reviews of specific subprograms to provide technical audiences with detailed information on work in progress.

External reviews of division headquarters activities are also held. A recent example is the assessment of program research projects by DOE's Office of Energy Research in 1989. The findings of that assessment have, in large part, defined the FY 1991-FY 1995 program described in this document.

The federal government plays a leading role in the research and development of photovoltaic materials and devices. The government allocates most of its program budget to fundamental and supporting research, to better understand and improve the materials used in thin-film and high-efficiency cells and prototype modules.

The National Photovoltaics Program awards a significant portion of its annual funds to industry, universities, and other research organizations. These awards are made chiefly through competitive procurements for research and development support.

Technical milestones and program assessment points are established to guide program managers in evaluating the progress and direction of research tasks (Table 8). These milestones represent target dates for technical achievements. The research centers are responsible for achieving these milestones through appropriate planning and allocation of resources. Milestones are evaluated annually to assess progress in research and development and to consider new opportunities.

The efficiency milestones in this program plan are confirmed by measurements at NREL or Sandia. These measurements are made under accepted standard conditions for temperature, illumination, and device-area definition. Historically, researchers in the program have sometimes achieved device efficiencies that have exceeded their planned program milestones. These achievements help program managers evaluate technical successes and provide a credible basis for future emphases in research and development. Through continual feedback, evaluations, and resetting of goals and priorities, the National Photovoltaics Program responds to the nation's challenge to supply clean, abundant, reliable sources of energy.

**Table 8.**
**Photovoltaic Program Plan**

| Task | FY 1991 | FY 1992 | FY 1993 | FY 1994 | FY 1995 |
|---|---|---|---|---|---|
| **Research and Development** | | | | | |
| Advanced Thin Films | Complete awards of cost-shared industry contracts | 10% stable prototype module | 11% stable prototype module<br><br>Status report on deposition methods for thin-film technologies | 12% stable prototype module | 13% stable prototype module |
| Crystalline Silicon | Evaluate interactions of defects, impurities, and passivation | Assess post-growth processes for improved cell performance | Evaluate impacts of PDFL[a]/industry collaborations | 16% prototype polycrystalline module | 20% 100-$cm^2$ commercial cell |
| Concentrators | Evaluate components for prototype modules | Evaluate prototype commercial modules | 35% multijunction laboratory cell | 25% stable prototype module | Evaluate prototype commercial arrays |
| **Manufacturing Technology** | | | | | |
| PV MaT and Module Development | Complete technology-specific problem identification and initiate problem solution contracts | Initiate multiyear contracts for manufacturing R&D | Initiate second group of technology-specific problem solution contracts<br><br>Report results of Concentrator Initiative | Assess impacts of first group of contracts on commercial module development<br><br>Develop comprehensive qualification test for flat-plate modules | Report impacts of 5-year project to improve module manufacturing processes and reduce costs |
| PV Industry | Market two new polycrystalline thin-film modules[b] | Start construction on 2-4 new 10-MW-scale manufacturing plants[b] | Publish ES&H[c] guidelines for 100-MW production (3 options) | 50-MW manufacturing capacity[b] | Commercial modules:[b] 10% thin films; 15% crystalline silicon; 20% concentrators — all @ <10% degradation in 10 years[d] |
| **Systems and Marketing** | | | | | |
| | Define and implement utility strategy<br><br>Begin Phase II, PVUSA | Assess utility market segment potential | Establish power processing hardware capability for diesel replacement and hybrid applications; at least 10 utilities with a total of 10 MW installed capacity[b] | Evaluate performance of strategically sited distributed systems | System cost for 10-MW field: 15-20¢/kWh (National Energy Strategy Goal)[b]; at least 50 MW of installed capacity[b] |

Note: All modules about 4000 $cm^2$; all efficiencies for prototype based on aperture area at stabilized levels before testing for efficiency or outdoor durability; efficiencies for commercial modules based on total area. Since module sizes may vary, we will also accept combinations of size and efficiency that are similar in technical difficulty. Prototype modules will be packaged and designed for less than 10% power loss over 10 years attributable to environmental conditions.

[a] Photovoltaic Device Fabrication Laboratory.
[b] Best-efforts milestone; critically dependent on private-sector investment.
[c] Environment, Safety, and Health.
[d] Based on projections from accelerated and outdoor tests.

# V. Providing for a Healthier Planet

*"The contribution of photovoltaics to [mitigating] global warming and other environmental [problems] is virtually certain. The only question is one of time."*

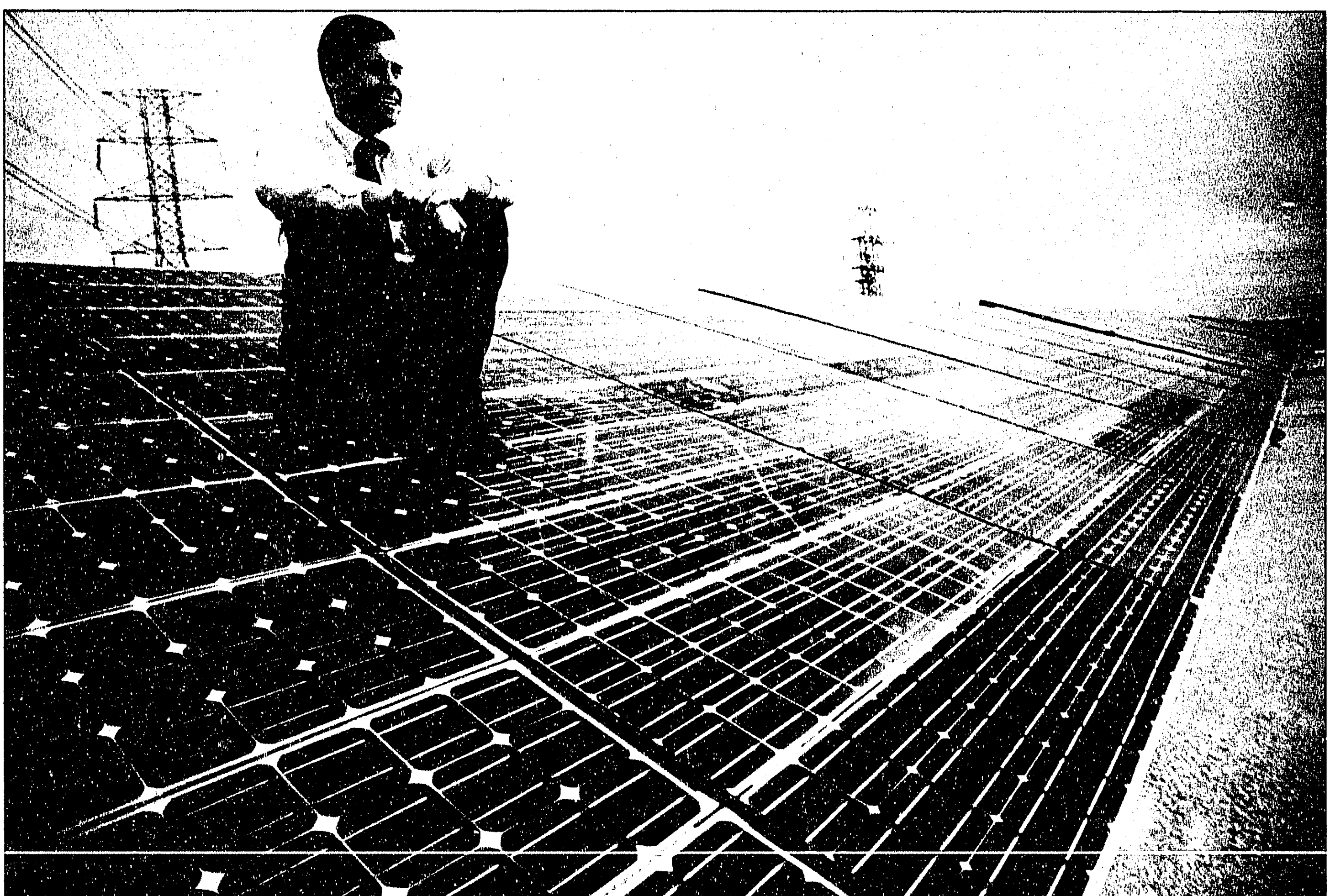
**John Corsi, CEO**
**Solarex Corp.**

We feel confident that this program will "prime the pump" by supporting industry's efforts to develop photovoltaic technology for large-scale generation of economically competitive electric power. It will also fulfill many interim needs in the consumer, industrial, military, and space sectors.

Our program will provide benefits to the private sector in helping them establish a strong PV industry, to the federal government in strengthening national security, and to the public by supplying needed energy while protecting the environment.

Our program is comprehensive, providing a balanced approach to all areas of photovoltaic research and development, from cells to systems. We intend to explore all promising leads, both with proven technologies and with new concepts.

Our program is directed. We are aiming for realistic cost and performance goals, based on historical precedents established in the 1970s



*John Hoffner, City of Austin, Texas, is shown with a 300-kW system, a forerunner of future utility systems.*

and 1980s. As costs drop, PV will be phased into new utility applications, becoming a cost-effective alternative in increasingly larger markets and in larger sizes. This will allow utilities to gain valuable operating experience at minimum risk.

Our program is flexible, allowing changes to be made in research thrusts as more promising concepts emerge and as the needs of industry change. We provide mechanisms for periodic reviews and technology assessments that will drive the program toward the most cost-effective and reliable systems for utilities.

Our program meets the needs of industry. Through innovative initiatives and cost-shared R&D, the lead time between laboratory and manufacturing line will be reduced to the minimum. Aggressive technology transfer activities will ensure that new developments reach the marketplace, where they can be used for the public benefit.

Equally as important, our program could help to meet a significant portion of the nation's energy needs with environmentally benign technologies. We anticipate that within the next five years, economically justified, nonpolluting photovoltaic systems will be fulfilling many utility applications. Later, as we enter the 21st century, we foresee that photovoltaics will attain its full potential by contributing significant amounts of electrical energy to the nation's needs.

The potential for photovoltaic-generated electricity is enormous, with estimates running as high as 100,000 MW of installed capacity by the year 2030. Cumulative sales of photovoltaics by that time may total more than *two hundred billion dollars*, bringing substantial profits to industry and electric power not only to Americans but also to millions of people around the world.

# Appendix A. For More Information

## Program Management

*U.S. Department of Energy*
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Photovoltaics Division — CE-131
Office of Solar Energy Conversion
Office of Utility Technologies
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*National Renewable Energy Laboratory*
Thomas Surek, Program Manager
Materials Science and Engineering Division
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Golden, CO 80401-3393
(303) 231-1371

*Sandia National Laboratories*
Gary Jones, Manager
Photovoltaics Projects
P.O. Box 5800
Albuquerque, NM 87185-5800
(505) 844-2433

## Program Services

Measurements and Performance
Lawrence L. Kazmerski, NREL
(303) 231-1115

Design Assistance Center:
Michael Thomas, Hal Post, Sandia
(505) 844-6111, 844-2154

Module Testing and Reliability:
Richard DeBlasio, NREL
(303) 231-1286

Concentrator Testing and Reliability:
David King, Sandia
(505) 844-8220

Solar Radiation Research and Metrology:
Roland L. Hulstrom, NREL
(303) 231-1220

Photovoltaic Device Fabrication Laboratory:
Paul Basore, Sandia
(505) 846-4516

Photovoltaic Environmental, Health, and Safety Bulletin Board:
P.D. Moskowitz, A. Meinhold,
Brookhaven National Laboratory
(516) 282-2019

PV Codes and Standards:
Douglas Ruby, Sandia
(505) 844-0317
Richard DeBlasio, NREL
(303) 231-1286

## Major Industry Initiatives

Photovoltaic Manufacturin
Technology Project:
Ed Witt, NREL
(303) 231-1402

Photovoltaic Concentrator Initiative:
David Hasti, Sandia
(505) 844-8161

Other industry initiatives:
Contact program management at DOE, NREL, or Sandia

## Technical Reports and Information

On-line data base of technical reports:
Office of Scientific and Technical Information (OSTI)
U.S. Department of Energy
P.O. Box 62
Oak Ridge, TN 37831
(615) 576-1303

Paper or microfiche copies of technical reports:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4929

Information assistance to
sionals:
l Inquiry Service (TIS), NREL
( 303

# Appendix B. Key Publications

*Five Year Research Plan 1987-1991*
*National Photovoltaic Program*
DOE/CH10093-7
U.S. Department of Energy
May 1987
Available from NTIS

*Photovoltaic Energy Program Summary*
*Volume I: Overview*
*Fiscal Year 1989*
DOE/CH10093-58
U.S. Department of Energy
January 1990
Available from NTIS:
Order No. DE89009473

*Photovoltaic Energy Program Summary*
*Volume II: Research Summaries*
*Fiscal Year 1989*
DOE/CH10093-59
U.S. Department of Energy
January 1990
Available from NTIS:
Order No. DE89009474

*Programs in Renewable Energy*
*Fiscal Year 1990*
DOE/CH10093-74
U.S. Department of Energy
January 1990
Available from NTIS:
Order No. DE89009489

*The Potential of Renewable Energy*
*An Interlaboratory White Paper*
U.S. Department of Energy
March 1990
Available from NTIS:
Order No. DE90000322

*Photovoltaic Energy: Electricity from Sunlight (PHV)* -2 (current abstracts of technical reports, available bimonthly)
DOE/PHV-88/6 (PB88-933006)
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4929

*Photo credits:* P. 2: Siemens Solar Industries; p. 3: Mobil Solar Energy Corporation; pp. 10, 12, & 14: Warren Gretz, NREL; p. 15: Advanced Photovoltaic Systems; p. 17, top: Warren Gretz, NREL; bottom: 3M Company and Entech; pp. 19 & 20: Warren Gretz, NREL; p. 21: Utility Power Group; p. 23: Spire Corporation; p. 24: Alpha Solarco; p. 25: PG&E; p. 26: Integrated Power Corp.; p. 27, top: Siemens Solar Industries; bottom: Richard J. King, DOE; p. 28: Mobil Solar Energy Corporation; pp. 29 & 33: NREL and Sandia files; pp. 35 & 36: Sandia; p. 37: Warren Gretz, NREL; p. 40: *Austin American Statesman.*

Front cover, top to bottom: Siemens Solar Industries, ECD, Solarex, 3M; back cover, top to bottom: NREL, PG&E, Mobil Solar Energy Corporation, DOE.



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# DATE FILMED

12 / 26 / 91