The DOE Photovoltaics Program*

Robert R. Ferber
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Solar cells convert sunlight to electricity directly. Such photovoltaic units have no moving parts and are quiet, nonpolluting, extremely reliable, and easy to operate. Although they are still expensive, they offer a promising way to use the Sun's inexhaustible energy here on Earth.

During the past 6 years the U.S. National Solar Energy program has grown from small, experimental, research-applications efforts at the National Science Foundation and at NASA in space applications, through a technology development and applications program under the Energy Research and Development Administration (ERDA), into a large technology, applications, and industry-oriented program managed by the Department of Energy (DOE).

The early application of photovoltaic systems was in aerospace (satellite) programs, and thus the technology was developed to be responsive to the demands of the aerospace industry. The major concerns were weight reduction, radiation tolerance, conversion efficiency, and very high levels of reliability. Customized requirements for each mission allowed little standardization and forestalled any serious attempts at cost reduction.

The U.S. Department of Energy, as part of the National Solar Energy program, is now engaged in the development of technically feasible, low-cost candidate component and system technologies to the point where technical readiness can be demonsrated by 1982. The overall strategy is to pursue parallel options that continue to show promise of meeting the program goals, thus increasing the probability that at least one technology will be successful. Included in technology development are both flat-plate solar collectors and concentrator solar collectors, as well as the balance-of-system components, such as structures, power conditioning, power controls, protection, and storage. Generally, these last items are common to both flat-plate and concentrator systems, but otherwise there is considerable disparity in design philosophy, photovoltaic cell requirements, and possible applications between the two systems.

Since 1973, when the Arab oil embargo initially underscored the world's dependence on petroleum, researchers have continued their efforts to build photovoltaic devices that can extract electricity from sunlight more cheaply than conventional generators produce it from fossil fuels. That goal has not been achieved yet, but today's photovoltaic technology development shows significant progress. Cells are more efficient and less expensive than ever and promise to become more so in the future.

To summarize the progress during the past several years

(1) The price of a typical commercial solar cell array has been reduced by a factor of 3 or more. In 1975 module prices ranged from $25 to $90 per watt. Today, a module with similar performance and far better reliability sells for about $5 to $15 per peak watt ($W_p$).

(2) Relatively large installations are beginning to be built for both flat-plate and concentrator technologies. These will produce major new operating system experience. The Mt. Laguna Air Force Station installation, which was dedicated in July 1979, has been for the past year the largest flat-plate

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installation, rated at 60 kilowatts. The Natural Bridges National Monument installation (100 kW, flat plate) was dedicated June 7, 1980. Similarly, large concentrator technology experimental systems are now being installed. The largest in the United States is at the Mississippi County Community College in Blytheville, Arkansas, with a rating of 240 kilowatts achieved by using 40X concentrating parabolic trough collectors.

(3) Conversion efficiencies of cells based on "mature" technologies (single-crystal and polycrystalline silicon) have risen dramatically, and several are now approaching their economic optimum.

(4) The U.S. Government, and other governments around the world, have recently increased funding for research and development programs aimed at identifying new technologies and reducing cell production costs.

Because array costs are dropping, the world-wide market for photovoltaics is beginning to expand. It is envisioned that annual installed capacity will rise from last year's level of about 1 megawatt to at least 50 000 megawatts by the year 2000. By 1982 it is anticipated the market will become large enough to justify significant automated mass production of photovoltaic systems; costs will continue to decrease, but at a much faster rate. That, in turn, will open up new markets and accelerate sales. With experience and production scaleup, price goals will finally be reached, and large-scale commercial deployment of systems can begin.

This essentially describes the main thrust and objectives of the U.S. Department of Energy Photovoltaics program. This paper reports the work being done today in the United States. The efforts are diverse, as are the estimates given for the potential viability of photovoltaics as an alternative energy source, but they do have several common denominators—a worldwide need for such an alternative, strong technology development programs, and great promise.

Photovoltaic System Price Goals

The U.S. Department of Energy has developed long-range goals to ensure that photovoltaics will supply a significant amount of electrical energy to the Nation by the year 2000, at which time the President has established a National goal of 20 percent solar electric energy production capability. Formal price goals have been established by DOE for the photovoltaics program. These goals have been chosen such that, if they are achieved, it is expected that photovoltaics will make significant penetrations into the small and remote (stand alone), utility-connected residential, intermediate-load, and central-station markets.

Figure 1 shows the DOE price targets for photovoltaic collectors and systems (in 1980 constant dollars), as well as the flat-plate-collector purchase price history. Because these goals apply to both flat-plate and concentrator technologies, direct comparisons require some normalization: Flat-plate collector price goals do not include supporting structures, but such structures are an integral part of concentrator collectors. The DOE commercial readiness price goals for complete systems (in 1980 dollars per peak watt of system output) are

(1) \$1.60 to \$2.20 per W_p for residential applications by 1986
(2) \$1.60 to \$2.60 per W_p for intermediate-load centers by 1986
(3) \$1.10 to \$1.80 per W_p for central stations by 1990

Photovoltaics Program Legislation

Photovoltaics RD&D Act

The National Photovoltaics RD&D Act, passed last year by the U.S. Congress, authorized the expenditure of \$1.5 billion over the next 10 years for photovoltaics research, development, and

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PHOTOVOLTAICS MODULE AND SYSTEM PROGRAM GOALS

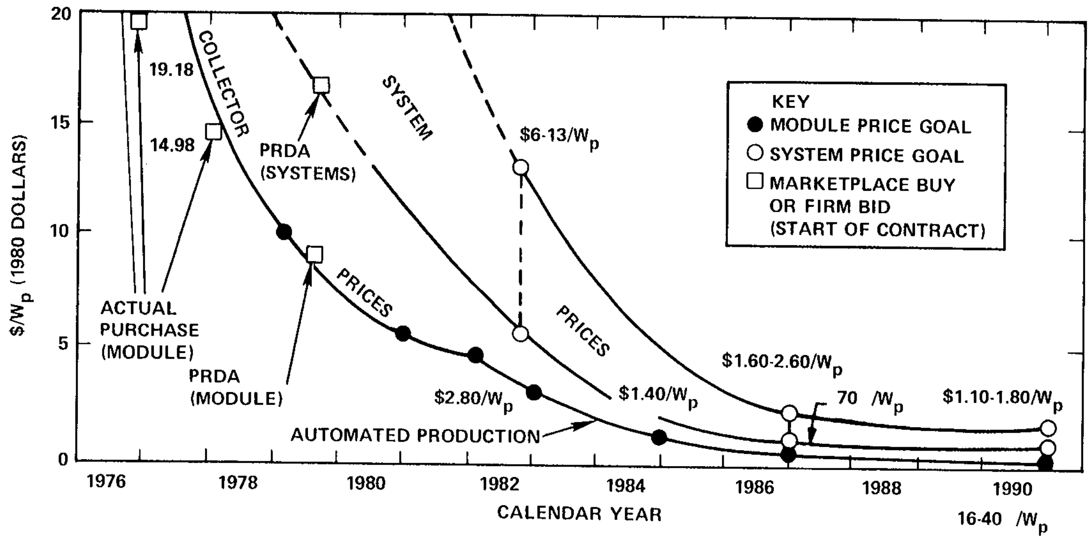

Figure 1

commercialization. This was an invitation to companies to make a market commitment to photovoltaics by investing in much-needed mass-production capacity. Funding through this legislation heavily favors research and technology development with supporting experiments for the next several years and will then gradually shift to emphasize larger, commercial demonstration projects in the field.

The Federal Photovoltaics Utilization Program

Recently, Federal legislation has been enacted to assure that photovoltaic systems are applied to various Government application sectors as they become cost effective. The Federal Government has initially authorized $98 million over a 3-year period for the Federal Photovoltaics Utilization program (FPUP) for purchases of photovoltaic energy systems. FPUP has two immediate goals: (1) to develop the Federal market by encouraging Government agencies to incorporate photovoltaic systems; and (2) to provide marketing support to commercial solar cell and system manufacturers, whose growth is crucial to the ultimate success of the photovoltaics program. The program will initially provide for procurement of the smaller remote systems and will be broadened to include residential and intermediate-load systems.

Advanced Research and Development

The Advanced Research and Development program in photovoltaics is the responsibility of the Solar Energy Research Institute, which is operated by the Midwest Research Institute for the Department of Energy. The main thrust of this effort is to achieve technical feasibility for a variety of advanced material technologies. These technologies are intended to have the potential for achieving 10 percent conversion efficiency with a cost potential of $0.15 to $0.40 per W_p (in 1980 dollars) leading to systems costs of $1.30 per W_p or less. Much of this AR&D effort is directed toward the investigation of concepts, materials, and structures leading to very low-cost solar cells with thin-film structures. Thin-film cells in particular offer high material conservation, simplified fabrication techniques that can be readily automated, and the possible use of inexpensive substrates. Higher conversion efficiencies are also being sought through advanced cells for use with concentrated sunlight.

The AR&D programs in photovoltaics encompass three major areas: advanced materials and cell research, high-risk research, and research support and fundamental studies. The advanced materials and cell research effort carries the development of selected solar cell technologies through the exploratory development phase to a point where technical feasibility is achieved. The high-risk research programs are directed toward those materials and concepts that are not well developed and that are perceived to carry high risk in terms of established R&D goals. The research support and fundamental studies effort is intended to enlarge the materials and technology base and to provide the research tools needed to improve general state-of-the-art cell development.

Thin-film cell technologies being studied in the advanced materials and cell research effort include polycrystalline silicon, cadmium-sulfide-based materials and structures, amorphous silicon, and gallium arsenide. The polycrystalline silicon task is already entering the exploratory development phase. The goals of the cadmium sulfide thin-film effort are to achieve an efficiency of at least 10 percent in fiscal year 1980 and to demonstrate suitable cell stability for large-area encapsulated cells and an 8-percent conversion efficiency for small-scale arrays by the end of fiscal year 1982. Amorphous silicon is being studied to obtain an understanding of the fundamentals of the defect-state passification process, with square-centimeter cells having 5.5 percent efficiency already being made and prospects of 10-percent-efficiency cells or better in the future. Gallium arsenide research is directed toward the deposition of films with large grain sizes, understanding the effects of grain boundaries on cell performance, and investigating different junction formation techniques. The objective of this effort is to achieve a thin-film cell conversion efficiency of 12 percent by fiscal year 1983.

High-risk research covers emerging materials, amorphous materials other than silicon, advanced concentrator concepts, electrochemical photovoltaic cells, and innovative concepts. A variety of emerging materials and device concepts are being studied that have potential in the long-range future. Low-cost technologies such as spray and screen-printing techniques using CdS/CdTe, CdS/Cu_2S, and CdS/Cu ternaries are being investigated. The photovoltaic properties of amorphous GaAs, boron, II–IV–VI compounds, and chalcogenide semiconductor glasses are being studied. Research on advanced concentrator concepts is being conducted, including the possibility of luminescent conversion and multijunction concentrator cells with potential efficiencies greater than 30 percent. The electrochemical photovoltaic cell work centers on fundamental studies of the semiconductor-electrolyte interface and semiconductor-electrolyte combination for high conversion efficiency and stability at low cost.

Activities in research support and fundamental studies include basic mechanism studies, test and measurements, technical issues, and development initiatives. Studies of basic mechanisms are intended to identify those mechanisms that limit the conversion efficiency of new-technology solar cells, along with the procedures needed to eliminate or passivate these mechanisms. The development of sophisticated material and cell evaluation techniques in the tests and measurements activity is aimed at establishing and measuring critical material and cell parameters that can influence cell performance. The technical issues area addresses topics such as environment, health and safety effects, materials availability, economic analysis, and the definition of systems requirements for advanced photovoltaic technologies.

Technology Development

Technology development objectives are to develop technically feasible, low-cost candidate photovoltaic component and subsystem technologies to the point where technology readiness can be demonstrated. The strategy is to pursue technology options that continue to show promise of meeting the program goals, thereby increasing the probability that at least one technology will be successful.

A subprogram includes the technology development of photovoltaic array components and modules for flat-plate and concentrator designs and the technology development of balance-of-system (BOS) components based on the requirements established by the system engineering group. The latter includes array structures, power conditioning, power controls, protection, and storage.

Flat-Plate Solar Arrays

Obstacles to the large-scale manufacture of solar cells and modules are being attacked on every level. The photovoltaic materials, processes, methods of production, and transparent encapsulants and the final module, complete with cells and electrical contacts, are all undergoing intense development. In the United States the current focus is on conventional crystalline silicon. Concurrently silicon ribbon and a variety of thin film materials—such as CdS, amorphous silicon, and other compound semiconductors—are also being investigated in research and development laboratories.

The Jet Propulsion Laboratory is managing the Department of Energy's Low-Cost Solar Array (LSA) project. This project is developing a variety of solar cell types made from both silicon single crystals and silicon ribbon to meet the 1982 and 1986 collector cost targets. The operating premise is that the well-understood and advanced silicon technology has the best probability of becoming cost effective in the short term (by 1986). Research and development continues in other areas, such as thin-film photovoltaics. Five tasks have been identified in the LSA project, with each task aimed at reducing one segment of the overall cost of photovoltaic conversion. These tasks include the production of polysilicon raw materials, the formation of flat solar cell blanks (sliced ingot wafers, grown ribbons, or silicon sheets), cell encapsulation and module fabrication, cell fabrication and automated manufacturing, and large-scale production. Figure 2 displays the LSA project master plan for accomplishing program objectives.

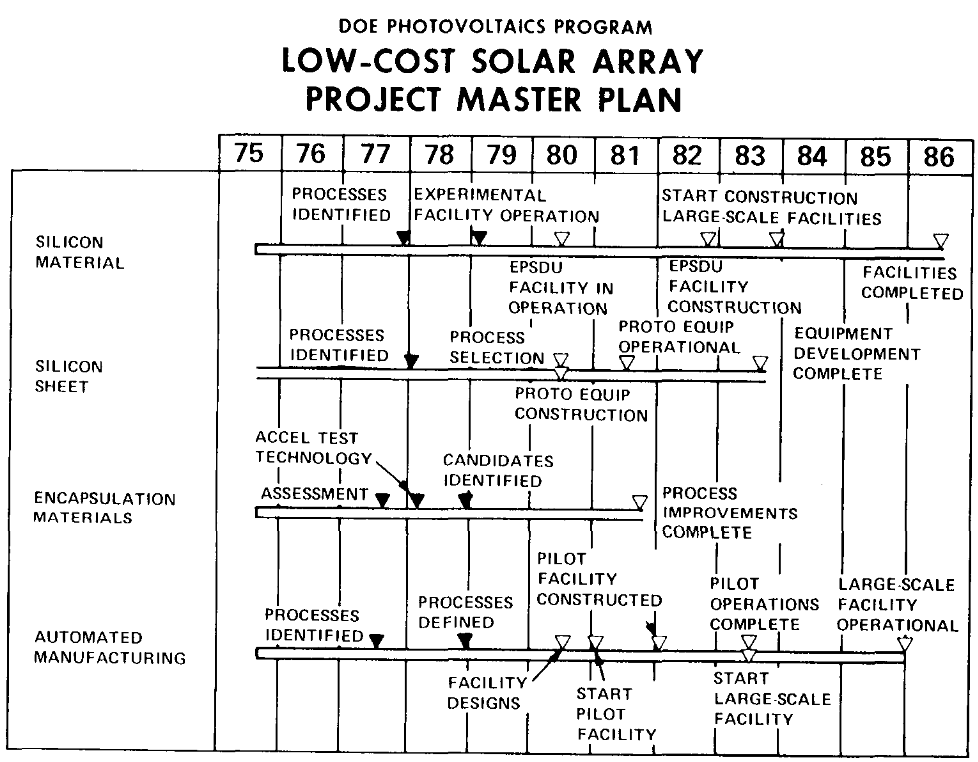

Figure 2

Reducing the cost of polysilicon is considered a crucial link in the production chain. Semiconductor grade (99.99999 percent pure) polysilicon, the feedstock for today's solar cells, now sells for $60 to $100 per kilogram. DOE hopes to cut that cost to $14 per kilogram (in 1980 dollars) by 1986 and, possibly at the same time, determine if less pure solar-grade polysilicon could be used to make cheaper cells with acceptable performance. With these prices and availability in mind, funding has been provided for four low-cost-polysilicon production processes being developed by U.S. companies. To develop a better understanding of the feasibility of using solar-grade polysilicon for cells, contractors are investigating the trade-offs between purity and cell performance.

The project is also working to reduce the cost of transforming purified polysilicon into large sheets of single-crystal material suitable for cell fabrication. This step has great potential for cost reduction—from about $5.80 per W_p in 1976 to $0.21 per W_p by 1986. Several different processes are also being funded that yield single-crystal silicon in one of three forms: ingots, shaped ribbons, or sheets.

Unlike solar cells used on spacecraft, terrestrial photovoltaics must survive sunlight, moisture, salt spray, animals, vandals, ice, and snow. The objective of the third task is to develop a low-cost module encapsulation system that can be expected to last for at least 20 years. Nine contractors are now working on encapsulants.

The final step in producing a solar cell is its conversion from wafer, ribbon, or film into a finished multicell module that is ready for installation. This process represents about 65 percent of the cost of a finished module. In 1976 this was about $15.40 per W_p. Based on studies of mass production techniques, we believe that finished modules can be reduced to less than $0.70 per W_p by 1986, if plants are built that produce at least 25 megawatts of cells annually. The project therefore aims to identify, develop, and demonstrate the feasibility of those processes that can be automated and incorporated into a mass-production sequence.

Concentrator Collector Technology Development Objectives

Because the primary limitation to photovoltaic conversion is currently the high cost, another approach is the use of concentrator optical systems that focus sunlight onto solar cells. Here, since the area of the cell is only a small portion of the collector area, the cell cost contribution is significantly smaller. The cost of the array then depends on the concentrator cost, the cost of the support structure, and the tracking mechanisms.

The development of a low-cost, concentrator collector is the responsibility of Sandia Laboratories, Albuquerque, New Mexico. The Concentrator Technology Development project objectives include the development and evaluation of solar concentrator system components, materials, and manufacturing processes leading to low-cost solar concentrator collectors for photovoltaic conversion. Stimulation of commercial availability is inherently part of the objectives. The project has three major tasks: solar concentrators, concentrator-enhanced subsystems, and concentrator cell technology. Figure 3 displays the Concentrator Technology Development master plan for accomplishing the objectives.

The concentrator-enhanced array subsystems task includes designing, optimizing, fabricating, testing, and evaluating full-sized arrays based on designs developed in the preceding task. The objectives of this task are to expose and solve problems associated with fabricating, testing, and operating full-sized, multikilowatt concentrating arrays. Procurement of these arrays will facilitate future array procurements by test and applications programs. Another important feature of this task is array testing and evaluation. Testing includes optical testing, accelerated lifetime testing, severe environment testing for array components and materials, and real-time continuous operation array testing to obtain performance data for the complete array subsystem over long periods of time.

The concentrator cell technology task is concerned with the development of silicon cells and advanced cells and conversion devices for use in concentrated sunlight. The objectives of this task are to investigate the performance potential of single-crystal silicon solar cells and compound semiconductor solar cells, such as single-crystal gallium-arsenide cells, under high illumination and at

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CONCENTRATOR TECHNOLOGY DEVELOPMENT PROJECT

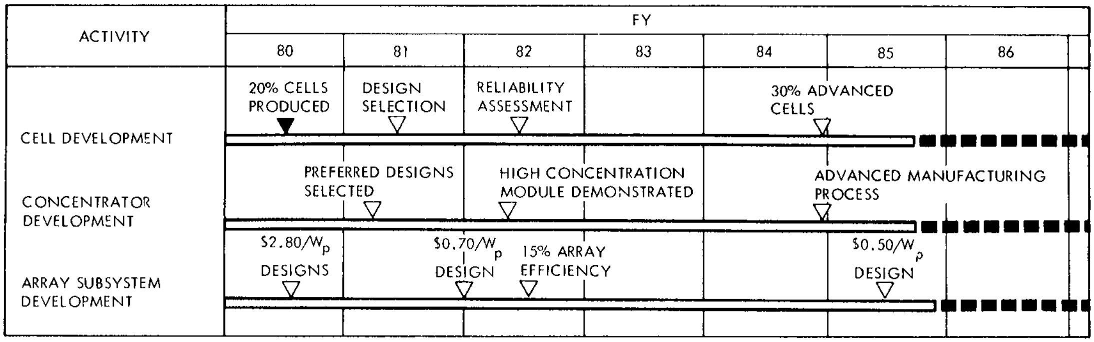

Figure 3

high temperatures, to define cell structures and designs that optimize cell performance for various intensity and temperature conditions; to develop viable cell production methods; to establish commercial sources of reliable cells; and to develop new, high-performance conversion concepts.

System Performance Requirements

The major components of a photovoltaic system are shown in figure 4 and include

(1) Collectors, including the solar photovoltaic conversion devices and their interconnections

(2) Power conditioning equipment to convert direct current to alternating current and to provide regulated outputs of voltage and current

(3) A processor-controller that automatically manages the operation of the total system

(4) A storage system (if used) that stores excess energy during periods of high collector output for use during periods of low (or zero) output

The power conditioning, processor-controller, and storage subsystems, along with their interconnections, are lumped under the term "balance of system" and may be very similar, or even identical, for both flat-plate and concentrator collectors. Not mentioned were the support structures,

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BALANCE OF SYSTEM COMPONENTS

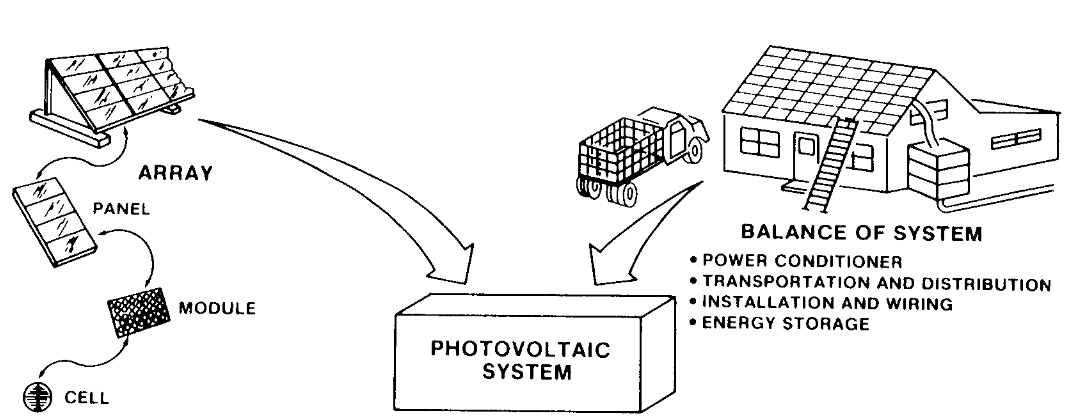

Figure 4

which are considered separately for flat-plate collectors but are usually an integral part of a concentrator collector. Because of the geometric optics involved, concentrator collectors are nearly always designed to provide tracking to maintain a high output throughout much of the solar day. Flat-plate collectors are usually mounted on fixed supports and have an output that varies approximately sinusoidally about solar noon.

The modularity of photovoltaic collectors permits a wide range of applications for these systems. As mentioned earlier the four types of applications presently considered viable are (1) stand-alone systems, primarily small power systems for remote applications; (2) residential systems; (3) intermediate-load centers; and (4) central stations. The last three systems are normally expected to be utility connected.

The performance requirements for a photovoltaic system are very similar to those for other electric power systems. They include low maintenance, high reliability, fail-safe capability, safety, and continual automatic operation that is responsive to the demands of the user, ensuring optimum use of the available energy.

Photovoltaic systems must maintain satisfactory output regardless of atmospheric environment, buildup of dust and dirt, and long exposure to possible corrosive materials. Mechanical damage from hail, high winds, and electrical storms can be minimized by proper design and choice of materials. The maintenance costs for cleaning and repair must be considered along with the initial installed system cost when choosing any photovoltaic installation.

Photovoltaics—Present and Future Applications

Each of the various field centers participating in the U.S. National Photovoltaics program focuses on a particular aspect of the ongoing tests and applications activities throughout the country. This also includes a measure of international activity, as summarized in table I.

Stand-Alone Applications

The NASA Lewis Research Center in Cleveland, Ohio, has the responsibility for the remote stand-alone applications sector. The objective is to develop photovoltaic systems that have the potential to be used in significant quantities in worldwide markets. An important part of this activity includes demonstrating these systems cooperatively with users in a way most likely to stimulate markets. Table II describes some of the completed tests and applications. During the next year and beyond, work will continue on additional international applications in the agricultural, cottage industry, health, and village power application areas. These systems will characteristically be modular, direct-current applications with battery storage; sizes will range from less than a kilowatt to 15 kilowatts.

The Massachusetts Institute of Technology and the Lincoln Laboratory (MIT/LL) have, in the past, conducted their activity in the stand-alone applications sector on larger alternating-current projects. Objectives were to establish the technical credibility of solar photovoltaic power systems, to identify and eliminate technical and institutional constraints that might inhibit widespread acceptance, to provide data for economic modeling, and to reinforce the goals of the National Photovoltaics program. Table III describes some of the completed tests and applications. MIT/LL has the responsibility for the residential applications sector and during the coming year and beyond will concentrate efforts on that sector, with the first residential system evaluation experiment expected to become operational in November 1980. Residential applications planned through 1986 include construction of several hundred photovoltaic residences in various geographic regions.

Intermediate-Load-Center Applications

The Sandia Laboratories in Albuquerque, New Mexico, is responsible for tests and applications in the intermediate-load-center applications sector. Their objectives parallel those of the residential

TABLE I.—U.S. DEPARTMENT OF ENERGY PHOTOVOLTAIC TESTS AND APPLICATIONS

Responsible organization	Remarks
Sandia Laboratories	
Five concentrator and four flat-plate projects entering construction phase in seven states (2020 kW)	------------
MIT/Lincoln Laboratory	
25-kW agricultural pump; Mead, Nebraska	Operational in 1977
100-kW power source; National Bridges National Monument, Utah	Operational in March 1980
15-kW daytime broadcast radio station; Bryan, Ohio	Operational in August 1979
Department of Defense	
60-kW grid-connected radar station; Mt. Laguna, California	Operational in June 1979
Oak Ridge National Laboratory	
240-kW power installation; Mississippi County Community College, Blytheville, Arkansas (trough concentrator technology)	Under construction
200-kW power installation; Northwest Mississippi Junior College, Senatobia, Mississippi	Under construction
500-kW power installation; Georgetown University, Washington, D.C.	In design
SERI	
350-kW village power system, Saudi Arabia (Soleras) (Fresnel lens concentrator technology)	Contract announced October 1979
NASA Lewis Research Center	
3.5-kW village power system; Papago Indian village Schuchuli, Arizona	Operational in December 1978
1.8-kW village power system; Tangaye, Upper Volta	Operational in March 1979
19 small stand-alone applications, less than 1 kW each	------------

applications, with emphasis on photovoltaic systems connected to the electric utility grid. In June 1979, twelve designs were selected for construction and operation by industry teams at locations throughout the United States. A total of 1.1 megawatts of these flat-plate and concentrating systems should be operational by the end of 1980. Industry teams will also design and conduct evaluation experiments on several other advanced systems in the megawatt range through 1986.

College Projects

The Oak Ridge National Laboratory (ORNL) is providing technical support to three college projects being designed and constructed under grants from DOE. These projects are

(1) A 240-kilowatt concentrating application, with active cooling and thermal utilization, at the Mississippi County Community College in Blytheville, Arkansas

(2) A 200-kilowatt testbed incorporating many photovoltaic technologies, as part of a total energy system, at the Northwest Mississippi Junior College in Senatobia, Mississippi

(3) A proposed 500-kilowatt exemplar project at Georgetown University, Washington, D.C.

The objective is to ensure that these grants projects derive maximum benefit from the ongoing photovoltaics program while experience is being gained in larger cogeneration energy systems.

International Applications

The Solar Energy Research Institute (SERI) is responsible for implementing a 350-kilowatt village photovoltaic power system near Riyadh, Saudi Arabia. The objective is to fulfill the terms of a

TABLE II.—NASA LEWIS RESEARCH CENTER

PHOTOVOLTAIC APPLICATIONS

Application	Service requirements	Operational period	Status
Refrigerator power (330 W) installed in July 1976	Medical and food supply storage at Papago Indian Village, Sil Nakya, Arizona	Continuous	In operation
Forest lookouts (588 W) installed in October 1976	Power for water, lights, radio, and refrigerator at two forest lookouts in California	May to October	↓
Weather stations (481 W) installed in April-August 1977	NQAA weather station power supply at five locations in New York, Florida, New Mexico, Arkansas, and Hawaii	Continuous	↓
Highway dust warning sign (116 W) installed in April 1977	Power for receiver, transmitter, motor, and lights on changeable messege sign near Tucson, Arizona	Continuous	↓
Water cooler (446 W) installed in July 1978	Demonstration photovoltaic powered water cooler for visitor center at Lone Pine, California	Continuous	↓
Refrigerator (220 W) installed in July 1978	Food storage for back country ranger station in wilderness area	Summers	↓
Village power (3500 W) installed in December 1978	Power supply for 95 people in Papago Indian village, Schuchuli, Arizona for water pump, 15 refrigerators, 47 lights, washing machine, and sewing machine	Continuous	↓

U.S.-Saudi bilateral agreement to foster alternative energy technology development and early demonstrations. This system will use Fresnel lens concentrating collectors.

Military Applications

The U.S. Army Mobility Equipment Research and Development Center, headquartered at Fort Belvoir, Virginia, participates in a joint Department of Defense/DOE solar energy research program and is responsible for the development of photovoltaic systems for the U.S. Armed Services. In this program military demonstration projects have been conducted using photovoltaics in remote instrumentation, a radar station, a telephone communication center, battery charging, and a remote water purification system. These systems ranged from 35 watts to 10 kilowatts. During August 1979 a 60-kilowatt system was dedicated that augments a 600-kilowatt diesel-powered grid at the Mt. Laguna Air Force Station, near San Diego, California.

TABLE III.—PHOTOVOLTAIC FIELD TESTS CONDUCTED BY MIT AND LINCOLN LABORATORY

Application	Size, kW_p	Location	Status
Agricultural test facility; large- and small-scale irrigation, crop drying, fertilizer manufacturing, etc.	25	Mead, Nebraska	Operational since July 1977
Public education (electric power for museum exhibit)	1.6	Chicago, Illinois	Operational since August 1977
Lincoln Laboratory Photovoltaic Systems Test Facility (test prototype residential system)	25	Lexington, Massachusetts	Installed in fall of 1979
Prototype photovoltaic load center system with stand-alone capability	100	Natural Bridges National Monument, Utah	Operational since May 1980
Power for radio broadcast station	20	Bryan, Ohio	Operational since August 1979

Central-Station Applications

Initial planning envisions four central-station system applications tests during the 1983–1986 period, each expected to be 2 megawatts in size. The objectives of these experiments will include technical verification as well as obtaining operating experience in a utility environment.

Conclusions

Current technology development projections indicate that both flat-plate and concentrator photovoltaic collectors are expected to meet the established 1986 collector cost goals. As a result it is expected that a variety of collectors using both the concentrator and flat-plate approaches will be commercially available for application, both in the United States and in the international marketplace.

The future commercial potential of both flat-plate and concentrator technologies will depend on the economics of each application, with broad applications potential foreseen for both technologies. There are some applications well served by both, other major applications best served by flat-plate collectors, and others likely to be best served by concentrator collectors.