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Photovoltaics Program
Technology Development and Applications
Lead Center

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# Photovoltaics as a Terrestrial Energy Source: Volume III, An Overview

Jeffrey L. Smith

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Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
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Jet Propulsion Laboratory
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(JPL PUBLICATION 81-103)

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# ABSTRACT

This volume concludes a series of Jet Propulsion Laboratory examinations of photovoltaic (PV) systems, their potential for terrestrial application, and JPL's role in their development. The purpose of this volume is to provide a comprehensive overview of important issues which bear on photovoltaic systems and JPL's involvement in their development. It summarizes two previous publications in this series as well as additional unpublished studies of PV system costs, the societal implications of PV system development and the strategy of JPL's involvement in PV research and development during the Carter Administration.

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# FOREWORD

This is the final volume in a series discussing the use of photovoltaic (PV) systems for terrestrial applications. The purpose of the series is to provide a forum for discussion of Jet Propulsion Laboratory (JPL) policy on the conduct of its photovoltaic projects, within the charter granted JPL by the Department of Energy Photovoltaics Program. These photovoltaic projects constitute a major part of JPL's Utilitarian Program. This Program applies skills developed in space exploration to problems of high national priority. JPL believes that its technical competence and success at managing complex research and development projects have wide applicability to many pressing issues of national scope.

While the overall intent of JPL's Utilitarian Program is straightforward, important questions surround the specific purposes, limitations, strategies and status of the individual projects, including the PV projects. It is hoped that the information presented here aids policy formulation with respect to these questions.

The purpose of this final volume is to summarize the major conclusions of this investigation. It begins with a review of material introduced in Volumes I and II of this series. Subsequent sections summarize important conclusions of three unpublished studies that reviewed PV system costs, societal implications of PV deployment and PV Program strategy of the Carter Administration.

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# INTRODUCTION

This volume summarizes a series of Jet Propulsion Laboratory (JPL) publications* discussing the potential for use of photovoltaic (PV) systems as generating sources for future electric utilities. For the past six years the United States federal government has supported an ambitious and substantial research and development (R&D) Program to develop PV systems capable of producing power at prices competitive with conventionally produced power (References 1, 2, and 3). JPL has been a major participant in this federal Program, functioning since its inception as the manager for development of cost-effective flat-plate photovoltaic collectors and since 1978 as the Department of Energy's Lead Center for management of Photovoltaic Technology Development and Applications.

For several reasons, JPL concluded early in 1980 that a detailed examination of the Photovoltaics Program would be beneficial. The PV Program strategy and tactics are complex, involving subtle interactions with the private PV industry, difficult assessments of a wide range of existing and potential PV technologies, and hard decisions on the appropriate role of government and scope of its involvement.

JPL believes that in some respects this R&D Program is unique, with important implications for the potential for PV application and for the conduct of other U.S. R&D Programs. The current restructuring of the national solar program, especially the FY82 60% reduction in PV Program funding, is of immediate concern. (How can the Program best be restructured to incorporate significantly reduced funding?) More generally, the organization and conduct of the PV Program provide insight into the process of technological advance and the appropriate roles of federal funding and national research laboratories in U.S. research and technology development.

This examination of the potential of photovoltaics has been produced by JPL staff working for the Photovoltaic Lead Center.** During the past year, an extensive set of discussions has been held among JPL managers and staff and a broad range of experienced energy managers and experts from outside JPL. The documents summarized here have evolved from discussion papers originally prepared as background material for these interactions.

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*Smith, J. L., Photovoltaics as a Terrestrial Energy Source: Vol. I, An Introduction, Vol. II, System Value, JPL Publication No. 5220-15, Jet Propulsion Laboratory, Pasadena, California, October 1, 1980.

**The Lead Center has prepared, in conjunction with DOE, major documentation of the PV Program, including the Multi-Year Program Plan of the National Photovoltaics Program (Reference 1) and a two-volume report (Reference 2) submitted by DOE to Congress in response to the Solar Photovoltaic Energy Research, Development and Demonstration Act of 1978 (Reference 3).

# PHOTOVOLTAIC POWER SYSTEMS

Photovoltaic systems employ semiconductor materials to convert a fraction of visible light directly to electrical energy. Powering spacecraft with sunlight was their first important practical application; it remains an important one. Mountaintop radio and microwave repeaters, ocean signal buoys and pipeline corrosion protection systems are typical of the terrestrial applications in which PV systems are now commercially attractive (see Table 1). Power requirements are small and the systems are usually remote from human habitation and from the conventional energy supplies of electric utilities. Figures 1, 2 and 3 show typical terrestrial photovoltaic systems.

A small, highly competitive U.S. industry is emerging to supply PV systems for this world-wide market; it produced approximately 4 peak megawatts ($MW_p$)* of generating capacity during 1980 (U.S. government purchases were less than 25% of this market). This generated a total sales revenue of approximately $40.7 million.** French, German and Japanese competition is challenging the early lead held by U.S. companies in this fledgling industry.

In less developed countries, potentially significant remote markets (e.g., village power, water pumping) exist for the obvious reason that grid networks are much less extensive in these countries.*** However, electrification is a primary goal of almost all less developed countries, and this has most often meant vigorous pursuit, within budget constraints, of grid extensions.

While most PV manufacturers remain preoccupied with expanding remote, world-wide power markets, there is reason to believe that PV systems can be useful in supplying power to modern electric utilities. Opportunities for PV technological advance are broad and substantial, and such advances may result in the development of PV systems capable of electricity production at costs that meet the more stringent competitive requirements of bulk electricity markets.

PV systems have many attractive features. They are highly modular; a basic PV unit typically generates 10 to 100 peak watts. Present systems are usually no larger than a few hundred watts, but photovoltaic systems for residences, commercial buildings, industrial parks, and large central stations on the order of hundreds of megawatts are in development or experimental construction. The high degree of modularity adds flexibility to the siting

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*PV systems are rated at their power output under standard illumination (irradiance) and weather conditions that correspond roughly to ideal conditions at sea level.

**Solar Energy Industry Association survey (September 1980) of PV manufacturer sales and revenue projections for 1980.

***Supplying electrical power in such areas has historically provided a large market for diesel generator manufacturers, who may soon begin to feel significant competitive pressure from PV suppliers. Small U.S. islands (e.g., Catalina, Molokai) are also supplied primarily by diesel generators. Diesel markets may support significant expansions of the PV industry.

Table 1. Current Photovoltaic Applications

| Marking & Warning Devices | Monitoring & Sensing Devices | Consumer Products |
|---|---|---|
| Remote airfield lighting | Pipeline controls | Watches |
| Destruction hazard lights | Instrusion alarms | Calculators |
| Navigation buoys | Pollution monitors | Boating applications |
| Onshore navigations systems | Gas detectors | Flashlights |
| Offshore platforms | Weather monitors | Pocket paging systems |
| Railroad crossings | Flood monitors | |
| Highway signs | Oceanographic data platforms | |
| | Earthquake monitors | |
| **Corrosion Protection** | **Communication Equipment** | **Miscellaneous PV Applications** |
| Pipelines | Portable radios (DOD) | Water pumping stations |
| Wellheads & casings | Repeater stations | Space satellite applications |
| Marine structures | Telephone call boxes | Military test sites<br>Instrumentation |
| Highway bridges | Air navigation systems | Railroad switching |
| | Remote TV | Remote housing and villages |

SOURCE: Photovoltaic Power Systems Market Identification and Analysis, Volume 1, BDM Corp., August 1978, p. II 9, with JPL modifications

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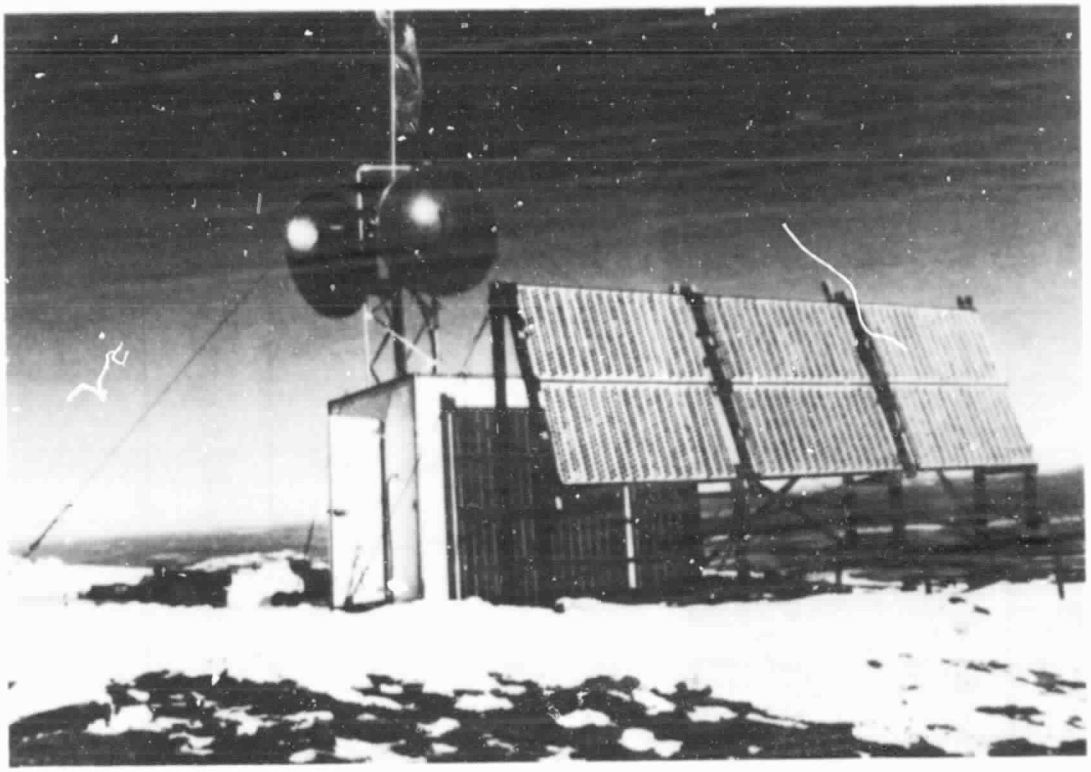

Figure 1. Microwave Repeater Station in Alaska (Courtesy of Spectrolab, Inc.)

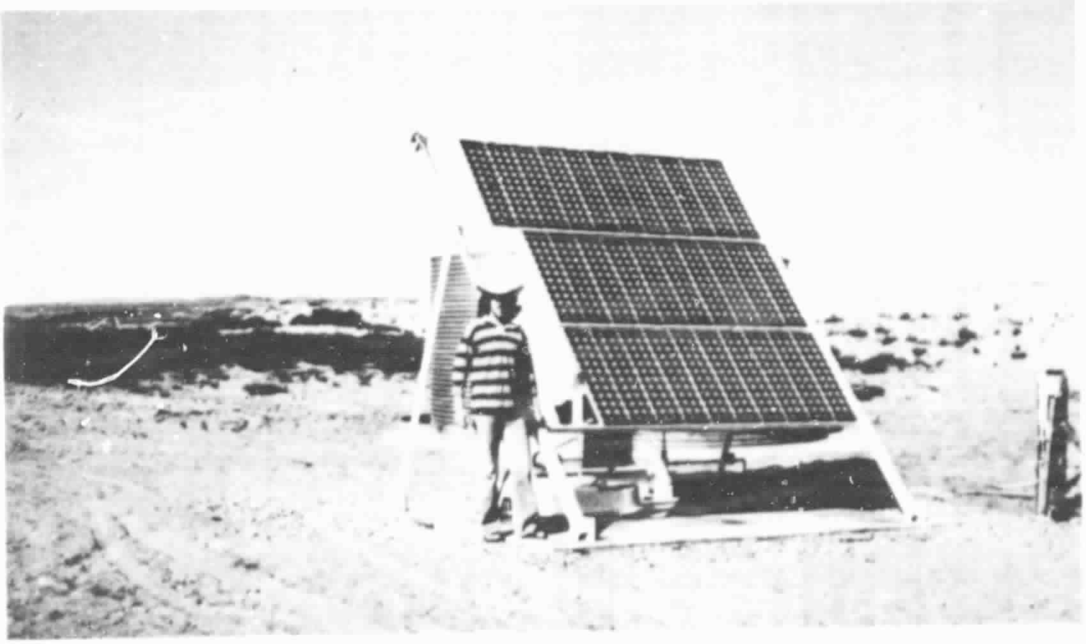

Figure 2. Livestock Watering on Indian Reservation in New Mexico; Water is Pumped from a 300-foot Well into a Storage Tank (Courtesy of Arco Solar, Inc.)

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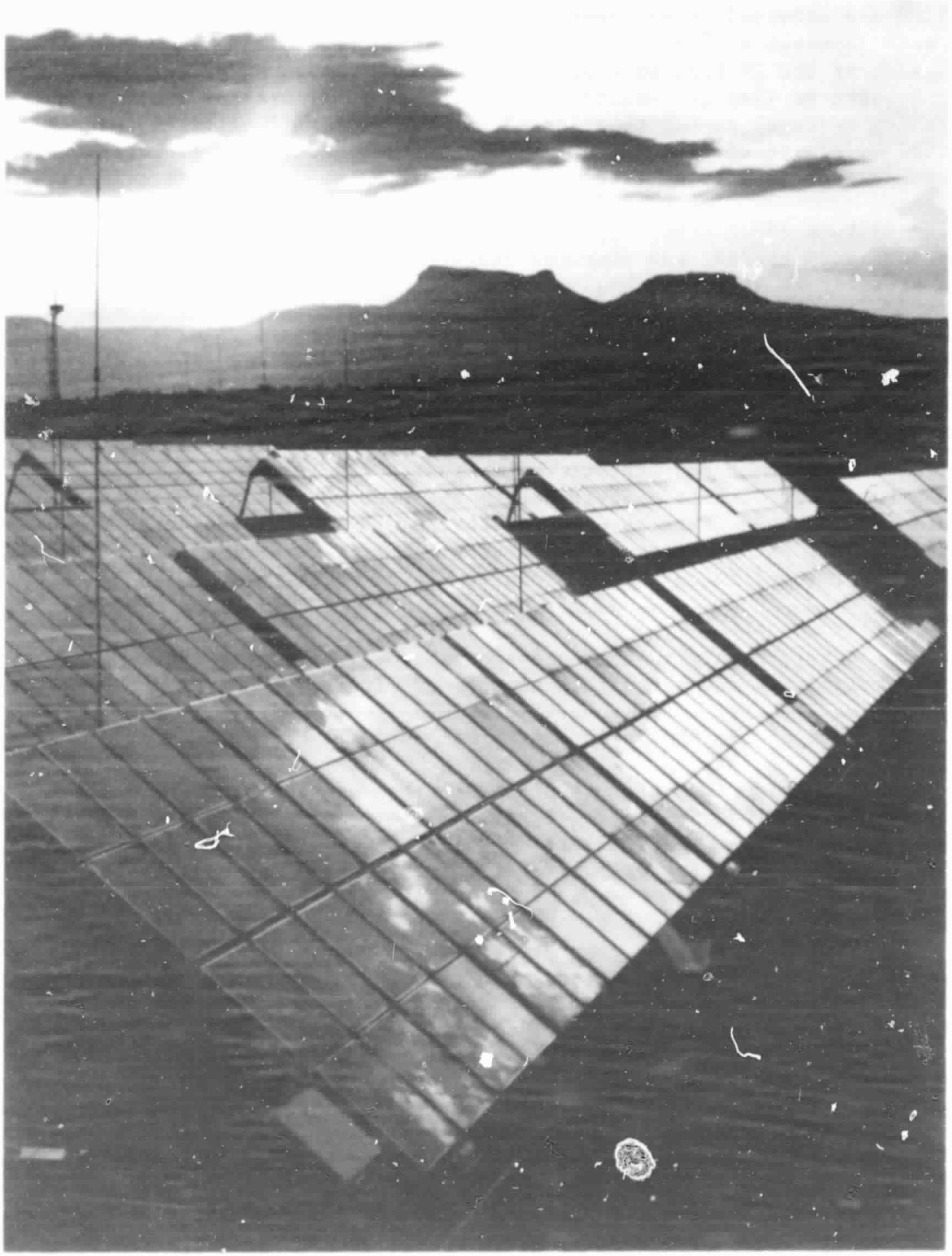


Figure 3. The 100-$kW_p$ Experimental PV System at Natural Bridges National Monument, Utah

(and testing) of PV systems and allows land-use impacts to be minimized. In addition, large systems can be manufactured, installed and maintained using mass-production techniques; thousands of identical components can be produced, installed and serviced in an identical manner, promoting standardization of components, systems and installation techniques. (Exploiting this characteristic is part of the PV Program cost-reduction strategy.) PV capacity additions can be brought on line in smaller increments, thereby entering the rate base (generating revenue) sooner than large coal and nuclear facilities, easing the financial burden on utilities. Shorter lead times also allow closer matching of capacity additions to uncertain growth rates in demand for electricity.

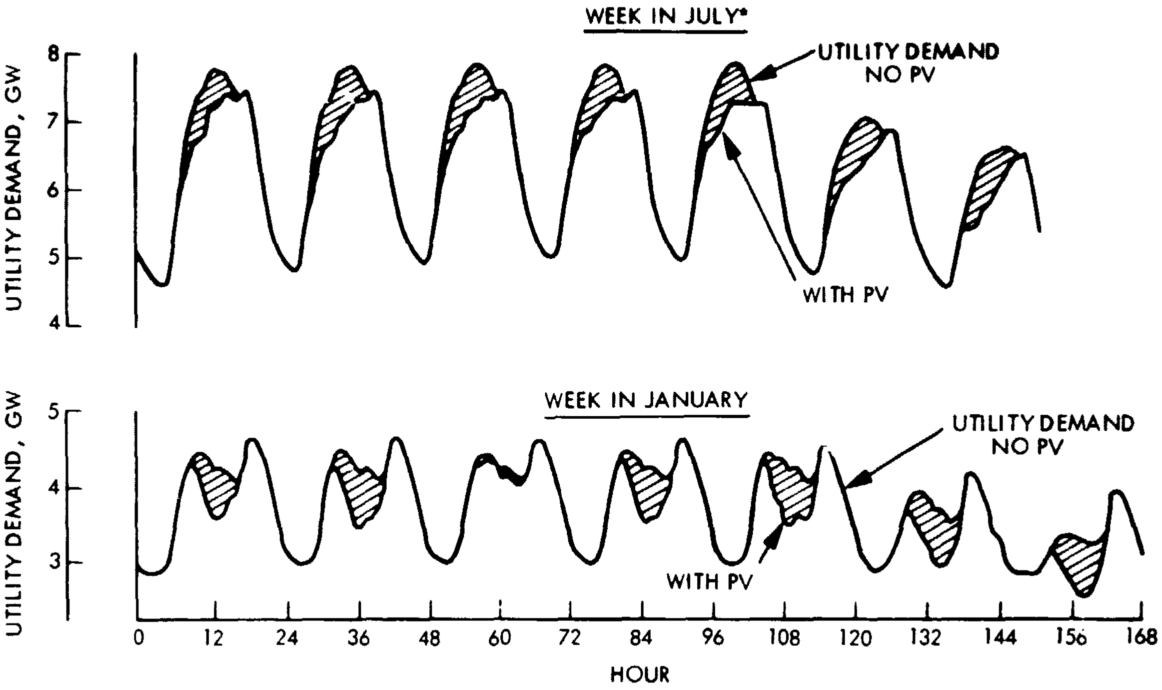
PV systems offer other apparent advantages. They operate silently, they can be passively cooled, and they can operate with no moving parts, depending on the specific PV system technology employed. They emit no effluents and their production need not cause significant or harmful emissions or waste products. The dominant photovoltaic material (silicon) is abundant, accessible and chemically inert. The production of PV systems does not depend on the availability of strategically vulnerable materials. Their energy source is secure and inexhaustible.

The intermittent and unpredictable nature of sunshine is a major disadvantage of PV, and it contributes to the high cost of present PV systems. This has led many observers to conclude that electrical storage must become an integral part of PV systems and PV research. For example, the Ford Foundation-sponsored Energy Study Group concluded in its discussion of PV potential:

> Unfortunately, the technology works best during the daytime and often not then because of clouds. Thus, an integral part of solar photovoltaic approach must be the storage of the energy in electrical form.... (Reference 4)

This conclusion is not correct when interconnection with the utility grid is possible. Interconnecting PV systems in parallel with the grid allows two-way power flow--excess PV electricity is fed into the grid, and the grid supplies power to any loads associated with the system whenever the PV power output is insufficient. In this configuration, PV systems become one of many generating sources supplying power to the electric utility grid. In many utility districts, PV systems generate primarily during periods of high electrical demand (daytime). Often, when PV systems are not operating (e.g., at night), sufficient unused generating capacity exists to satisfy electrical demands. An interconnected arrangement can prove beneficial to the PV system owner, to the electric utility and to its customers.

Figure 4 shows the simulated effect of including 800 $MW_p$ of PV-generated electricity on the net load seen by conventional generators in a Southwestern utility. In this hypothetical case, PV produces 3% to 4% of the total electrical energy of the utility. Note the high correlation of system-demand peaks and PV output in the summer. Under such favorable circumstances, the addition of PV systems to electric grids may allow a significant reduction in the capacity additions of other generating sources required to maintain utility system generation reliability. At worst, all capacity additions required without photovoltaics may still be required, although the optimal configuration (generation mix) of grid generating sources may still be altered in PV's



*Shaded area shows photovoltaic output

Source: Aerospace Corp. Presentation at Photovoltaics Program Annual Review Meeting, April 1980.

Figure 4. Simulation of Southwestern United States Utility Load Profile, With and Without Photovoltaics

presence. In most cases, the primary benefit to utilities arising from PV additions will be displacement of conventional fuels (e.g., oil, coal, gas, uranium), although PV is most likely to be deployed in areas where capacity credits will also accrue.*

Somewhat surprisingly, the addition of photovoltaics to utility grids where PV is most useful may reduce the value of additions of electrical storage systems to the same utilities (and vice versa). Until PV capacity reaches high

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*While PV may displace significant quantities of oil in a few areas of the country (e.g., Hawaii, California), reducing oil consumption will probably not be the primary benefit of widespread PV deployment in the United States. Electric utilities consume only 10% of our crude oil supplies, most areas of the country do not generate electricity from oil, and many of the attractive opportunities for oil substitution under electric utility boilers and elsewhere (e.g., home heating) may already have been taken before competitive PV systems are likely to become generally available. Opportunities for displacement of consumption of oil in foreign countries could be more substantial.

proportions of total grid generation, storage systems will be charged primarily during periods when PV is not producing (e.g., at night), since these are the periods of lowest short-run marginal production costs for most utilities. Conversely, storage will tend to be discharged during peak and shoulder demand periods, when PV is producing. Electrical storage and PV systems are consequently partial substitutes for each other; each derives value from production during high marginal-cost periods. Additions of interconnected PV systems may reduce the incentive and need for electrical storage in the short run.*

On the other hand, if PV capacities become very significant or if PV is added to utilities whose peak and shoulder periods occur primarily after dark, storage and PV systems would be complementary. The expense of adding electrical storage (or other peaking capacity) could eventually set an upper limit to grid-connected PV capacity additions, although very significant deployments of PV (5% to 30% of energy produced) appear possible without an increase in peaking or storage requirements in many major U.S. electricity markets. There appear to be no insurmountable technical problems in fully interconnecting PV systems with electric grids, even at the end of distribution feeders such as with residential PV systems. At larger PV penetrations, stability and control of the grid could pose substantial technical or economic difficulties.

Thus, PV is believed capable of becoming a significant portion of the electrical generation mix of the U.S. and the world through competitive application in private electricity markets. In addition to direct application in the U.S., an enormous potential exists for profitable application by less developed countries as they expand their electricity systems. The possible moderation by PV of harmful local and global environmental consequences of electricity generation also deserves mention.

A grid-connected photovoltaic system is composed of two primary subsystems--array and power processor. The array subsystem consists of the PV collector (which converts sunlight into direct current), and when required, the support structure, foundation, tracking mechanism, and land. The power processor subsystem converts the dc energy into ac energy suitable for loads, or for being fed into the utility grid. It consists of the power conditioner, switch gear, utility interconnection equipment, and associated wiring. The total price of a PV system is the hardware price, including marketing and distribution, and the indirect (non-hardware) costs, viz., architect-engineer, design and project management fees, interest during construction, and sales fee. Historically, attention has been focused on the photovoltaic collector, as it is this portion of the system that contains the true photovoltaic elements. Nevertheless, the balance of the system hardware and the indirect (non-hardware) items presently constitute about half of the total cost of a PV system.

PV collectors may themselves be sorted into two groups: flat-plate collectors, which intercept sunlight directly with the semiconductor PV cells (units of active material), and concentrating collectors, which use reflective

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*The use of storage for load-following capability, the short-term operating capability needed to adjust generating units to meet fluctuations in total demand, is not considered here.

or refractive devices to concentrate sunlight onto smaller areas, thereby conserving semiconductor material.

Potential concentration ratios range as high as 2000 suns; that is, the intensity of light striking the PV cell may be as high as 2000 times the intensity of the sunlight striking the earth's surface. The efficiency of photovoltaic conversion is, by and large, an increasing function of the concentration ratio at a constant temperature.* Photovoltaic cells respond to light regardless of its angle of incidence; flat-plate collectors are able to convert both direct and diffuse radiation. Most concentrators, however, are able to concentrate direct radiation only. Thus, as the concentration ratio increases, collectors become more dependent on the direct component of the radiation. For example, most concentrators will not operate on cloudy days, while flat-plate systems may (although with substantially reduced output).

A wide variety of semiconducting materials may be suitable for use in PV collectors. In addition to single-crystal silicon, polycrystalline and amorphous silicon, cadmium sulfide-copper sulfide, gallium arsenide, titanium oxide, and a broad range of other uncommon materials are being investigated. A wide variety of concentrating approaches are available, including Fresnel lenses, parabolic troughs, split-beam concentrators (which refract light of different wavelengths onto PV cells that are optimal for the wavelength each receives), luminescent dye concentrators, and thermophotovoltaics. Opportunities abound for experimental and theoretical investigation of various PV collector materials and devices.

Photovoltaic collectors may be fixed in place or they may track the sun. Tracking collectors range from those with seasonally adjustable tilt angles to two-axis continuous trackers. In general, concentration ratios above 8 require at least one-axis tracking. High concentration ratios (above 50) require accurate two-axis tracking to maximize the direct component of incident radiation. In addition, the shape of the output profile of a PV system (through the course of a day or year) depends primarily on the tracking scheme, ignoring variations due to weather. For example, fixed-tilt systems (typically flat-plate) have sharply peaked daily output profiles, as they cannot collect the morning and afternoon sunlight as well as can systems that track the sun from east to west.

Presently, prototypical grid-connected PV systems are in experimental development and performance testing. A significant commercial market does not exist at present costs of such systems, which range from \$15/$W_p$ to \$60/$W_p$. It is expected that simple, flat-plate silicon systems will soon become available at prices near \$10/$W_p$. Even so, analyses indicate that this would still be five to 10 times the price at which photovoltaics will become widely attractive in the United States. Thus, very significant cost reduction must be effected if PV is to become an important source of electricity in the developed world.

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*For example, the efficiency of a typical concentrator silicon cell rises from 13% at 1 sun to 22% at 300 suns, dropping off thereafter.

Grid-connected PV system costs may differ significantly among potential applications and system sizes. For at least one important grid-connected application--multi-megawatt, ground-mounted flat-plate systems--attainment of inexpensive balance-of-system (non-collector) costs appears relatively straightforward. Land costs are likely to be less than 5% of total system costs. Inexpensive support structures can be fashioned from 4 x 4-in. wooden trusses anchored in back-filled dirt trenches. Inexpensive power-conditioning devices (inverters) can be adapted from existing commercial converters used in applications such as high-voltage dc transmission. The modularity of these simple systems greatly enhances potential economies in installation, finance, shipping and maintenance. Attainment of collector cost and performance goals is the crucial cost uncertainty facing these large, ground-mounted flat-plate systems.

Other system concepts may face more formidable balance-of-system cost obstacles. Small distributed systems require substantial power-conditioning development, and may bear substantial indirect costs, e.g., from marketing and distribution.

Within the distributed sector, newly constructed single-family and low-density homes are one of the most attractive applications. Businesses can deduct conventional fuel costs from their taxable income; homeowners cannot. The available roof area on most commercial and industrial establishments is often adequate to serve only small fractions of their load. New construction can employ roof-integral PV modules, which actually replace and act as the roof of the house. (Prototypes of such modules exist.) Adequate appropriate roof area exists in most new residential subdivisions that they could easily become net exporters of electricity, given proper initial design, without serious disruption to the aesthetic attractiveness of the neighborhood. Retrofit of existing buildings with photovoltaics can be hampered by inadequate roof supports, inappropriate building orientation and roof-tilt angles, zoning and building code restrictions, financing, and solar access difficulties. For these reasons, newly constructed single-family and low-density homes seem to be the most attractive distributed market.

## THE NATIONAL PHOTOVOLTAICS PROGRAM

The National PV Program began in FY72 as a small NSF research effort devoted primarily to collector development. The major legislative mandate for the Photovoltaics Program is found in the Solar Photovoltaic Energy Research, Development and Demonstration Act of 1978 (Reference 3). This Act, signed in November 1978, established a 10-year, $1.5 billion Photovoltaics Program. Several goals for the Program were included in the Act:

(1) To establish "...an aggressive research, development and demonstration program..." for PV systems to produce electricity "...cost competitive with utility-generated electricity...."

(2) To double the annual production of PV systems every year beginning in FY79 and culminating with 2000 peak megawatts ($MW_p$) annually in FY88.

(3) To reduce the average cost of installed PV systems to $\$1/W_p$ by FY88.

(4) To ensure that at least 90% of all PV systems produced in FY88 are purchased by private buyers.

A few months before passing this legislation, Congress established the Federal Photovoltaics Utilization Program (FPUP), authorizing the expenditure of $98 million over three years (FY79-81) for the purchase of photovoltaic systems for federal buildings and other federal applications. Approximately $29 million has been spent by the Department of Energy for this purpose. Appropriations for the Photovoltaics Program through FY80 have totalled almost $500 million.

The Department of Energy (DOE) has responded to this legislation in the report Federal Policies to Promote the Widespread Utilization of Photovoltaic Systems. In this report the goals set by Congress for PV development are discussed in relation to the PV development strategy of the ongoing DOE PV Program. The primary objective of the DOE Photovoltaics Program, as set forth in this report and the Multi-Year Program Plan, is to make possible the competitive supply of photovoltaic systems by a private industry to bulk electricity markets in the United States. Specific goals have been set by the Program that require a tenfold or more reduction in present PV system prices to allow the production of electricity at 5-10¢/kWh (1980$). While the PV cost-reduction goals of Congress and DOE are similar, the ambitious PV production targets set by Congress are not part of the DOE strategy.

The primary technique applied by DOE to attain the cost-reduction objective is sponsorship of research and development--that is, sponsorship of searches for new, relevant photovoltaic materials, products, processes and information concerning their beneficial supply and use.

The National Program is closely linked with and dependent on cost-reduction activities of the private PV industry. Fostering the evolution of a competitive industry that can supply PV systems to major electricity markets is a cornerstone of the Program. Most of the technical activities of the Program are proposed and conducted by private industry and universities. More than 200 major R&D contracts are presently sponsored and coordinated by the Program through a highly structured, goal-oriented process that has been designed and implemented by the Department of Energy and several national laboratories. Systems tested in test facilities and engineering field tests are usually designed and constructed by private PV companies.

Figure 5 classifies Program R&D activities by stage of development. Research includes activities directed at PV collector materials, processes, and devices that have not yet demonstrated Technical Feasibility (see Table 2). These efforts are managed by the Solar Energy Research Institute. When a material or device achieves Technical Feasibility it advances into Technology Development. In this phase of Program R&D, managed by JPL, collectors are designed and tested, component production technology is developed, and complete PV systems are designed and tested. Development of PV components and their production processes is aimed at achieving Technology Readiness while systems must achieve System Readiness, thereby imposing strict production cost and

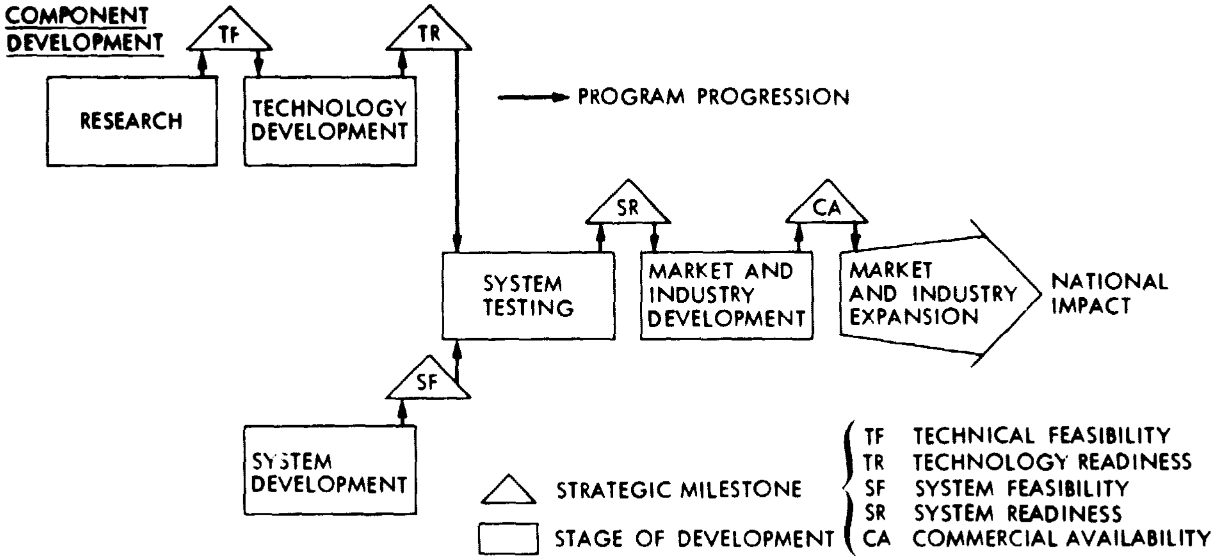

Figure 5. Research and Development Process for Photovoltaic Components and Systems

performance goals on the Technology Development activities. Upon achievement of these goals, complete cost-effective PV systems have been developed and tested.

The silicon PV technologies that are now Technically Feasible and for which cost-effective production technology is presently being developed are referred to as baseline technologies. Non-technically feasible concepts are termed advanced.

The baseline technologies are believed capable of significant impacts in some U.S. electricity markets. Successful development of silicon photovoltaic systems is predicted by the Program to lead to hundreds or thousands of megawatts of annual PV sales in the 1990s. In addition, should one or more advanced materials or devices prove reliable and very inexpensive, the nation will be poised to expand its photovoltaic generation capacity rapidly. Successful completion of baseline System Readiness will create a photovoltaic option for the nation whose value could be greatly increased by the emergence of a very inexpensive advanced collector.

Confusion has sometimes arisen over the definition, and need, of a "breakthrough" in PV technology in order for photovoltaics to become competitive.* This confusion may have arisen because of inadequate differentiation between

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*At least four recent reviews of photovoltaics have emphasized the importance of a breakthrough (References 5, 6, 7, and 8).

Table 2. Key Milestones in the Photovoltaic R&D Process

| Milestone | Definitions/Requirements |
|---|---|
| Technical Feasibility (TF) of components is reached for a particular technology when: | (a) stable and reproducible performance characteristics have been achieved<br>(b) a laboratory-scale process has been defined that yields products with consistent characteristics<br>(c) analysis indicates that mass production is technically feasible and likely to yield a technically and economically viable product after suitable technology development |
| Technology Readiness (TR) of components is achieved: | (a) with a successful subscale demonstration of the individual steps in a production process that would yield economically competitive and reliable products <u>if</u> produced in sufficient quantity, and<br>(b) <u>when</u> prototypes are available for intensive performance and reliability analysis |
| System Feasibility (SF) is achieved in a given application when: | a photovoltaic system concept is first carried through design, installation, and operation in an actual user's environment |
| System Readiness (SR) is accomplished when: | (a) fully integrated systems, using available technology-ready components or prototypes thereof, are designed, built and successfully operated in an actual user's environment<br>(b) it is shown that the system price goal and performance goals are likely to be met with high-volume sales |
| Commercial Availability (CA) of components & systems in a given application class is accomplished when: | products or systems in a given application class are offered for sale at a given competitive price |

Research and Technology Development. For each of the not-yet Technically Feasible materials and devices (those in Research), a major obstacle is perceived to prevent that device from attaining Technical Feasibility (e.g., inherently low efficiency, inability to achieve competitive costs, environmental unacceptability, unreliability, instability). Removal of these obstacles requires basic research into device physics, materials properties, etc., of a kind generically different from the R&D conducted on Technically Feasible collectors (those that are undergoing production technology development). It is this fundamental research that is more likely to result in breakthroughs. But achievement of the baseline price goals of the Program does not depend on any non-Technically Feasible concepts--they can be achieved with single-crystal silicon and related technology through aggressive TD, according to JPL and the PV Program. While the possibility of a breakthrough is not discounted, it is not required to achieve PV collector and system prices that allow private, unsubsidized producers to compete successfully in some major U.S. electricity markets.

With the achievement of System Readiness, PV systems are shown to be technically capable of competitively-priced electricity production. This is to be confirmed through system tests designed and conducted by PV companies and electric utilities. Two phases of system experiments are planned. The first consists of behind-the-fence experiments in system test facilities. Engineering field tests in the user environment are the final phase. These tests are required to properly identify and rectify potential problems with PV system operation, maintenance, and grid interface. Tests are necessary to assess PV system designs and costs adequately and, thus, to achieve the major technical goals of the Program.

A variety of activities have been proposed beyond System Readiness and the completion of R&D. Clearly, achieving technical capability does not, by itself, guarantee that a private domestic industry will quickly arise to supply PV systems, nor that potential PV buyers will quickly perceive and act on the expected benefits of PV systems. Regulatory, tax or market barriers could inhibit PV market growth. Government actions have been proposed to prevent or ameliorate these barriers.

On the other hand, the failure of a private industry and market to arise spontaneously as System Readiness is approached may be interpreted as strong evidence that the PV product is not truly cost-competitive. With this interpretation, government action beyond System Readiness is not productive. The present PV Program consists primarily of research and development and may never proceed beyond System Readiness. Or it may prove beneficial to continue selected information dissemination. industry assistance or market development activities, in conjunction with continued R&D on advanced collectors, beyond the achievement of System Readiness for baseline systems. In any event, success of the PV Program is not predicated upon large PV hardware purchases, demonstrations by governments or upon special PV or solar tax credits. If the present rapid growth of PV production, sales and industry investment continues, market and industry stimulation by government should not be needed. In this situation the appropriate roles for government and private funding of PV research and development becomes a more important issue.

Even though the primary intent of most Program-sponsored actions is research and development, the form these activities take is influenced by information dissemination and industry assistance objectives. This is illustrated by the technology development efforts of JPL's Flat-Plate Solar Array (FSA) Project.

The FSA Project divides the development of cost-effective flat-plate collectors into several steps. Ambitious, long-range cost-reduction objectives are set for each step and competitive proposals are solicited from private or other bidders to achieve them. Several proposals are selected for each important step, and a phased R&D program is negotiated with each contractor, whose ultimate purpose is achievement of the long-range objectives. Commitments are then made to the first development phase. Continuation into the second and later phases is contingent upon successful performance in the preceding phase, as well as upon changing Program circumstances and additional competition with other processes either already under Program sponsorship or newly entering. As the Program advances, less successful or less important development efforts are dropped and new, promising ideas are added.

Proper phasing of R&D contracts is crucial, especially for hardware development. Phases and their criteria for success must be well-defined. For example, contracts for development of cost-effective production equipment and production processes usually have at least three phases. The first consists of laboratory investigations and feasibility testing, including analyses of projected production costs. Construction and testing of pilot-scale prototype hardware, again coupled with comprehensive cost analyses, usually constitutes the second phase. The third consists of design and manufacture of actual commercial production hardware capable of cost-effective PV component production. R&D costs grow substantially in later phases. This gives substantial incentive to contractors to perform well in early phases and reduces the total number of approaches to each development step that can be retained as the Program advances. It also encourages contractors to reveal information they produce to prove their worthiness for continued support. While many contractors fund substantial proprietary in-house photovoltaic R&D, they share much of their results with PV Program managers.

It is also essential that multiple approaches be pursued at each major development step. Not only does this increase the probability that each technical goal will be achieved, but also it sets up a competition among companies that forces examination of development objectives and criteria for judging success, and enhances the rewards both for superior contractor performance and for quick reporting of development successes. Finally, pursuit of multiple approaches enhances the likelihood that a competitive photovoltaic industry will develop by increasing the diversity of technical approaches, the level of public knowledge of the technology base, and the number of firms interested in and knowledgeable about photovoltaics. Thus, contract phasing and multiple awards promote the dissemination of information and the development of a competitive PV industry.

The FSA Project holds well-attended contractor review meetings in which progress in all areas is reviewed. Contractors are encouraged to discuss freely the relevance of their activities and their potential for integration into commercial PV production. Project managers present their own assessments of progress, attempting to evaluate objectively the relative progress of each development contract and to share existing information among all interested participants.

Finally, standardized photovoltaic module testing procedures have been developed to test experimental modules of various producers and contractors, facilitating comparison of the effects of various designs and production techniques.

In-house activities of the FSA Project are thus directed primarily at integration and management of development activities. Strong interdependence of the various technical developments undertaken by the project limit opportunities for rapid schedule and budget variations.

While exact amounts are not publicly known, it is clear that private expenditures on research, development, and prototype production lines have grown substantially in the past two years. These R&D activities have already led to the emergence of several competing technologies. Wacker, of Germany, and Solarex have separately entered the marketplace with semicrystalline silicon products from prototype production lines. Solarex Corp. has recently announced plans to build, by 1983, 40 $MW_p$ of annual module production capacity in the United States and 40 $MW_p$ in Europe (in four separate facilities), all using polycrystalline silicon. SES, Inc. (Shell Oil) and Photon Power, Inc., are beginning to market cadmium sulfide-copper sulfide panels; ARCO Solar, Inc., has installed an advanced single-crystal line, and Mobil Tyco Solar Energy Corp. is marketing modules from its silicon edge-defined film-fed growth (EFG) ribbon pilot facility. The Japanese are marketing amorphous silicon PV cells in wristwatches and portable radios. Several U.S. producers have PV concentrator systems in various stages of development and system test, which they would like to market. Some of these attempts at early production with new technologies will undoubtedly fail, but others may exceed expectations. Technological diversity and competition among technologies exist in the private market, and should lead to better understanding of the relative merits of each approach.

The emerging photovoltaics industry has attracted much interest and industrial participation, in both production and R&D. There is little doubt that the existence of a clearly articulated, adequately funded National Program has had a large effect on knowledge and interest in photovoltaics by many industrial concerns of diverse backgrounds (e.g., chemicals, computers, photography, semiconductors, metals, glass, oil). It is likely that the presence of government funding has increased total private photovoltaic R&D funding, as many otherwise uninterested firms seek technical positions complementary to what they see forthcoming from the PV Program. Many large and small firms maintain an active interest in photovoltaics, apparently hoping to enter from the wings when they judge the time to be right.

The development activities of the PV Program have attained a momentum, whose interruption could jeopardize not only many of the in-process technical developments but also the present industrial scrutiny of PV's potential. Even with continued support, however, it is essential that the photovoltaic R&D program conduct its activities to mesh with the likely future development of the PV industry--a requirement that has led the government technology development effort to be characterized as a "moving baseline."

If the PV Program is successful, detailed designs of complete, end-to-end production processes and installed photovoltaic systems that can meet the price goals of the Program will be produced and publicly documented. Most of the specific technological investigations funded by the Program are carried out in private industry, thereby creating natural potential investors for each process step. Nevertheless, it is unrealistic to assume that when technology development is completed, companies will simply install complete government-developed production lines for photovoltaic collectors or systems.

On the contrary, most companies seriously engaged in photovoltaic research have as a prime objective the development of a process that can be patented or kept secret to protect a proprietary interest. They intend to exploit their proprietary position through production or licenses. Many companies are conducting both privately and publicly funded PV research. For these reasons the government Program should be regarded as a moving baseline that each private company must surpass to gain a competitive position. Since there are numerous steps in collector and system production processes, a company with a good idea can concentrate its research on only those portions of the process that interest it--other steps can be adopted from the federal development effort or other publicly known or licensed processes.

It is the strategy of the government Program to seek simultaneous improvement of at least several approaches to each major step in PV system development and to make these improvements public in order to foster rapid, competitive evolution of PV production technology. This should provide ample information and opportunity for successful entry by many companies into the PV industry. In addition, existing production lines will incrementally adopt both private and federal improvements. This process is already evident; manufacturers are now incorporating improvements in encapsulation, metallization, and other steps developed by DOE and private researchers during the past several years. It is likely that a large number of different processes and technologies will exist, compete, and thrive simultaneously. Each company will believe its proprietary position to be superior, and each will try to determine which market segments are best suited for its technology. The picture that develops is one of rapid technological evolution, rather than revolution, leading--it is hoped--to rapidly falling collector prices in the next several years.

## THE VALUE OF PHOTOVOLTAIC SYSTEMS

Considerable uncertainty surrounds the future costs and availability of conventional sources of electricity (hydro, oil, natural gas, coal, nuclear). While several of these sources could conceivably develop and expand to meet, at reasonable total costs, all of our future needs for electricity, the fuel availability, siting, cost and environmental uncertainties that cloud their future encourage a search for new, attractive sources of power. Photovoltaics is one of a number of potential long-term alternative sources of electrical energy. Each of these potential new sources (e.g., fusion, solar thermal, wind, geothermal, magnetohydrodynamics) should be pursued in proportion to the expected net social benefits from developing and supplying electricity with that source.

Large uncertainties permeate the levels and patterns of future demand for electricity and the future availability, cost and attractiveness of both conventional and new electricity generation sources. It is not possible to predict accurately the extent to which actual deployment of photovoltaic systems (or other new sources) will become attractive.

The national PV effort is intended to create a readily available and attractive photovoltaic option. The extent to which this option will be profitably exploited by the nation and the world depends on the outcome of uncertain events. Nevertheless, the PV Program believes that photovoltaics is a potential major source of power for the United States and the world that could eventually supply as much as 30% of total electrical energy needs in areas ideally suited to its characteristics, although most regions of the United States (excepting California and Hawaii) do not fall into this favorable category.

As discussed above, the economic value of PV is estimated by valuing the types of changes in the net load curve shown in Figure 4 extended to the expected life of the PV systems. The value of these changes consists primarily of the conventional fuel and capacity savings that result from the PV output. However, potential effects (positive and negative) on other utility system costs, such as transmission and distribution, reactive power requirements, and network stability and control must also be considered.

To estimate the value of PV systems to their potential owners, we must know who the owners are and what types of PV systems they are likely to prefer. All major new sources of electricity in the developed world must compete with utility-supplied power. It appears very likely that grid interconnection, with the grid supplying backup power and purchasing PV excess, will become the dominant system configuration. Beyond that, however, the preferred system configuration, size, and ownership are in much doubt. Small dispersed systems mounted on residential or commercial rooftops owned by homeowners, utilities, or businesses may become attractive. Larger industrial or utility central-station systems (e.g., ground-mounted) could prove to be commercially dominant. The attractiveness of photovoltaics may be strongly influenced by the tax and financial situation of the potential owner.

A second set of complications is introduced by the nature of the photovoltaic product and its interaction with the competition--grid-supplied power. Properly designed photovoltaic systems can supply ac electricity to the grid that is equivalent in a technical sense to the conventionally produced electricity the PV displaces.* Thus, under the assumption that energy markets are perfect, the "social value" of PV kilowatt hours can be defined as the private cost of producing those same kilowatt hours with the best alternative source, if PV is unavailable.** That is, society should be willing to pay no more for PV electricity than the entire cost of producing the same product with the best alternative source. Thus defined, the value of PV to society is a function solely of the cost of the competition.

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*Reactive power and harmonic content requirements have become important parameters in cost-effective power conditioning development.

**While energy market failures such as those arising from pollution and national security can be corrected for in principle, no analysis of the marginal product of photovoltaics (PV value) has yet attempted to do so.

In particular, the value of a photovoltaic system is defined as the combination of: (1) the savings of utility expenditures for conventional capacity (including its maintenance) and fuel that result from the photovoltaic system, and (2) the value of any changes in the costs of transmission, distribution and system operation occurring as a result of the system. Published, numerical estimates exist only for the first category of possible PV benefits. These estimates are difficult to produce and suffer significant conceptual ambiguities. Nevertheless, it is the sum of these conventional utility savings in fuel and capital (capacity) that constitutes the principal existing numerical measure of the potential value of photovoltaics.

When these basic savings are translated on a life-cycle basis into the actual savings realized by the system owner, they yield the PV system break-even price for that owner. This is the price at which a photovoltaic system can be purchased and still cost no more than the best alternative method of accomplishing the same electricity production. The Photovoltaics Program has selected price goals to guide its research and development that reflect present estimates of PV system break-even values.

Tables 3 and 4 present the primary cost (or price) goals of the National Photovoltaics Program for grid-connected markets. Note that the markets are divided into three segments--residential, intermediate-load center (ILC), and central (or utility) markets. The ILC market includes all distributed systems other than low-density residential housing (e.g., commercial and industrial buildings, schools, apartments). Not only do system sizes differ among these three application sectors, but also financial and tax environments and electricity rate structures differ substantially. Thus, break-even prices and the relative attractiveness of the various market sectors may also differ.

The tables show the distributed system price goal to be \$1.60/$W_p$ and the central station goal \$1.10 to \$1.30/$W_p$. Component Technology Readiness goals are set for 1982 and 1986, respectively, with System Readiness to occur in 1984 and 1988. These technical goals (which guide the PV Program) are scheduled to allow PV systems to become Commercially Available at the price goals as early as 1986 (distributed systems) and 1990 (central station).

The timing of these goals, especially the 1986 Commercial Availability goal, has been questioned. Many PV company managers and employees do not believe that this goal will be achieved, at least not by 1986. Furthermore, some industry members complain that the ambitious goals of the PV Program have reduced their credibility with potential customers and internal corporate decision-makers, because of present high prices for PV modules (\$10-\$30/$W_p$). Clearly, such potentially adverse consequences of PV Program goals and other management activities must be carefully assessed.

It is the express purpose of the DOE PV Program, however, to accelerate the development of new PV technology, thereby making inexpensive PV systems available earlier. JPL believes that selecting ambitious (and realistic) price goals is an important part of that effort, whose benefits outweigh potential harm. Of course, the PV R&D Program has less control over the attainment of Commercial Availability goals than it does over the technical development goals. Technical milestones should be set as early as is reasonable within budgetary constraints.

Table 3. Photovoltaic System Price Goals: Residential and Intermediate-Load Centers (1980 $)

| Application and Year of System Readiness | Location | Observed Range of Energy Prices (¢/kWh) | System Prices Required to Compete ($/W$_p$) | System Readiness Price Goal ($/W$_p$) | PV Energy Prices Assuming Price Goal is Met (¢/kWh) | |
|---|---|---|---|---|---|---|
| | | | | | 50% Sellback[(a)] | 100% Sellback |
| Residential | Phoenix | 4.5 - 5.7 | 1.35 - 1.80 | | 5.2 | 3.9 |
| 1984 | Miami | 4.3 - 5.5 | 0.85 - 1.20 | 1.60 | 6.9 | 5.2 |
| | Boston | 7.4 - 9.4 | 1.30 - 1.75 | | 8.7 | 6.6 |
| Selected Intermediate | Phoenix | 5.1 - 6.4 | 1.45 - 1.90 | | NA | 5.5 |
| Load Centers | Miami | 5.5 - 7.0 | 1.15 - 1.55 | 1.60 | NA | 7.3 |
| 1984 | Boston | 6.7 - 8.0 | 1.00 - 1.35 | | NA | 9.2 |

(a) Sellback refers to the ratio of the price a utility offers to pay for PV power over the price it offers to sell power to the PV system owner.

Source: National Photovoltaic Program Multi-Year Program Plan, U.S. Department of Energy, September 1980, pp. 2-3.

Table 4. Photovoltaic System Price Goals: Central Station (1980 $)

| Application and Year of System Readiness | Location | Break-Even System Prices $(\$/W_p)$ | System Readiness Price Goal $(\$W_p)$ | Resultant Energy Prices Assuming System Price Goal is Met (¢/kWh) |
|---|---|---|---|---|
| Central Station 1988 | Phoenix | 0.85 - 1.35 | 1.10 - 1.30(a) | 4.2 - 4.8 |
| | Miami | 0.65 - 1.25 | | 5.5 - 6.4 |
| | Boston | 0.75 - 1.30 | | 7.0 - 8.1 |

(a)The range reflects uncertainty about the best goal.

Source: National Photovoltaic Program Multi-Year Program Plan, U.S. Department of Energy, September 1980, pp. 2-3.

JPL believes that the primary technical goals of the Program are achievable, although recent budget reductions may delay achievement a year or more. Important members of the industry also believe that PV system prices substantially lower than present prices are achievable, and have made substantial financial commitments based on this belief.

For most customers a utility supplies more than simply a total quantity of kilowatt hours per period. Unless a customer has contracted for an interruptible supply and associated electricity rate, the utility also promises to supply kilowatt hours at precisely the time they are demanded. Viewed from the utility perspective, this implies that the utility not only must be prepared to supply the total energy demanded during a period, but must also have sufficient generation sources (capacity) to meet the instantaneous rate of demand at (almost) every moment in time. Since total demand seen by a utility can easily fluctuate by a factor of 2 or 3 over the course of a day or a season, utilities have been led to construct a mix of generation sources: some that operate most of the time (baseload), others that operate cyclically (intermediate), and a final category that generates only briefly during system peaks (peaking capacity).

Electric generation systems that exploit a resource whose supply is dependent on stochastic weather patterns--PV, run-of-the-river hydro, solar-thermal, wind--do not fit neatly into these traditional categories. On the one hand, they appear most like baseload systems in that their operating costs are low since their fuel is "free." This implies that such systems will practically always be dispatched first--they should always be operated when available. On the other hand, their output is less predictable and more intermittent than that of conventional baseload systems, implying that their contribution to the reliability of the grid is not directly comparable to that of any of the sources in the three conventional categories.

Since the outputs of weather-dependent sources have stochastic elements and are always dispatched when available, they are effectively removed from the control of the utility dispatcher--they assume the character of a negative load on the system (see Figure 4).

The computation of utility fuel and capital-cost savings expected to result from a given quantity of photovoltaic systems interconnected with a particular utility can be accomplished in four steps, each of which consists of a computer simulation of the predicted phenomenon. The first step consists of simulating the performance of the photovoltaic system(s) through time. This produces an output profile of photovoltaic electricity that is then subtracted from the projected utility load curve to yield the net load faced by the utility. In the second step, the reliability of the grid including the PV system is calculated. If the utility system is found to be more reliable than it was before the addition of PV, conventional units are withdrawn from the projected generation mix until the reliability of the grid returns to its previous (exogenously selected) value. The present value of conventional plant deferred represents the value of capacity displaced by PV (capacity credit). The third step involves the calculation of the projected production cost savings arising from the PV addition. To accomplish this the dispatch of the newly configured grid is simulated and the total projected costs for fuel and conventional plant maintenance are estimated. These are subtracted from the same results for the grid configuration without PV. This difference represents the short-run costs that the PV saves. Adding the present value of these projected savings to the present value of the displaced investment in conventional capacity (calculated above) yields the present value of projected utility conventional-generation cost savings resulting from the PV addition. The fourth and final step is to search all possible combinations of generation mixes with the PV included that satisfy the reliability constraint, looking for the mix that maximizes the total savings.

Each of these steps involves considerable complexity. PV system output is a complicated function of direct and diffuse insolation, cell temperature (and thus wind speed), tracking mechanism and location. Available weather data is insufficient to simulate adequately the performance of many types of PV collectors or of the simplest collectors in many locations. Since in practice only one year's PV output is simulated, variations in annual weather patterns and their interactions with electric demand have not been investigated. Adequate system lifetime performance data do not exist to predict confidently the performance degradation and lifetime of most PV systems.

Traditional utility methods for gauging system generation reliability (adequacy of generating sources), such as reserve margin and loss-of-load probability, are inadequate to capture the complex, stochastic contributions to generation reliability of PV and other weather-dependent sources. Reliability simulations must use much finer sampling intervals (e.g., hourly) and require theoretical extension to explore confidently the implications of positive PV output correlation with utility system demand. In addition, existing techniques do not adequately consider the effects of shorter PV installation lead times and the modularity of PV systems on optimal capacity expansion paths (as opposed to static optimizations for a given year in the future). And no attempt has been made to estimate the value of diversification of generation sources. While development of such techniques is actively sought by several research groups, considerable uncertainty surrounds present estimates of PV values (marginal product). This is especially true of estimates of PV capacity credits, which are not always negligible.

The value of PV decreases significantly as the total quantity of PV interconnected with a given grid increases. Since PV is available for only one-third of each day (eight hours out of 24), increases in PV penetrations can move rather quickly into baseload displacement, where the value of fuel displaced is small and where requirements for cycling baseload facilities introduce serious operational problems for the utility. The correlation between load and PV output is critical. Present evidence indicates that PV value may begin to decline almost immediately or may remain relatively constant until PV penetrations reach as much as 18% to 20% of energy produced. Wide variations across utilities and the analytical complexities involved have not allowed estimates of PV demand price elasticity to be made with confidence.

After projecting the direct fuel, capital and other costs saved by the utility as a result of PV generation, it is still necessary to translate these savings into a figure of merit that accurately describes the actual effect of the PV system on the balance sheet of the prospective system owner. The most widely accepted figure of merit is the net present value (NPV) of the total expected savings from the PV system over its lifetime. This NPV represents the total economic value of the PV system (expressed in constant dollars) and can therefore be compared directly with the total cost of the PV system--that is, the NPV of expected expenditures on the PV system during its lifetime. In order to solve for the break-even purchase price of the PV system, one simply subtracts from the value of the system (NPV of total savings) the NPV of all other PV system costs (except the purchase price). This value represents the maximum sales price the PV system owner could afford to pay for the installed PV system and still incur total expenditures no greater than he would with the best alternative electricity source.

An important complication is introduced to the analysis when prospective non-utility owners of PV systems are considered. The capital and fuel costs saved by a PV system are realized directly by the utility. Thus, these savings can be directly translated into after-tax cash flow savings of the utility. For non-utility owners, however, the savings are realized only indirectly--the savings of utility fuel and capacity charges must be transmitted through electricity prices (the rate structure) before they can be realized by non-utility PV system owners.

Congress has specifically addressed the issue of rates for small power producers and cogenerators in the Public Utilities Regulatory Policies Act (PURPA). Final rules have been promulgated recently (March 1980) by the Federal Energy Regulatory Commission (FERC) for PURPA with regard to these rates. FERC established the principle that rates must be set such that the entire net avoided costs* of the utility be returned to the small power producer or cogenerator while, simultaneously, the general consumers of utility

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*Net avoided cost is essentially the value (marginal product) of the PV system, at least for early PV units. There is uncertainty as to whether the actual application of net avoided cost will result in marginal or average product pricing.

power do not subsidize the purchase or operation of the small power producer or cogenerator.

With rates established in this manner, the non-photovoltaic customers of the utility will be no worse off and possibly better off with photovoltaic power systems operating within the utility than they would have been without the PV systems in existence.

Notwithstanding the considerable ambiguities and uncertainties surrounding computations of PV value to prospective PV purchasers, many researchers have published empirical results from investigations of simulated PV/utility systems. A summary of these, prepared for this publication, showed that PV break-even prices to utility purchasers in the United States as presently calculated generally fall in the range $0.40/$W_p$ to $1.10/$W_p$ (1980$) for results characterized as "base case." Non-base-case assumptions yield considerably higher and lower break-even prices. Capacity credits range from 0% to 40% of these values. Calculated break-even values for non-utility PV system owners, reported less often, are often as much as twice the value of utility-owned systems, primarily because of favorable tax and financial assumptions (e.g., financing of residential PV systems at traditional first-mortgage rates).

## THE COSTS OF PHOTOVOLTAIC SYSTEMS

Table 5 presents a recent summary of present PV system prices prepared by JPL's PV Lead Center. System prices for duplicates of existing designs are an order of magnitude greater than the break-even price estimates summarized above, and more for first-of-a-kind systems. This implies that PV systems currently cost approximately 10 times the value of these systems to prospective purchasers in grid-connected applications. Profound changes are required in present methods of configuring, designing, producing, and supplying photovoltaic systems if they are to become available at low enough prices to be practical sources of bulk power.

Successful firms in a private, competitive, grid-connected photovoltaic industry must be capable of producing PV systems at a total cost (including profit) less than or equal to the price at which they can be sold (the market price). We call this total cost the supplier's required price--the market price, which if attained (or exceeded), would allow him to pay all normal costs of doing business and to obtain (or exceed) a stated competitive rate of return on the equity invested in the business. It is the objective of the Program to develop requisite technologies to allow profitable production of PV systems at a required price equal to (or less than) the price goals of the Program.

To accomplish this, the Program has undertaken parallel cost-reduction activities aimed at reducing the cost of each element that constitutes an installed PV system. $0.70/$W_p$ collectors and associated power-conditioning components are to attain Technology Readiness by the end of FY82. Since, in most cases, only the collector technology is expected to differ between the two generations of PV technology, development of other components and complete systems is common between them--second-generation collector concepts will probably be substitutive in first-generation systems.

Table 5. Photovoltaic Systems Price* Status ($\$/W_p$, 1980)

| System Price Elements | Remote Stand-Alone | Residential | Intermediate | Central Station |
|---|---|---|---|---|
| Collector<br>Structures and foundations<br>Site and preparation<br>Field wiring<br>Lightning protection | \$13-\$25 | \$7-\$13 | \$7-\$20 | \$7-\$20 |
| Power processor<br>Electrical switchgear & wiring<br>Control building | \$1-\$2 | \$1-\$2 | \$1-\$2 | \$0.10 |
| Battery<br>Charger<br>Battery Bldg. | \$2-\$3 | NA | NA | NA |
| Sales Fee<br>Interest during construction<br>Design | First-of-a-kind<br>\$3-\$10<br>Duplications<br>\$2-\$5 | First-of-a-kind<br>\$10-\$12<br>Duplications<br>\$2-\$6 | First-of-a-kind<br>\$3-\$8<br>Duplications<br>\$1-\$14 | |
| Totals | | | | |
| First-of-a-kind | \$19-\$40 | \$18-\$27 | \$11-\$30 | \$10-\$30 |
| Duplicated design | \$18-\$35 | \$10-\$21 | \$ 9-\$26 | \$ 9-\$26 |

*Initial flat-plate silicon system prices, compiled July 1980.

Source: Photovoltaic Program Systems Development Plan, draft, U.S. Department of Energy (in press).

The Program has established a Price Goal Allocation (PGA) process through which the system price goals are allocated among the various cost elements. Table 6 shows an initial price goal allocation for a hypothetical $\$1.60/W_p$ residential photovoltaic system.

Table 6. 1986 Price Projections and Initial Price Goal Allocations: $10\text{-kW}_p$ Residential System (as of July 1980)

| | SYSTEM PRICE ELEMENT | INITIAL PRICE, $\$/W_p$ (1980 \$) | | | | ENERGY PRICE ELEMENTS, $\$/W_p$ (1980 \$) | | ENERGY PRICE, ¢/kWh (1980 \$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | FOB MANUFACTURER | MARKETING & DISTRIBUTION | INSTALLATION | SUBTOTAL | INITAIL INSTALLED SYSTEM PRICE | LIFE-CYCLE OPERATION & MAINTENANCE | PHOENIX | MIAMI | BOSTON |
| ARRAY | • COLLECTOR | 0.70 | 0.21 | 0.17 | 1.08 | 1.12 | 0.22 | 3.4 | 4.5 | 5.7 |
| | • STRUCTURES AND FOUNDATIONS | - | - | - | - | | | | | |
| | • SITE AND PREPARATION | - | - | - | - | | | | | |
| | • FIELD WIRING | - | - | 0.04 | 0.04 | | | | | |
| | • LIGHTNING PROTECTION | - | - | - | - | | | | | |
| POWER PROCESSOR | • POWER CONDITIONER | 0.20 | 0.10 | 0.04 | 0.34 | 0.34 | 0.22 | 1.4 | 1.9 | 2.4 |
| | • ELECTRICAL SWITCHGEAR AND WIRING | - | - | - | INCL. IN POWER COND. | | | | | |
| | • CONTROL BUILDING | - | - | - | - | | | | | |
| STORAGE | • BATTERY | - | - | - | - | - | - | - | - | - |
| | • CHARGER | - | - | - | - | | | | | |
| | • BATTERY BUILDING | - | - | - | - | | | | | |
| INDIRECTS | • DESIGN AND PROJECT MANAGEMENT FEE | | | | 0.07 | 0.14 | | 0.4 | 0.5 | 0.6 |
| | • SALES FEE | | | | 0.07 | | | | | |
| | • INTEREST DURING CONSTRUCTION | | | | - | | | | | |
| | TOTALS | 0.90 | 0.31 | 0.25 | | 1.60 | 0.44 | 5.2 | 6.9 | 8.7 |

ASSUMPTIONS

- 10% COLLECTOR AREA EFFICIENCY
- MARKETING & DISTRIBUTION: COLLECTOR 30%, STRUCTURE -%, POWER CONDITIONING & ELECTRICAL 50%, STORAGE & EQUIPMENT -%
- FEES: DESIGN AND PROJECT MANAGEMENT 5%, SALES 5%
- LIFETIMES: SYSTEM 30 years, ECONOMIC 30 years
- OPERATION & MAINTENANCE: $\$16/\text{kW}_p$/year
- UTILIZATION FACTOR (U): 0.63
- FIXED CHARGE RATE: 0.08
- DISCOUNT RATE: BEFORE TAXES 10%, AFTER TAXES (k) 6.5%
- SOLAR AVAILABILITY ($\text{kWh/kW}_p$/yr): PHOENIX 2350, MIAMI 1770, BOSTON 1400
- INFLATION RATE (g): 6%
- CAPITAL RECOVERY FACTOR: 0.077
- FACTOR TO CONVERT FROM LEVELIZED NORMAL TO REAL ENERGY PRICE (F): 2.10
- TRACT HOUSE

Table 7 shows a second level of the Price Goal Allocation process as applied by the LSA Project to the PV module for each of the five silicon sheet alternatives presently under development by LSA: Czochralski ingot (Cz), heat exchanger method ingot (HEM), edge-defined film-fed growth ribbon (EFG), dendritic web ribbon (web) and silicon-on-ceramic (SOC).

The module manufacturing process is divided into five basic activities, each of which is allocated a certain fraction of the total goal. Parallel paths are then pursued to attain each allocation. The allocations among the steps are arrived at through joint consideration of the technical opportunities thought to be available. There is no simple way to judge the acuity or the technical foresight of the experts involved with each piece in the puzzle. There are no reliable indicators of the technical promise of a particular field of scientific inquiry.

Fortunately, the PV development effort has progressed to a point where actual achievement can be gauged, especially with respect to flat-plate module development. From this evidence, a portion of which is summarized below, a feeling for the trend of recent and potential research activities can be obtained.

Attainment of the technical goals, however, does not guarantee that the new techniques will enter production, nor that market prices will quickly fall to competitive levels that reflect the new technology. Market dynamics of production investment and new-technology adoption are complex and cannot be forecast easily or controlled by federal action. If the efficient scales of production inherent in new PV technology are small relative to the likely size of available PV markets, however, then it is likely that a sufficient number of companies will adopt new technologies to lead to competitive markets. This underlines the importance of worldwide remote PV markets and the present expectation that efficient PV production need not require large scales. For example, analyses have shown that advanced flat-plate silicon PV collectors can be efficiently manufactured at a \$0.70/$W_p$ factory price at scales as low as 30 $MW_p$/year, requiring a capital investment, including silicon material refinement capacity, of no more than \$25 to \$50 million (Reference 3).

The photovoltaic collector is the heart of, and constitutes half of, the total cost of PV systems. Until recently, the commercial photovoltaic industry manufactured only flat-plate single-crystal silicon collectors (modules) and systems (this technology still dominates commercial sales). The solar cells are manufactured from wafers that are sawed from cylindrical ingots of single-crystal silicon produced by the Czochralski (Cz) growth method. Such modules presently sell for \$10 to \$30/$W_p$. Industrial production of these flat-plate modules can be divided into four steps: (1) refinement of pure polysilicon from quartzite (sand); (2) conversion of this polysilicon into a sheet material suitable for photovoltaic devices and collectors, (3) cell processing and module assembly, and (4) provision of suitable encapsulation materials and processes. Many present production techniques have been borrowed from the semiconductor industry.

A wide diversity of approaches have been proposed for reducing the costs of collector production. One important approach is highly incremental, relying on engineering development, automation and good production practice--the presently evolving advanced Cz technologies. Other approaches combine

Table 7. Price Allocation Guidelines (1980 $)

| Module Component | Guidelines | $\$/W_p$ For Each Sheet Alternative | | | | |
|---|---|---|---|---|---|---|
| | | Cz | HEM | EFG | Web | SOC |
| Silicon (polycrystalline) | 14 $/kg | 0.126 | 0.107 | 0.073 | 0.047 | 0.040 |
| Sheet alternatives: | | | | | | |
| Cz ingot and slicing | 27.4 $\$/m^2$ of wafer | 0.193 | --- | --- | --- | --- |
| HEM ingot and slicing | 36.3 $\$/m^2$ of wafer | --- | 0.256 | --- | --- | --- |
| EFG | 23.3 $\$/m^2$ of wafer | --- | --- | 0.205 | --- | --- |
| Dendritic web | 38.6 $\$/m^2$ of wafer | --- | --- | --- | 0.292 | --- |
| SOC | 19.8 $\$/m^2$ of wafer | --- | --- | --- | --- | 0.190 |
| Cell fabrication | 21 $\$/m^2$ of cells | 0.141 | 0.141 | 0.176 | 0.151 | 0.192 |
| Encapsulation materials | 14 $\$/m^2$ of module | 0.120 | 0.098 | 0.123 | 0.105 | 0.139 |
| Module assembly | 14 $\$/m^2$ of module | 0.120 | 0.098 | 0.123 | 0.105 | 0.139 |
| | | 0.700 | 0.700 | 0.700 | 0.700 | 0.700 |

Source: Aster, R. W., Price Allocation Guidelines, JPL Internal Document No. 5101-68, Rev. A., pp. 1-2, 1-4, Jet Propulsion Laboratory, Pasadena, California, 15 January 1980.

bold innovation in some steps with incremental improvements in others, e.g., sheets or ribbons of nearly single-crystal silicon grown directly from molten silicon, skipping the ingot growth and slicing steps but retaining other flat-plate silicon module processing steps and materials. Still other approaches suggest radical departures from present techniques such as abandonment of relatively thick silicon sheets in favor of concentrators or thin films of amorphous silicon and other PV materials.

Thick single-crystal and polycrystalline silicon sheets (50 micrometers or greater) formed by a variety of techniques and used in flat-plate and in several types of concentrating collectors constitute the presently Technically Feasible set. These collectors are undergoing technical and engineering development that is believed by the PV Program to have a high likelihood of achieving the $0.70/$W_p$ collector price goal with several production approaches.

Substantial research on other PV conversion materials, more advanced sheet technologies such as true thin films (e.g., amorphous silicon), and advanced concentrating devices is also supported. None of these materials or concepts has yet shown Technical Feasibility of sufficient cost reduction while retaining acceptable performance. Many are plagued by low sunlight-to-electricity conversion efficiencies and by PV conversion material degradation. Nevertheless, the promise they hold for inherently low material utilization and for mass production at very low costs would make them an extremely attractive option if their present limitations can be overcome. Furthermore, the wide variety of unexplored and interesting materials and concepts offers hope that a breakthrough in one area or another will make very low cost PV collectors ($0.15 to $0.40/$W_p$) feasible. Attainment of the $1.10 to $1.30/$W_p$ system price goal depends on such a breakthrough.

Photovoltaic collector technology may be on the verge of rapid evolution in several directions simultaneously. The details of that evolution cannot be predicted. Nevertheless, close examination of present technological status, its recent progress and proposed R&D investigations allows judgments to be made on probabilities of further success. To illustrate the status of flat-plate silicon collector technology development, silicon-sheet formation is briefly discussed below.

Choice of silicon sheet production technology is important to PV silicon module production since material utilization, module design and cell processing are often partially affected by this choice.* As mentioned above, until very recently all commercial collectors have been based on Cz single-crystal ingot growth and wafering (sawing), the technology designed to meet silicon wafer requirements of the electronics industry. Unfortunately, this technology has been quite expensive:

(1) It is a batch process--single-crystal ingots are grown from a silicon melt in crucibles. Crucibles are small (20 kg of silicon per crucible) and are not reusable.

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*Other important cost drivers in silicon module production include silicon material refinement, encapsulation, cell processing and module assembly.

(2) The wafering process is wasteful. Nearly 50% of the expensive ingot is lost as sawdust (the kerf loss), the wafers are thick, and the wafering is slow (1 wafer every 3 minutes).

The present market price of wafers ranges from $\$500/\text{m}^2$ to $\$800/\text{m}^2$.* The price objective of the government's silicon sheet technology development effort is $\$20/\text{m}^2$ to $\$25/\text{m}^2$, clearly a significant reduction.

Significant advances have been made in Cz ingot technology by developing low-cost processes such as continuous growth, silicon melt replenishment and advanced sawing techniques. Major government-funded developmental activity in these areas is pursued at Kayex Corp. and Siltec Corp. Both companies have successfully demonstrated continuous ingot growth with melt replenishment and are developing prototype automated ingot growers. Kayex has incorporated new features in its existing commercial grower and several PV companies have bought these new machines for production.

In addition to Cz ingot growth, development of cast ingots is receiving government funding at Crystal Systems, Inc., and Semix Inc., a subsidiary of Solarex Corp. Crystal Systems has demonstrated the casting of 45 kg of nearly single-crystal ingots by the heat exchanger method (HEM). The technology is well understood and scale-up of the process is under way. Crystal Systems has recently begun to market 10 x 10-cm HEM silicon wafers. Semix has constructed a small-scale commercial module production facility that uses its proprietary ingot-casting process and has announced plans to add 80 MW$_p$ of additional capacity by 1983. Flat-plate PV collectors using Semix wafers are now part of several PV Program system tests and are being marketed by Solarex. Both cast-ingot processes show significant prospects for cost reduction and for meeting the price goals for silicon-sheet development when combined with appropriate wafering techniques.

Low-cost wafering is important to the successful approach of the $\$0.70/\text{W}_p$ PV collector goal by any of the ingot processes. Several advanced wafering technology development efforts are under way. The key features of these processes are thinner kerf (lower sawdust loss), thinner wafers and higher throughput (1 wafer/minute). Multiblade slurry saws (MBS), multiwire fixed-abrasive slicing (FAST) and advanced inner-diameter (ID) saws are the three processes under development. A 1000-blade prototype MBS has been developed and is undergoing production testing at Semix. Fabrication of an automated prototype FAST machine, which is the prime process for achieving 30% kerf loss and 250-micrometer-thick wafers, is under way. Advanced ID technology is now entering the PV industry. Nevertheless, inexpensive, reliable wafering remains an important undemonstrated step in the production of silicon from silicon ingots.

A promising alternative to ingot growth and wafering is the growth of silicon sheets directly from a silicon melt, such as edge-defined film-fed growth and web dendritic growth of shaped ribbons. Both of these processes, which require much less silicon material than ingot sheets, have made significant technical progress. Mobil Tyco Solar Energy Corp., the developer of EFG,

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*A major source of dramatic reductions in transistor prices over the past 15 or 20 years has been advances that allowed more compact circuitry, thereby reducing requirements for these expensive silicon wafers.

has constructed a prototype production facility from which it is offering PV modules of EFG solar cells for sale. And Westinghouse, developer of web, has signed a cooperative agreement with Pacific Gas and Electric and Southern California Edison, two large West-coast investor-owned utilities, for funding of a 50 $kW_p$ web PV module production pilot facility including agreements for future commercial production and deployment. JPL believes that the probability is high that at least one of these ribbons will achieve the Technology Readiness $\$0.70/W_p$ price goal by 1983, if planned development activities are continued. In addition, the ribbons hold significant promise for further cost reduction.

Supported films (50 to 100 micrometers thick), such as the silicon-on-ceramic (SOC) process, are even more conserving of silicon material. The SOC process coats low-cost ceramic by skimming it over molten silicon. This process has demonstrated Technical Feasibility and prototype coating machines have been built. Large-area sheet coating is under way at Honeywell Corp., the SOC developer.

While flat-plate modules of solar cells produced from Cz silicon ingots remain the principal commercial photovoltaic technology, many doubt that this technology can be improved sufficiently to compete with other PV technologies in the long run. Nevertheless, progress in Cz technology has been favorable. An examination of that progress yields significant insight into the near-term future of the photovoltaic industry and into the nature of many of the developmental improvements in production technology that are sought. The Flat-Plate Solar Array Project believes that Cz technology is now capable of module production in advanced production facilities at a total factory price of less than $\$3.00/W_p$, and that expected technical improvements have a high probability of leading to $\$1.00/W_p$ technical capability by 1983. One major manufacturer (ARCO Solar, Inc.) has constructed a large advanced Cz production facility.

Given the importance of the projected costs of various production processes in the choice of which processes to pursue, it is essential that projections be done with consistent methodological approaches and assumptions, and that they be as accurate as possible. The Flat-Plate Solar Array Project has developed, documented, applied, and validated a method (SAMICS) of comparing experimental flat-plate PV module manufacturing processes in order to guide research priorities and to measure progress toward price goals.* Recently, the methodology has been successfully applied to other manufactured products. The PV Program is able to use SAMICS to produce standardized, comparable estimates of the manufacturing cost (the required price) of both major PV system components (i.e., collectors and power conditioners), with various prospective production processes, product designs, and plant sizes.

Table 8 presents SAMICS module required-price estimates at three times in the recent past (1976, 1978, 1980). The SAMICS estimates are module production required prices for the best production techniques thought to be available for incorporation into commercial production lines during that year (all employ Cz ingot technology). Actual commercial production facilities have been

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*The methodology is documented in a two-volume publication (Reference 9). SAMICS is the acronym for Solar Array Manufacturing Industry Costing Standards.

Table 8. History of Flat-Plate Silicon Module Required Prices

| Year of Technical Readiness | SAMICS Required Price Estimate ($/$W_p$) (1980$) |
|---|---|
| 1976 | 16.60 |
| 1978 | 5.54 |
| 1980 | 2.70 |

Source: Aster, R. W., and Henry, P. K., "1980 $2.80 Technical Readiness Assessment," presented at 16th LSA Project Integration Meeting, September 25, 1980.

constructed using all of the techniques assumed for the 1976 and 1978 estimates (although they are not all owned by the same company or located at the same facility). Present commercial PV module prices generally range from $10 to $30/$W_p$, depending on manufacturer and order size (prices as low as $7/$W_p$ have been reported for large orders). Before the PV Program, module prices generally ranged from $30 to $100/$W_p$. Further significant price reductions are expected soon.

Table 9 shows important technical improvements on the horizon for flat-plate silicon modules. Some of these could possibly be implemented in production facilities by 1982; many are now being tested or readied for testing in pilot plants. An additional group is expected to be ready for implementation by 1986.

Three basic concentrator concepts, whose development is managed by Sandia National Laboratory, are leading contenders for PV applications. These are parabolic reflective troughs and linear-focus and point-focus Fresnel lenses. Each has characteristics that may make it desirable for particular applications.

Parabolic troughs use a curved reflective surface to concentrate sunlight onto a linear receiver. Since these units are actively cooled, they are suited for use in applications where the removed thermal energy is of economic value. Because the maximum operating cooling-water output temperature for most actively cooled concentrators is only about 100°C, the thermal energy is useful only for space heating and water heating and other low-temperature applications.

Fresnel lenses make excellent optical concentrators. Measured efficiencies are 80% to 87%, comparing favorably with the best measured optical efficiency of parabolic troughs (83%).

Table 9. Major Improvements Foreseen in Flat-Plate Silicon Module Technology

| Near-Term Improvements | Additional 1986 \$0.70/$W_p$ Improvements |
|---|---|
| Semix ingot | Silicon material refinement options |
| HEM cast ingot | Silicon-on-ceramic sheet |
| EFG sheet | Ribbon-to-ribbon silicon sheet |
| Web sheet (50 $kW_p$ pilot) | Full integration and automation of production facility |
| Molybdenum-tin metallization | |
| Ion implant junction formation | |
| Plating metallization | |
| Improved sawing | |

Source: Aster, R. W., and Henry, P. K., "1980 \$2.80 Technical Readiness Assessment," presented at 16th LSA Project Integration Meeting, September 25, 1980.

In addition to optical concentrators, a concentrator collector contains concentrator PV cells and a receiver and associated cooling equipment onto which the cells are mounted. Since much less cell area is required (due to the concentration), concentrator cells can be much more expensive per unit than those in flat-plate collectors, thereby allowing more attention to be devoted to improving their efficiency and performance. However, the operating environment for concentrator cells is much more extreme with wider, faster temperature cycling. This has created substantial problems with material compatibility (e.g., cell materials, adhesives, substrates, encapsulants) and reliability in concentrator cell assemblies. Single-crystal silicon is the only material presently targeted for use in \$0.70/$W_p$ concentrator modules by the PV Program.

There are two major categories of cell receiver and assembly development: linear cell assemblies for parabolic troughs and linear Fresnel lens applications, and point-focus cell receivers for use with point-focusing Fresnel lenses. A significant amount of reliability and durability testing has been done on linear and point-focus cell receivers in the past year. Receivers have experienced technical difficulties and failures due to a variety of causes, including extreme operating conditions. Most of these difficulties have solutions, and at least one cell receiver and assembly has demonstrated reliable operation. In addition, an automated concentrator cell receiver assembly machine has demonstrated feasibility and reliable operation. However, the ability to produce low-cost, reliable cell receivers and assemblies remains an undemonstrated major step in concentrator collector development.

Initial SAMICS estimates for two concentrator collectors have been produced (Reference 10). Table 10 reproduces results of that analysis. Technology presently available (1980) for production of linear parabolic trough and linear Fresnel-lens PV arrays is modelled in this SAMICS analysis. Required price estimates are \$7.71/$W_p$ and \$7.59/$W_p$ respectively. PV concentrator cells are assumed to be purchased by the receiver/collector plants.

An area of concern for concentrator collectors is their life expectancy, performance and reliability. Sparse data on concentrator performance and reliability exist. Sandia remains confident that cell receiver, performance, reliability, and cost uncertainties facing concentrator collectors will soon be overcome.

Whether the Program and the photovoltaic industry can succeed at the system level is another principal remaining uncertainty in photovoltaic development. The techniques of research, directed technology development and engineering improvement employed by the projects charged with PV collector development are the same processes applied to all PV system hardware components. In some cases this requires substantial redesign and engineering (e.g., residential power conditioners); in others it requires an analysis of requirements and an investigation or search for the minimum-cost solution.

As discussed above, system costs may differ significantly among applications. Large ground-mounted systems appear to have few important cost uncertainties other than low-cost, reliable, efficient collectors. Smaller distributed systems face larger cost uncertainties.

## SOCIETAL IMPLICATIONS

The techniques reviewed above for estimating the value of future grid-connected PV systems and for setting Program price goals employed estimates of prices and conditions in future electricity markets. This approach accepts private market conditions and prices as socially optimal.

In an ideal market economy, prices correctly measure producers' marginal production costs as well as the marginal valuations of products by consumers. Prices act as rationing devices, allocating available supplies among demanders. Prices act as signalling devices to consumers, identifying bargains and overpriced products, and to businesses, identifying industries where entry is profitable. Prices direct the dynamic adjustment of an economy toward long-run equilibrium in which all of the profitable opportunities available in the economy are fully exploited. Under ideal conditions, markets are efficient in the sense that the market prices of commodities incorporate all of the information available concerning the future price prospects for the commodity.

Actual markets, however, fail to exhibit these perfect characteristics for a number of reasons. If property rights are unenforceable, (e.g., in a patent or a proprietary process) if markets are not perfectly competitive, or if the commodity is partly or wholly a public good (national security,

Table 10. 1980 Commercial Concentrator-Collector Technology Required-Price Analysis Summary (SAMICS Model Results)

| Company Summary | Parabolic Trough | Linear Fresnel |
|---|---|---|
| Total employees | 77 | 156 |
| Factory floor space | 45,000 ft$^2$ | 96,000 ft$^2$ |
| Capital investment ($M) | | |
| Equipment | 0.7 | 1.3 |
| Facilities & land | 3.1 | 6.5 |
| Working capital | 2.1 | 3.4 |
| Annual Sales ($M) | 25.5 | 46.4 |
| Return on investment | 21% | 21% |
| **Array Price Summary** | | |
| Receiver assembly | \$556/m$^2$ | \$500/m$^2$ |
| Collector & structure | 138/m$^2$ | 335/m$^2$ |
| Total | 694/m$^2$ | 835/m$^2$ |
| | \$7.71/Wp | \$7.59/Wp |

Source: Photovoltaic Concentrator Technology Development Project, 6th Project Integration Meeting, Fall 1980, Albuquerque, New Mexico.

pollution abatement, information) then a market failure occurs and private market prices will not correctly reflect the consumption of productive resources.* In addition, government regulation and taxes have apparently distorted many private markets.

It is well known that energy markets fail from a variety of important causes. These include air and water pollution, nuclear safety and waste disposal, and vulnerability to international political blackmail. Electric utilities are regulated monopolies, thereby introducing the effects of nonoptimal price regulation as well as complex effects on the ability of utility executives to diversify risks optimally, especially in generation and fuel

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*In a Pareto optimal sense. Failure can also arise in general equilibrium. High transaction costs can prevent many otherwise valuable transactions, especially in the presence of uncertainty, moral hazard, and dynamic adjustment.

portfolio, interconnections and power transfer. Photovoltaic systems offer real opportunities to reduce some of these harmful side effects if they can be manufactured at competitive costs. Photovoltaic systems have apparent environmental and national security benefits compared with conventional power sources. In addition, the modularity and simplicity of PV systems may allow customer and third-party ownership, thereby promoting competitive electricity generation.

Potential adverse environmental consequences from large-scale production, installation, operation and decommissioning of PV systems have been alleged, however. Considerable attention has been directed at the potential consequences of silicon mining, refining and sheet conversion, especially with respect to silicosis. While control of silicon dust and silicon and silicate fumes from refining may be required, the potential incremental risk to the general and worker population from properly designed and operated silicon mining and production facilities does not appear large. Uncertainty clouds some potential dangers, such as exposure to silicon and silicon oxide fumes, but the primary impact of these is on control technology requirements and costs. A major expansion of the silicon photovoltaic industry would add only modestly to the existing demand for silica in steel refining.

Even though the potential use of cadmium and arsenic in cadmium sulfide-copper sulfide and gallium arsenide PV cells has drawn widespread speculation about possible acute and chronic exposure to these poisons (such as in roof fires or in collector fabrication), the actual risks do not seem to be substantial to the general or worker population (Reference 11). Potential worker exposure requires further investigation and development of appropriate control technology.

Control of hazardous chemicals and agents used in cell production is quite important. While cost impacts of environmental control technology have not been fully assessed, the technology is available. Automation of collector production will greatly lessen potential worker exposure to hazardous agents. The safe disposal of hazardous waste products from PV collector and system production is not a major technical or economic problem.

Estimates of worker accidental injury and death during system production and installation have been produced. The simplicity and repetitiveness of PV production and installation operations should promote the development of standard and safe operating procedures. While the hazards from electrocution and other accidents are not insubstantial, they do not appear to be different from those found in similar traditional production and construction industries.

Although large-scale development of photovoltaic systems poses some environmental concerns associated with extracting and processing large amounts of materials, these concerns appear relatively benign compared with similar problems associated with coal-based technologies. The materials needed to sustain large-scale photovoltaic development are obtainable without straining the productive capacity of the nation. Silicon and glass production would have to increase significantly, but given sufficient lead times there are no inherent barriers to this expansion. Significant price increases due to scarcity of PV production materials does not seem to be an important danger.

Ground-mounted photovoltaic power systems presently require 5 to 10 acres per $MW_p$. Thus, a one-quad deployment of photovoltaic power systems by the year 2000 would require approximately 400 $mi^2$ of PV panels. A reduction in this land requirement to 3.5 to 5 acres per $MW_p$ may be expected in the future as PV efficiencies increase.

In comparison, a coal facility that produces an equivalent energy output requires about 0.5 acres for the coal-fired plant and 1.5 acres for 20 years of coal strip mining. Thus, land requirements for ground-mounted PV systems will be 2 to 7 times that of coal-fired facilities. (Land devoted to PV materials mining and production is negligible.)

Microclimatic effects may arise in association with large-scale photovoltaic systems. Shading of the ground surface will result in a significant reduction of surface temperature. In addition, the collectors will substantially deflect surface wind flow with a consequent reduction in wind velocity in the interior of large array fields. These effects will result in reduced evapotranspiration and, hence, conservation of soil moisture. The microenvironment within the panel field will be cooler and moister than the surrounding undisturbed area. In arid locations, species diversity, standing biomass and energy flow rates could all increase if local vegetation is allowed to remain within the construction area.*

Mesoscale impacts of very large facilities (2 $mi^2$) may be considerable. Installation and operation of photovoltaic collectors will cause signficant changes in the surface characteristics in the area of the facility. Potentially, these changes could lead to local variations in wind, temperature and humidity.

If the photovoltaic industry and the Program are successful in their search for grid-competitive PV systems, rapid expansion in PV capacity appears possible. Thus, PV development can be viewed as an insurance against unfortunate developments with respect to other electricity generation options. Rapid expansion of coal-fired electric generation, for instance, may produce hard evidence on $CO_2$ emissions and acid rain that would make further expansion unacceptable. In this case, if PV were ready for rapid expansion it would be a valuable asset for the nation. This view places a premium on large ground-mounted PV systems as the nature of small residential and other dispersed systems inherently resists rapid increases in deployment rates. (Even if very large numbers of newly constructed homes incorporate PV systems, the rate of PV expansion will be small compared to total U.S. electricity demand.)

## CONCLUSION

### RATIONALE FOR NATIONAL PHOTOVOLTAICS PROGRAM

The National PV Program plays an important role in PV development and technical advance. Federal sponsorship has greatly increased PV R&D activity.

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*Land surfaces would be stablized and the general area could be enhanced by such a practice. This seems preferable to paving or irreversibly compacting large tracts of land.

The substantial uncertainties that still cloud PV's future and the nonappropriability* of many PV developments would probably lead to a substantial reduction in PV research and development if government support is severely curtailed. R&D would likely be re-oriented toward nearer-term remote market applications and narrowed to only a few approaches that appear promising to one firm or another; activities would become more sequential. Advanced collector development may be continued by a few firms, while new device and material research would be pursued in universities and other non-profit research centers, but probably at a much less vigorous pace. System development for grid-connected markets would fall very substantially.

While the presence of government funding has increased the pace and scope of PV research and development activities, it does not guarantee, a priori, that the developments actually forthcoming will be attractive to industry. JPL believes that a continuous dialogue and interaction between the PV Program and the PV industry is the most fruitful and judicious method by which government-funded development activities can be kept relevant and applicable. Given that the objectives of industry and government do not always coincide, the interactive process involves both cooperation and tension. Opinions differ widely among various PV industrial participants on the promise of PV, the significance and likely effects of forthcoming developments, and the most beneficial role for government sponsorship.

As discussed above, it is the prominence of failures in energy markets that provides the primary motivation for government action. These failures, however, do not necessarily require government-managed energy R&D programs. In fact, most economists would argue that the most direct and efficient policy for counteracting an external cost is an excise tax on the offending transaction (e.g., an oil importation tax) equivalent to the marginal external cost at equilibrium. A second-best solution is the subsidization of substitutes for the undesirable commodity. For example, existing federal subsidies to solar energy and energy conservation are often interpreted in this way.

Nevertheless, government sponsorship of energy R&D is prominent, and there are persuasive arguments in its favor. One such argument arises from the non-appropriability of information, the output of research and development. It is extremely difficult to reap the eventual benefits of much research activity. Technological insights gained after years of hard work and expense may be instantly applied by many firms without adequate compensation to the originator. While governments have passed patent and copyright laws to increase the probability of sufficient reward to technological advance, much research output cannot qualify. This argument applies with more force the further from commercial application (more basic) the research activities and information sought. The National Photovoltaics Program spent $40 million in FY80 out of a total R&D budget of $120 million supporting university and private laboratories doing basic physical research and exploratory development into photovoltaic materials and collector concepts.

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*Potential patentability is unlikely to provide much motivation to basic PV research activity.

A more powerful argument in favor of government support for patentable developments is the socially efficient nature of free information. Since the sharing of existing information does not deplete its source (it is a public good), the marginal production cost and socially efficient price of existing information is zero. Free access (other than charges for costs of transmittal) to existing information produces socially efficient use of that information, but runs directly counter to the patents and industrial secrecy meant to encourage efficient production of new information. Through the sponsorship and coordination of contracts whose relevant results enter the public domain, government can simultaneously encourage efficient production and use of new information. This may be important in the development of complex, highly interdependent new technologies, and may have implications for the conduct and funding of technology development objectives in free societies.

The federal Program structure and design are important to its success. While the success of any individual R&D effort cannot be predicted in advance, sufficient redundancy is established at each major cost driver to obtain reasonable probabilities of Program success. This process has several important advantages. It allows small firms, groups, or individuals to propose very specialized research on one step or another, while the Program provides assurance that all activities undertaken are relevant to the objectives. It encourages firms to share information on the status and promise of their R&D activities, thereby giving rise to much R&D cross-fertilization.

The PV Program has increased the pace and vigor of PV R&D activities and the interest and investment in PV by private industry. There is significant hope that PV system prices can soon fall to levels that make them attractive in utility-interactive applications within the United States. Continuation of the PV research and development Program to its conclusion in the mid-80s may yield substantial social and economic benefits to the United States and the world.

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