Photovoltaics

Jeffrey L. Smith

For the past 6 years the federal government has supported a substantial research and development program on terrestrial photovoltaic (PV) systems. The object is to develop PV systems that will be capable of producing electricity at prices competitive with those of conventionally produced power (*1–3*). At present, PV systems produce electricity at $0.50 to $2 per kilowatt-hour, roughly an order of magnitude higher than the cost of electricity supplied by electric utilities. Hence the primary objective of the program is to reduce the costs of PV collectors and systems through technological and engineering advances.

The federal program is closely linked with and dependent on cost-reduction activities of the private PV industry and vanced production facilities. However, there are critical uncertainties that must be resolved before terrestrial application of PV systems can begin to have a significant impact on the supply of bulk electricity in U.S. or world markets.

Summary. The federal government has sponsored a program of research and development on terrestrial photovoltaic systems that is designed to reduce the costs of such systems through technological advances. There are many potential paths to lower system costs, and successful developments have led to increased private investment in photovoltaics. The prices for photovoltaic collectors and systems that appear to be achievable within this decade offer hope that the systems will soon be attractive in utility applications within the United States. Most of the advances achieved will also be directly applicable to the remote markets in which photovoltaic systems are now commercially successful.

is designed to foster the evolution of a competitive industry that can supply PV systems to major electricity markets (*2*). 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 being sponsored by the program; they are coordinated through a highly structured, goal-oriented process that has been designed and implemented by the Department of Energy and several national laboratories.

In this article I review some of the technical progress achieved in this program. Successful developments have led to substantially increased private investment in photovoltaic R & D and to ad-

The author is a staff economist in the Photovoltaic Lead Center, Jet Propulsion Laboratory, Pasadena, California 91109.

Potential for Terrestrial Application of Photovoltaic Systems

Photovoltaic systems employ semiconductor materials to convert a small fraction of visible light to electrical energy. Powering spacecraft with sunlight was their first important practical application, and 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. Power requirements are small, and the systems are usually remote from human habitation and the conventional energy supplies of electric utilities.

A small, highly competitive U.S. industry has sprung up to supply PV systems for this worldwide market; its generating capacity during 1980 was approximately 4.2 peak megawatts (MWp) (*4*). This corresponded to a total sales revenue of approximately $40.7 million, about one-fourth of the present annual federal PV program budget (*5*). French, German, and Japanese competition is challenging the early lead held by U.S. companies in this fledgling industry.

Although most PV manufacturers remain preoccupied with expanding these and other power markets remote from conventional electricity supplies—for instance, supplying power for villages and for water pumping (*6*)—there is reason to believe that PV systems can be useful in supplying power to modern electric utilities. Opportunities for technological advances in photovoltaics are broad and substantial, and such advances may result in the development of PV systems that will be competitive in bulk electricity markets. However, most of the advances in PV technology that will enable profitable application in U.S. utilities will also be directly applicable in remote markets. And as PV prices fall, increases in demand for remote PV systems may allow commercial application of new technological developments.

There is considerable uncertainty about the future costs and availability of conventional sources of electricity (hydropower, oil, natural gas, coal, and nuclear power). Athough several of these sources could conceivably develop and expand to meet all of our future needs for electricity at reasonable total costs, questions about fuel availability, siting, cost, and environmental effects cloud their future and encourage a search for new sources of power. In addition to photovoltaics, potential alternative sources of power include fusion, solar thermal energy, wind, ocean thermal energy, coal gasification, and magnetohydrodynamics. Each potential source should be pursued in proportion to the net social benefits expected from its development. There is also considerable uncertainty about the levels and patterns of future demand for electricity. Thus it is not possible to predict accurately the extent to which deployment of PV systems (or other new sources) may become attractive.

Photovoltaic systems have many attractive features. They are highly modular; a basic PV unit (flat-plate module) typically generates 10 to 100 peak watts. Present systems are usually no larger than a few hundred watts, but systems generating hundreds of megawatts are under development. The high degree of modularity adds flexibility to the siting (and testing) of PV systems and allows land-use impacts to be minimized. In addition, it permits large systems to be manufactured by mass-production techniques; thousands of identical components can be produced and installed in an identical manner, promoting standardization of components and systems. (Exploiting this characteristic is part of the PV program's cost-reduction strategy.) Photovoltaic capacity can be added in small increments, so that PV systems

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can enter the rate base (generate revenue) much 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.

In addition, PV systems can be silent, can be passively cooled, and can have no moving parts, depending on the specific technology employed. They emit no effluents and their manufacture need not produce harmful emissions or waste products. The dominant PV 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.

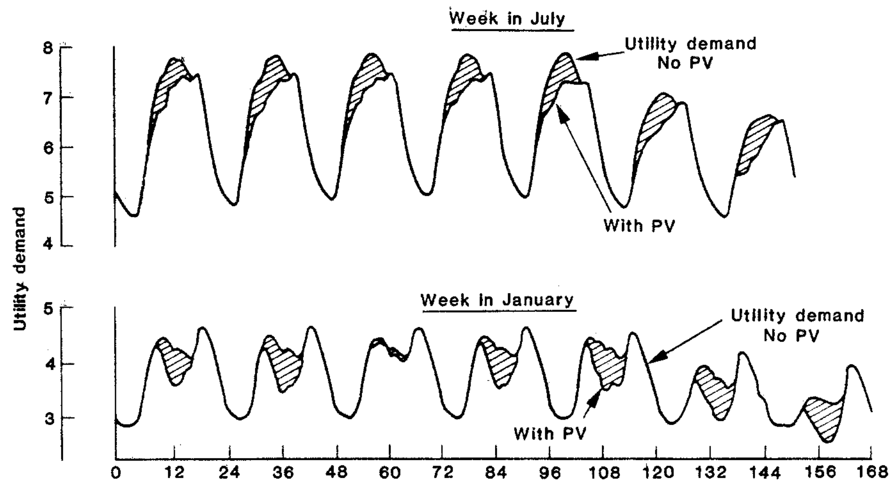

Fig. 1. Simulation of a utility load profile with and without photovoltaics in the southwestern United States. Utility demand (gigawatts) is plotted against time (hours); the shaded area shows PV output. Adapted from (*20*).

A major disadvantage of photovoltaics, however, is the intermittent and unpredictable nature of sunshine. This contributes to the high cost of present PV systems, and it has led many observers to conclude that electrical storage must become an integral part of PV systems and PV research. For example, an energy study group sponsored by the Ford Foundation concluded that "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" (*7*).

This conclusion is not correct when grid interconnection is possible. 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, there is sufficient unused generating capacity to satisfy electrical demands. An interconnected arrangement can prove beneficial to the PV system owner, to the electric utility, and to its customers.

Figure 1 shows the simulated effect of including 800 MWp of PV-generated electricity on the net load seen by conventional generators in a southwestern utility. In this hypothetical case, photovoltaics produces 3 to 4 percent 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 additions of capacity from other generating sources. At worst, all non-PV capacity additions may still be required, although the optimal configuration (mix) of grid generating sources may be altered by the presence of photovoltaics. In most cases, the primary benefit of PV additions to utilities will be displacement of conventional fuels such as oil, coal, and uranium, although photovoltaics is likely to be deployed earlier in areas where capacity credits will also accrue (*8*).

Somewhat surprisingly, where photovoltaics is most useful its addition to utility grids may reduce the value of additions of electrical storage systems and vice versa. Until PV capacity supplies a high proportion of total grid generation, storage systems will be charged primarily during periods when photovoltaics is not producing (for example, 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 photovoltaics is producing. Electrical storage and PV systems are thus substitutes for each other; each derives value from production during high marginal-cost periods. Addition of interconnected PV systems may reduce the incentive and need for electrical storage in the short run (*9*). On the other hand, if PV capacity becomes large, or if photovoltaics is added to utilities whose peak and shoulder periods occur primarily after dark, storage and PV systems will be complementary. There appear to be no insurmountable technical problems in fully interconnecting PV systems with electric grids, even at the end of distribution feeders (for instance, residential PV systems). At larger PV penetrations, stability and control of the grid could pose substantial difficulties.

If PV systems can be produced cheaply enough, there do not appear to be technical barriers to their practical use for supplying modern electric utilities. In addition to direct application in the developed world, there is a large potential for profitable applications by less-developed countries as they expand their utility systems. Finally, the possible role of photovoltaics in moderating harmful local and global environmental effects of electricity generation should be considered.

Recent Technical Progress in Photovoltaics

Prototype grid-connected PV systems are in experimental development and performance testing. A significant commercial market does not exist at the present costs of such prototype systems, which range from \$15 to \$60 per peak watt. It is expected that simple, flat-plate silicon systems will soon become available at prices near \$10 per peak watt; however, analyses indicate that this will still be five to ten times the price at which photovoltaics will become widely attractive in the United States (*10*).

To accomplish the significant cost reduction needed for photovoltaics to become an important source of electricity in the developed world, the federal PV program includes activities aimed at reducing the cost of each element of an installed PV system. To guide this effort, the program has adopted the goals of achieving technical capability that will allow commercial market prices for installed PV systems of \$1.60 per peak watt by 1986 and \$1.10 to \$1.30 per peak watt by 1990 (in 1980 dollars) (*11*). From these system goals, the derived goals for PV collector development are \$0.70 per peak watt for 1986 and \$0.15 to \$0.40 per peak watt for 1990. Principal activities of the program are directed toward technical advances that will lead to these commercial objectives. In particular, all PV system components (including collectors) are to demonstrate technical readiness 4 years before the goals cited above (that is, in 1982 and 1986, respectively) and complete PV systems are to demonstrate system readiness by 1984 (*12*). In most cases, only the collector technology is expected to change greatly; second-generation collector concepts will probably be substitutive in first-generation systems.

Attainment of the technical goals does not guarantee that the new techniques will enter production, or that market prices will quickly fall to competitive levels that reflect the new technology. The market dynamics of production investment and new technology adoption are complex and cannot be forecast completely, or controlled completely by federal action. However, if the efficient scales of production inherent in new PV technology are small relative to the likely size of available PV markets, then it is more likely that a sufficient number of firms will adopt the new technology 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 factory price of $0.70 per peak watt at scales as low as 30 MWp per year [requiring a capital investment of $25 million to $50 million (*3*)].

The PV collector forms the heart of, and constitutes half of the total cost of, PV systems. Cost-reduction activities in the PV program began in 1975 with silicon flat-plate collectors and have made significant progress. More recently, concerns have surfaced about the attainability of system price goals even if collector development is successful. As discussed further below, these concerns appear unwarranted, at least for large, ground-mounted systems (*13*), although important questions concerning system design and configuration require resolution through engineering tests and analyses.

Collector Cost Reduction

Until recently, the commercial PV 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 $20 per peak watt. Present industrial production of these flat-plate modules can be divided into four steps: (i) refinement of pure polysilicon from quartzite (sand); (ii) conversion of this polysilicon into a suitable sheet material for PV devices and collectors, (iii) provision of suitable encapsulation materials and processes, and (iv) cell processing and module assembly. Many production techniques have been borrowed from the semiconductor industry.

A diversity of approaches has been proposed for reducing the costs of collector production. One important approach is highly incremental, relying on engineering development, automation, and good production practice; this is the approach taken in the evolving advanced Cz technologies. Other approaches combine bold innovation in some steps with incremental improvements in other steps—for example, growing sheets or ribbons of nearly single-crystal silicon 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 abandoning relatively thick silicon sheets in favor of concentrators or thin films of amorphous silicon and other PV materials.

Many of these proposals for collector cost reduction have received significant government R & D support; successful activities continue to receive PV program funding. The program has divided collector concepts into two broad groups, depending on present technological status. Collectors that use thick sheets of silicon (approximately 50 micrometers or thicker) as the PV conversion material are now considered technically feasible. This formal milestone implies that a PV conversion material (and associated collection devices) is a candidate for development to attain a factory price of $0.70 (or less) per peak watt (*14*). Single-crystal and polycrystalline thick silicon sheets formed by a variety of techniques, and used in flat-plate collectors and several types of concentrating collectors, constitute the presently technically feasible set. These collectors are undergoing technical and engineering development to achieve the collector and system price goals ($0.70 and $1.60 per peak watt, respectively) by 1986 with several production approaches.

Substantial research on other PV conversion materials, more advanced sheet technologies such as true thin films (for instance, amorphous silicon), and advanced concentrating devices is also supported by the program. None of these materials or concepts has yet shown promise of sufficient cost reduction combined with acceptable performance to be designated technically feasible. Many are plagued by low efficiencies for conversion of sunlight to electricity and by degradation of PV conversion material. Nevertheless, their potential for inherently low material utilization and for mass production at very low cost would make them extremely attractive if their present limitations could 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 per peak watt) feasible. Attainment of the system price goal of $1.10 to $1.30 per peak watt by 1990 depends on such a breakthrough.

Some of the more fully developed collector production techniques are beginning to be used commercially. Private funding of both R & D and production facilities is expanding rapidly. Six firms have completed or begun construction of privately funded pilot and commercial production facilities using advanced collector technologies, including polycrystalline silicon ingot, silicon ribbon, advanced Cz, and cadmium sulfide cells; others may soon be introduced. Some of these technologies have been developed primarily with private funding and some with government sponsorship.

Thus PV 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 its present status, its recent progress, and proposed R & D investigations gives some basis for judgments on probabilities of further success. Only a portion of recent and anticipated PV developments can be reviewed below; other important areas (for instance, concentrators) are unavoidably slighted. A more complete review of PV technical status is given in (*15*).

Silicon Materials

Until recently, all the silicon material used in semiconductor and PV applications was manufactured by a technique known as the Siemens process, which produces high-purity trichlorosilane from quartzite and then decomposes the trichlorosilane, yielding a deposit of pure silicon. The process is designed to yield a nearly pure product suitable for fabricating microelectronic devices. (Reductions in impurities also improve PV conversion efficiencies.) However, the process is characterized by high energy consumption, a low deposition rate in a batch process, and a high production cost ($80 per kilogram).

The objective of the PV program's silicon cost reduction task is to develop technology capable of producing silicon profitably at $14 per kilogram or less (*16*). The leading government-funded technology that has the potential to meet this price goal is being developed by Union Carbide Corporation, Sisterville, Wisconsin. It produces silane from metallurgical grade silicon (which sells commercially for $2 per kilogram) and subsequently produces nearly pure silicon by pyrolysis. This process differs significantly from the current Siemens process in the following features: (i) lower energy consumption (26 percent of Siemens energy requirements), (ii) higher throughput rate (300 percent increase), (iii) continuous operation, and (iv) closed-cycle production. The technical feasibility of every phase of this process was established (in 1975 to 1978) through extensive laboratory experiments and operation of a process development unit. A detailed process design for an experimental facility with a capacity of 100 metric tons per year and a functional process design for a commercial plant producing 1000 tons per year have been prepared to develop an overview of process costs. An experimental system development unit (100 tons per year) is under construction to test and demonstrate the process. The product price required to cover all costs at a capacity of 1000 tons per year is projected to be $10 per kilogram. Union Carbide is expected to construct a commercial facility if the experimental facility is successful and will license the technology to competitors.

Another silicon material process under PV program sponsorship at Hemlock Semiconductor Inc., Hemlock, Michigan, is based on the Siemens approach, but with significant variations: (i) dichlorosilane is used instead of trichlorosilane, (ii) a higher deposition rate (300 percent increase) is achieved, and (iii) less energy is consumed (18 percent of the Siemens requirements). There is a high likelihood of technical success with this process, which was demonstrated to be technically feasible in 1980. The product price is projected to be less than $20 per kilogram.

Hemlock and other developments have led to increased understanding of the Siemens refinement process. Several manufacturers are modifying or planning to modify existing Siemens capacity to take advantage of this understanding. At least five separate approaches to modification of Siemens reactors have been identified, of which the Hemlock process is the most advanced. These modifications allow less expensive production, often by increasing throughput and thus reactor capacity.

Table 1. Required prices for flat-plate silicon modules (*21*).

Year	SAMICS price estimate (1980 dollars per peak watt)
1976	16.60
1978	5.54
1980	2.70

Several additional silicon material cost reduction approaches have been proposed and funded by government or private industry (Battelle Laboratories, Columbus, Ohio; SRI International, Inc., Menlo Park, California; and Texas Instruments, Inc., Dallas).

Large-Area Silicon Sheet

The choice of production technology for silicon sheet is important for PV silicon modules, since material utilization, module design, and cell processing are often 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. This technology has been quite expensive for two principal reasons. First, it is a batch process in which single-crystal ingots are grown from a silicon melt in crucibles. The crucibles are small (typically, 20 kg of silicon per crucible) and are not reusable. Second, the wafering process is wasteful. Nearly 50 percent of the expensive ingot is lost as sawdust (the kerf loss), the wafers are thick, and the wafering is slow (one wafer every 3 minutes). The present market price of wafers ranges from $500 to $800 per square meter. (Dramatic reductions in transistor prices over the past 15 or 20 years have been made because of advances that allowed more compact circuitry, thereby reducing requirements for these expensive silicon wafers.) The price objective of the government's effort to develop silicon sheet technology is $20 to $25 per square meter, a considerable reduction.

Significant advances have been made in Cz ingot technology by developing low-cost processes such as growth of larger ingots (150 kg per crucible), silicon melt replenishment, and advanced sawing techniques. Major government-funded developmental activity in ingot growth is pursued at Kayex Corporation, Rochester, New York (Hamco), and Siltec Corporation, Menlo Park, California. Both companies have successfully demonstrated continuous ingot growth with melt replenishment and are developing prototype automated ingot growers. Hamco has incorporated new features in its existing commercial grower, and several PV companies have bought these new machines for production. (Silicon sheet technology based on this process is discussed further below.)

In addition to Cz ingot growth, development of cast ingots is receiving government funding at Crystal Systems, Inc., Salem, Massachusetts, and at Semix, a subsidiary of Solarex, Rockville, Maryland. 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 HEM 10 by 10 centimeter silicon wafers for $6 per wafer ($600 per square meter). Semix has constructed a small-scale facility for commercial module production employing its proprietary ingot-casting process. Flat-plate PV collectors with 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 an important factor in successfully reaching the PV collector goal by any of the ingot processes. Several efforts to develop advanced wafering technology are under way, employing multiblade slurry saws (MBS), multiwire fixed-abrasive slicing (FAST), and advanced inner-diameter (ID) saws. The key features of these processes are thinner kerf (lower sawdust loss), thinner wafers, and higher throughput (one wafer per minute). A 1000-blade prototype MBS has been developed and is undergoing production testing at Semix. Fabrication and testing of an automated prototype FAST machine, which is the prime process for achieving 30 percent kerf loss and 250-micrometer-thick wafers, is under way. Advanced ID technology is now entering the PV industry. Reliable, low-cost wafering remains an important, undemonstrated step in the production of silicon sheet from silicon ingots.

A promising alternative to ingot growth and wafering is growth of silicon sheets directly from a silicon melt, such as edge-defined, film-fed growth (EFG) and web dendritic growth (web) of shaped ribbons. Both of these processes, which require much less silicon material than do ingot sheets, have made significant technical progress. Mobil Tyco Solar Energy Corporation, Waltham, Massachusetts, the developer of EFG, has constructed a prototype production facility from which it is offering PV modules of EFG solar cells for sale. And Westinghouse Electric, the developer of web, has signed a cooperative agreement with Pacific Gas and Electric and Southern California Edison, two large investor-owned utilities, for funding of a pilot facility for 50-kWp web PV module production, including future commercial production and deployment. Jet Propulsion Laboratory's low-cost solar array (LSA) project, which manages flat-plate module development efforts for the PV program, considers it likely that at least one of these ribbons will achieve the price goal of $0.70 per peak watt by 1983 if planned development activities are continued. In addition, the ribbons hold promise for further cost reduction.

Supported films 50 to 100 μm thick, such as those manufactured by the silicon-on-ceramic (SOC) process, are still more conserving of silicon material. In the SOC process, low-cost ceramic is coated 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, Inc., Bloomington, Minnesota, the SOC developer.

Czochralski Ingots: Technical Progress

Production of flat-plate modules of solar cells from Cz silicon ingots remains the principal commercial PV technology. Many doubt that this method can be improved sufficiently to compete with other PV technologies in the long run.

Table 2. Description of major technological improvements incorporated in estimates of Table 1 (*21*).

1976	1978	1980
Capacity, 500 kWp One-shift operation Cz wafers (3-in. diameter) purchased from semiconductor firms Module size, 1 × 2 ft	Case ground rules All equipment and processes must be in full-scale production somewhere in the industry Not required that all equipment and processes be colocated	Case ground rules All equipment and processes must be in use or proven and available for purchase, installation, and commercial operation by late 1982; all parameters very well known
Pa/Ni-plate metallization Cell efficiencies, 10 to 12% Silicone encapsulants Required total investment, $4.5 million	General Production year, 1980 Factory size—5 MW/year Three shifts per day, 7 days per week, for ingot growth and slicing One shift per day, 5 days per week, for all other work stations Required total investment, $14 million	General Full-scale production start late in 1982* Factory size, 30 MW/year* Three shifts per day, 7 days per week, for all work stations* Required total investment, $33 million
	Silicon material Polysilicon cost, $84 per kilogram	Silicon material Polysilicon cost, $84 per kilogram†
	Module design and performance Cell diameter, 4.015 in. (102 mm) Module, 2.5 × 4 ft (0.76 × 1.22 m) Glass superstrate, polyvinyl butyral, Crane glass, Tedlar Extruded aluminum frame Packing factor, 77% Module efficiency, 9.47% Encapsulated cell efficiency, 12.3% Module performance, 88 Wp per module Series-paralleling, 11 cells per string, 8 parallel strings Bypass diode	Module design and performance Cell diameter, 4.015 in. (102 mm) Module, 4 × 4 ft (1.22 × 1.22 m)* Glass superstrate, ethylene vinyl acetate*, Crane glass, Tedlar No frame* Packing factor, 78% (round cells)* Encapsulated cell efficiency, 12.3% Module performance, 143 Wp per module* Series-paralleling, 11 cells per string, 13 parallel strings* Bypass diode
	Ingot growth Cz ingot per crucible, 1 to 20 kg	Ingot growth Cz ingot per crucible, 2 to 26 kg*
	Ingot sawing ID sawing, 25 mils per slice plus kerf Sawing rate, 1.5 in./min Sawing yield, 95% Saws per operator, 3 Blade life, 2500 slices	Ingot sawing ID sawing, 20 mils per slice plus kerf* Sawing rate, 2.0 in./min* Sawing yield, 95% Saws per operator, 5* Blade life, 3100 slices*
	Cell processing Texture-etched $POCl_3$ junction formation Aluminum back surface field Clean and brush Printed silver front and back contacts ($18.40 per ounce of silver) Cell processing yield, 87%	Cell processing Texture-etched $POCl_3$ junction formation Aluminum back surface field Clean and brush Printed silver front and back contacts ($18.40 per ounce of silver) Cell processing yield, 89.1%*
	Module assembly Cell stringer—$75,000 each Cell stringers per operator, 1 Module test yield, 90%	Module assembly Cell stringer, $200,000 each* Cell stringers per operator, 4* Module test yield, 99%*

*Indicates change from 1978 case. †Cost in 1980 dollars.

Table 3. Commercial technology value added (*21*).

Product step	Value added (1980 dollars per peak watt)	
	1978	1980
Ingot growth (including silicon)	2.83	1.63
Sawing	0.86	0.37
Cell processing	0.65	0.36
Module assembly (including encapsulated material)	1.20	0.34
Total	5.54	2.70

Nevertheless, progress in Cz technology has been rapid. An examination of that progress yields insight into the near-term future of the PV industry as well as the nature of many of the improvements in production technology sought. The LSA project considers that Cz technology is now capable of module production in advanced facilities at a total factory price of less than $3 per peak watt, and that expected technical improvements have a high probability of reducing this to $1 per peak watt by 1983. One major manufacturer, Arco Solar, Inc., in Camarillo, California, has constructed a large advanced Cz production facility.

Table 1 presents module prices estimated by the SAMICS (*17*) computer program at three different times in the recent past: 1976, 1978, and 1980. The SAMICS estimates are module prices based on the best production techniques thought to be available for incorporation into commercial production lines during that year (all employ Cz ingot technology); they cover all costs of producing and selling modules, including competitive rates of profit. Commercial production facilities have been constructed using all the techniques assumed for the 1976 and 1978 estimates (although not all at the same facility). Actual market prices are lagging behind available technology by approximately 2 years, which is about the time needed to incorporate major new technical developments. Of course, it is necessary that improvements be generally incorporated by the industry and that other conditions be fulfilled, including market demand conditions, before market prices can reflect new production technology. Recently, module prices have stabilized in the range $10 to $20 per peak watt. Demand has apparently grown faster than capacity. However, as advanced production facilities attain their potential during the next several years, module prices should substantially decrease, unless very rapid demand growth continues.

Table 2 summarizes the production steps assumed to be available in each of the three cases of Table 1, with emphasis on the 1978 and 1980 technologies. Table 3 shows a breakdown of SAMICS prices for the 1978 and 1980 technologies into value added by each of four major production steps.

A gauge of the sources of the technological improvements realized in Cz ingot technology between 1978 and 1980 can be found in Table 4. The most important changes were (i) pulling of two ingots per crucible instead of one; (ii) production of thinner wafers with lower kerf loss (25 percent improvement); (iii) redesign of module and support, eliminating the module frame; (iv) greater automation and larger production scale resulting in increased module yield; and (v) continuous operation of all production steps. The improvements are highly incremental, often resulting from improved engineering and good industrial practice.

System Costs

Considerable attention has been focused on elements of PV system cost other than the collector—the balance-of-system costs. Recent investigations have shown that these costs differ significantly among potential PV applications and system sizes.

For at least one important application—multimegawatt, ground-mounted, flat-plate systems—attainment of system price goals appears relatively straightforward. Land costs are likely to be less than 5 percent of total system costs. Inexpensive structures can be fashioned from 4 by 4 inch wooden trusses anchored in backfilled dirt trenches. Inexpensive power-conditioning devices (inverters) can be adapted easily from existing commercial converters used in applications such as high-voltage d-c transmission. The modularity of these simple systems greatly enhances potential economies in installation, finance, shipping, and maintenance. Attainment of collector cost goals is the crucial cost uncertainty facing these large, ground-mounted, flat-plate systems.

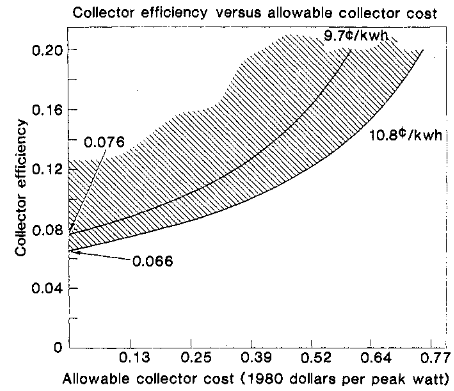

Fig. 2. Collector efficiency versus allowable collector cost.

Collector efficiency is an important driver of system costs, since many important costs are related to system area (land, structures, wiring). Since higher collector and system efficiencies reduce the area required per unit of power out, area-related costs can be reduced by increasing collector efficiency. Figure 2 illustrates this trade-off for a particular

Table 4. Sources of changes between 1978 and 1980 technologies (*21*).

Production step	Parameter	1978	1980	Change (1980 dollars per peak watt)
Ingot growth	Ingots per crucible	1	2	0.40
Sawing	Slice and kerf (mils)	25	20	0.39
	Saws per operator	3	5	0.18
	Blade life (slices)	2500	3100	0.02
Aluminum back	Yield, percent	98	99	0.04
	Printers per operator	2	3	0.02
Silver front and back	Yield, percent	98	99	0.08
	Printers per operator	2	3	0.04
Lamination	Throughput rate (modules per minute)	0.2	0.3	0.03
Edge trim and seal	Frame	Yes	No	0.48
Module test	Yield, percent	90	99	0.50
				2.18
Shifts per day		One*	Continuous	0.54
(Miscellaneous)				(0.12)
Total cost ($/Wp)		5.54	2.70	2.84

*Except for ingot growth and sawing, which are continuous.

flat-plate PV system design by showing the relation between collector efficiency and allowed collector cost for systems that produce power at 9.7 and 10.8 cents per kilowatt-hour. This trade-off is dependent on assumed PV system design and system costs other than the collector. The shaded area in Fig. 2 indicates points with lower energy costs than the 10.8 cent/kWh isoenergy cost line. Note that with this PV system design and costs and with collector efficiencies below 6.6 percent, it would not be possible to produce power at less than 10.8 cent/kWh, even if the collectors were free.

Other system concepts may face more formidable cost obstacles. Small distributed systems require substantial power-conditioning development and may have substantial indirect costs—for example, for marketing and distribution. [More complete reviews of various potential applications and systems can be found in (*15*)].

The Photovoltaics Program

Federal sponsorship has greatly increased photovoltaic R & D activity. Because of the uncertainties that still cloud the future of photovoltaics and the nonappropriability of many PV developments (the potential for profits from patents is unlikely to provide much motivation for basic PV research), there would probably be a substantial reduction in photovoltaic R & D if government support were severely curtailed. Furthermore, important market failures (*18*) present in energy markets (for instance, pollution, national security, and monopoly) give incentives to government that are not found in private markets to pursue technologies, such as photovoltaics, which promise to reduce such externalities.

The structure and design of the PV program are important to its success. Its management is decentralized. National laboratories with considerable technical competence in photovoltaics and proven success in the management of large complex R & D programs have been given responsibility for implementation. Specific goals are selected and detailed plans are proposed to attain them (*1*). The production of PV systems is divided into a number of steps, and parallel contracts are let with private industry and universities (most of the R & D proposals originate with the contractors) to attain the targets for each step. While the outcome of any individual R & D effort cannot be predicted in advance, there is sufficient redundancy to give reasonable probabilities of success.

This structure has several advantages. It allows small firms, groups, or individuals to propose very specialized research on one step or another, while providing assurance that all activities undertaken are relevant to the objectives of the program. It encourages firms to share information on the status and promise of their R & D activities; in contrast, a large private firm attempting the same PV development effort would be motivated to conceal its activities and developments. [Efficient use of existing information in R & D activities is discussed more fully in (*19*).]

The PV program has increased the pace and vigor of R & D activities and the interest and investment in photovoltaics by private industry. Continuation of this program to its conclusion in the middle 1980's (*1*) may yield substantial social and economic benefits.

References and Notes

1. *Multi-Year Program Plan, National Photovoltaics Program* (Department of Energy, Washington, D.C., 30 September 1980).
2. Solar Photovoltaic Energy Research Development and Demonstration Act of 1978 (Public Law 95-590, 92 Stat. 2513).
3. *Federal Policies to Promote the Widespread Utilization of Photovoltaic Systems* (Jet Propulsion Laboratory, Pasadena, Calif., 1980), vols. 1–3.
4. Photovoltaic systems are rated at their power output under standard illumination (irradiance) and weather conditions that correspond roughly to ideal conditions at sea level.
5. Energy Information Agency semiannual survey.
6. 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 (for instance, Catalina and Molokai) are also supplied primarily by diesel generators. These markets may support significant expansions of the PV industry.
7. H. H. Landsberg, *Energy: The Next Twenty Years* (Ballinger, Cambridge, Mass., 1979).
8. While photovoltaics may displace significant quantities of oil in a few areas of the country (for instance, Hawaii and California), reducing oil consumption is not its primary potential benefit. Electric utilities consume only 10 percent 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 in electric utility boilers and elsewhere (for example, home heating) may already have been taken before competitive PV systems become generally available [J. L. Smith, *Photovoltaics as a Terrestrial Energy Source*, vol. 1, *An Introduction* (Jet Propulsion Laboratory, Pasadena, Calif., in press)]. Opportunities for displacement of oil in foreign countries could be more substantial.
9. 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.
10. J. L. Smith, *Photovoltaics as a Terrestrial Energy Source*, vol. 2, *System Value* (Jet Propulsion Laboratory, Pasadena, Calif., in press).
11. These price goals include all costs of supplying acceptable quality a-c power to the grid, including interface costs. At $1.60 per peak watt, PV systems will produce power at 5 to 10 cents per kilowatt-hour, depending on location.
12. In essence, achievement of technical readiness implies that (i) the production equipment or machinery for competitively priced production of PV components has been designed, built, and demonstrated in small pilot facilities; (ii) prototype collectors and other components have been produced and field-tested; and (iii) analysis indicates that full-scale integrated facilities would meet the price goals. Thus technical readiness implies that construction of full-scale facilities is the only remaining step to demonstrate fully the achievement of total production costs that will allow profitable sale of PV collectors and other components at prices meeting the program component price goals, given competitive markets. No PV collector concept is considered technically ready for grid competitive applications at present, and none is expected to become technically ready before the end of fiscal 1982. System readiness implies that PV systems have been shown, in prototype facilities and related analyses, capable of meeting system price goals in commercial-scale facilities.
13. Roof mounting of PV systems is also attracting much attention.
14. Requirements for the technically feasible rating include a minimum conversion efficiency of 10 percent, reproducibility and stability of the material, environmental acceptability, and amenability to development of low-cost production equipment.
15. J. L. Smith, *Photovoltaics as a Terrestrial Energy Source*, vol. 3, *System Cost* (Jet Propulsion Laboratory, Pasadena, Calif., in press).
16. This goal is derived from consideration of PV values and costs in a process known as price goal allocation [R. W. Aster, "Price allocation guidelines," internal document 5101-68, Jet Propulsion Laboratory, Pasadena, Calif. (1980), revision A].
17. Solar Array Manufacturing Industry Costing Standards (SAMICS) is a computer program for estimating the manufacturing costs and selling prices of advanced PV collectors and other assembly-line products, given estimates or measurements of the technical parameters that govern production.
18. Private markets fail when they do not yield product prices that reflect correctly at the margin all social costs and benefits.
19. J. L. Smith, *Photovoltaics as a Terrestrial Energy Source*, vol. 5, *Strategy of the National Photovoltaics Program* (Jet Propulsion Laboratory, Pasadena, Calif., in press).
20. "Integration of PV units in electric utility grids: Experiment information requirements and selected issues," ATR-80(7694-21)-1, Energy and Resources Division, Aerospace Corp., El Segundo, Calif. (1980).
21. R. W. Aster and P. K. Henry, paper presented at the 16th LSA Project Integration Meeting, Pasadena, Calif., 25 September 1980.

22. This article is excerpted from J. L. Smith, *Photovoltaics as a Terrestrial Energy Source* (Jet Propulsion Laboratory, Pasadena, Calif., in press), vols. 1–5. Significant contributions to this article were made by T. W. Hamilton and K. M. Koliwad.