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Solar Photovoltaic Power Systems: An Electric Utility R & D Perspective

Edgar A. DeMeo and Roger W. Taylor

Ten years ago, photovoltaic energy conversion was a little-known technology that had found an important niche in the supply of electric power to spacecraft. The ability to convert sunlight directly into a few hundred watts of electricity for extended periods without excessive weight justified the very high costs of photovoltaic (PV) space-power systems, reported to be several hundred dollars per watt. While a few members of the fledgling solar energy community had visions of billions of watts from inexpensive PV power plants at some point in the future, most observers saw the achievement of bulk power from PV as extremely unlikely.

Summary. Solar photovoltaic technology is receiving increasing attention as a prospective source of bulk, electric utility power within the next 10 to 20 years. Successful development will require solar energy conversion efficiencies of about 15 percent for photovoltaic flat-plate modules, or about 25 percent for photovoltaic cells using highly concentrated sunlight. Three different cell technologies have a better than even chance of achieving these target efficiencies with costs and operating lifetimes that would allow significant use by electric utilities. The challenge for the next decade is to push photovoltaic technology to its physical limits while expanding markets and user confidence with currently available systems.

Today, the concept of photovoltaic power, or solar cells, is generally familiar to a sizable segment of the public. Remote power and consumer product markets have developed that support a rapidly growing business, estimated to exceed \$80 million in 1982 sales (*1*). Perhaps more significant, PV power is receiving increasing attention from the U.S. electric utility industry as a potential source of bulk electricity supply within the next 10 to 20 years. Annual Electric Power Research Institute (EPRI) surveys of U.S. electric utility activities in solar energy indicate a steady growth in efforts related to PV. Over the period 1976 to 1982, the number of reported PV projects increased from 5 to 74, and the number of utilities reporting the projects increased from 5 to 41 (*2, 3*).

What has occurred over the past decade to bring about such an increase in national awareness of PV? The single most important factor has been the attention given to PV research and development by the U.S. federal energy program. Since the 1973 oil embargo, federal programs have focused some \$700 million on PV, with a peak annual budget of \$150 million in 1980 (*4*). Although the rapid growth of the federal PV budget in the late 1970's compounded the challenge of effective program management, a great deal of excellent work has been carried out with public funds in the research, development, deployment, and testing of PV cells, components, and systems (*5*).

Attention from the private sector was also extensive over this period and continues to grow. It is generally thought that private funding for PV research has exceeded federal funding for several years. An emerging PV industry supplies systems and components for remote applications such as mountain-top communications relay stations and for consumer products such as calculators and battery chargers. But, to an ever-increasing extent, this industry has its eye on potential billion-watt markets such as village power systems for developing countries and, as costs are reduced further, bulk utility-interconnected applications (*6*). The international utility market could indeed reach tens of gigawatts per year after the turn of the century, corresponding to sales revenues in excess of \$20 billion annually.

Photovoltaic power is an inherently appealing technology. It offers electricity from sunlight with few, if any, moving parts. The prospect of unattended operation with very low maintenance requirements is highly attractive. A PV system is silent and promises minimal environmental impact. The technology is also highly modular, so that large systems could be constructed by aggregating a number of small identical systems. Above a system-size threshold that may be as low as 1 megawatt, economies of scale in capital and operating costs are expected to be small. This last feature may be of crucial importance to the advancement and acceptance of PV as a utility power technology, because (i) experience and cost reductions resulting from the development of intermediate markets such as village power will be directly applicable to bulk-power PV systems, and (ii) prospective large-scale users such as utilities can obtain significant experience with PV systems that are small relative to conventional generating units, minimizing the utilities' financial exposure. New technologies whose initial introduction requires large financial risks will experience great difficulty in moving forward even if promising in the long run; because of the regu-

Edgar A. DeMeo is Solar Power Systems Program Manager at the Electric Power Research Institute (EPRI), Palo Alto, California 94303. Roger W. Taylor is Project Manager, Photovoltaic Systems Development, at EPRI.

lated nature of the utility business, such risks cannot be commensurately rewarded in the event of success.

Compared to the late 1970's, when solar energy R & D funds were readily available, energy issues were afforded crisis status, and general economic conditions were less restrained, the climate today for renewable-energy technologies such as solar and wind power is considerably subdued. Nevertheless, PV technology is alive and well. While evolution into a bulk-power option for electric utilities cannot be assured, PV seems to enjoy the greatest technical momentum of all the emerging renewable technologies.

Requirements for Utility Bulk-Power Applications

For PV systems to make a significant contribution of energy toward future electricity requirements in the United States, the cost of electricity from such systems must become comparable to that for other new generation options. The allowable price for an individual installation will be fixed through the interaction of a large set of factors—some technical and others, more difficult to quantify, institutional or political. However, it is possible to establish general cost and performance targets without resorting to detailed site- and utility-specific analyses. With the aim of aiding in the establishment of R & D priorities for PV cells and systems, both general (*7*) and utility-specific analyses (*8–10*) have been conducted. The current understanding is described in detail in (*11*).

Utility-interconnected PV systems, whether small rooftop installations or large central stations, must be considered in the context of long-range utility system planning. Utilities generally decide on the installation of a new generating plant on the basis of life-cycle costs, which include capital costs (construction costs including financing charges) and operating costs (fuel, and operations and maintenance costs) over the useful life of the facility. Of course, the fuel for PV systems, sunlight, is free; but this advantage is countered by high capital costs for the solar collection and conversion hardware.

One way to combine capital and operating costs on a consistent basis is shown in Fig. 1, where estimates of levelized electricity cost (*12*) for a range of new conventional generation alternatives are plotted against capacity factor (*11*). Capacity factor is the ratio of the average power output of a plant over a specified period of time to its rated power output. When the required capacity factor is above 15 to 20 percent, new coal plants are projected to provide the least expensive electricity. Oil-fired plants are projected to be more cost-effective if they are required to operate for only a few hundred hours per year. Clearly, if PV systems are to become a significant source of energy, they must be able to generate electricity at costs below those for oil. Whether they must compete directly with electricity from coal will depend, in large part, on the influence of institutional and resource-availability issues, which in turn will depend on the utility.

As a baseline for determining PV cost and performance targets, an allowable current-dollar levelized energy cost of 15 cents per kilowatt-hour has been chosen, corresponding to 6.5 cents per kilowatt-hour in constant 1982 dollars. As seen in Fig. 1, this cost is midway between projected energy costs with new oil plants and new coal generation and is comparable to the cost of energy from new coal plants operating at capacity factors that can be expected from PV generation.

In making the comparison in Fig. 1, it is assumed that the technologies considered can provide the same level of service—specifically, energy and capacity on demand over useful operating lifetimes of 20 to 30 years. Photovoltaic generation, because it depends on the weather, does not meet the on-demand criteria. In utility systems where increased capacity is the driving force for new generation and where the increase in utility system electrical load-carrying capability attributable to PV is small compared to the installed PV capacity, the allowable levelized electricity cost may be substantially lower than the baseline current-dollar 15 cents per kilowatt-hour assumed in this article.

On the other hand, there is a near-term opportunity for PV systems in areas where utilities are heavily dependent on oil. The Public Utility Regulatory Policies Act of 1978 established the right of small power producers (non–utility-owned generation less than 80 MW in size) to interconnect with and sell power to utilities at "avoided cost." Avoided cost is "the cost of energy to the utility, which, but for the purchase, the utility would generate itself or purchase from another source" (*13*). This provision has often been interpreted as meaning energy from oil. Until most of the oil is displaced by new generation (installed by the utility, purchased from a neighboring utility, or purchased from non–utility-owners), the small power producer is in a favorable position to sell power. Coupling this favorable selling situation with present tax incentives can provide the catalyst for early installation of systems that would otherwise be noneconomic. The systems being installed today because of the combined incentives will provide a significant amount of early operating experience that will be valuable in determining the operational advantages and limitations of PV systems.

However, as more oil is displaced, the favorable avoided-cost situation will become less significant and the allowable cost of PV systems will drop. Thus, a cost target comparable to that shown in Fig. 1 must be met in the long term if PV systems are to become a major, sustainable generation option.

Central stations, rather than rooftop systems, are likely to dominate future PV installations. Both technical and economic considerations lead to this conclusion. Product marketing and distribution costs contribute substantially to the installed price of home appliances and building products. If large numbers of small systems must be deployed, it is not likely that the business costs of the wholesale-retail chain can be avoided (*14*). Direct sale of megawatts of modules for central stations is likely to be the easiest way to minimize marketing and distribution costs. In addition, very few organizations or individuals, other than utilities, make purchase decisions based on 20- or 30-year life-cycle economics. Other more commonly used criteria such as after-tax return on investment and short-term simple payback lead to allowable costs significantly lower than those derived from life-cycle comparisons (*14*). Finally, a number of unresolved issues concerning interconnection of distributed systems will become important at moderate and high levels of local use. These issues include requirements for d-c isolation or dedicated transformers; the quality of relays required in protection circuitry; the need for, and location of, power factor correction capacitors; metering and load-reporting requirements; allowable levels of harmonic distortion; and concerns about utility system protection. Safety of personnel and equipment is a primary concern at all levels of use (*14, 15*). These interconnection requirements translate directly into increased system costs.

The costs of product marketing and distribution, stringent purchase criteria, potentially expensive interconnection requirements, and a host of institutional issues such as liability, code requirements, and insurance all make it unlikely that distributed rooftop PV systems will be a major new source of electricity in the United States. Stated in different terms, at significant levels of energy production (hundreds of megawatts per year), the allowable factory selling price of PV systems can be highest in sales to large-scale installations financed by utilities (or investors, depending on the tax laws at the time).

What are reasonable long-run efficiency and module cost targets? In order to answer this it is necessary to estimate PV system performance at various sites and non-PV (balance-of-system, or BOS) costs. To determine the output of a PV system one must take into account (i) the availability of insolation (concentrators use only the direct component of solar radiation, while flat-plate arrays use both direct and diffuse radiation) and (ii) module and BOS performance. Estimates of plant degradation over time due to dirt accumulation or module failures must also be considered. The primary result of a performance calculation is the number of kilowatt-hours per year for the specified plant. Implicit in the analysis is an assumption of PV component and system reliability consistent with 20- to 30-year operating lifetimes.

Balance-of-system costs (all components, labor and overhead, exclusive of PV module or receiver costs) can be divided into area-related and power-related costs. Area-related costs include those for array structure and foundation, sunlight-concentrating components (if used), site preparation, roads, fences, land, and array installation. Power-related costs include those for d-c and a-c wiring, the d-c to a-c power conditioning subsystem, and the high-voltage transformer (*16*).

For a 100-$MW_{a\text{-}c}$ fixed flat-plate system, BOS costs have been estimated at about \$50 per square meter plus \$130 per kilowatt. For a concentrating system of comparable size, BOS costs are estimated at about \$200 per square meter plus \$180 per kilowatt. While these costs have yet to be achieved, there is wide agreement within the PV systems engineering community that they are achievable (*16–21*). With estimates of the indirect costs (engineering fees, owner's costs, contingencies, and interest during construction—expressed as a percentage of direct costs) and operation and maintenance costs (plant supervision, security, array cleaning, module replacement, and general maintenance), it is possible to derive the allowable cost and required performance of PV modules necessary to meet the target cost of electricity (*11*).

Figure 2 shows the resulting cost-performance trade-off for fixed flat-plate

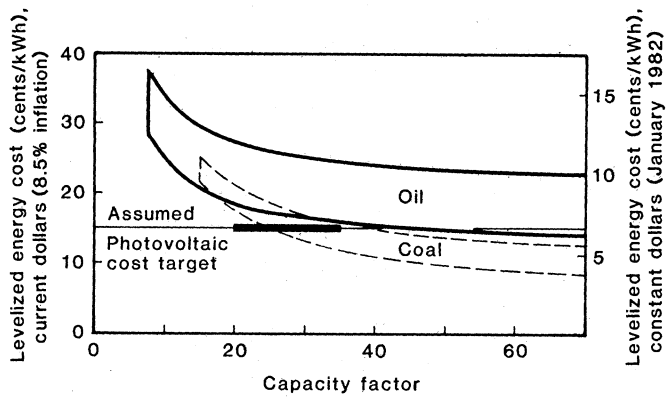


Fig. 1. Levelized electricity cost versus capacity factor for a range of conventional generation options. Levelized electricity cost (*12*) is presented in both current- and constant-dollar terms over the period 1982–2012, using costs that reflect installation in 1990. Assumptions include a 30-year plant life, 15-year book depreciation (appropriate for fossil plants; solar plants can use 10-year depreciation), and a 12.5 percent discount rate. Plant capital costs, fuel costs, and fuel escalation rates are consistent with the EPRI Technical Assessment Guide (*37*). The lower extreme of the oil cost range represents less expensive residual oil in a modern advanced combined-cycle power plant; the upper extreme represents more expensive distillate oil in a fuel cell. The coal range includes conventional coal with flue gas desulfurization and gasification-combined-cycle units with a range of coal cost assumptions. The assumed PV levelized electricity cost target is 15 cents per kilowatt-hour in current-year dollar terms (including the effects of general inflation), approximately equivalent to 6.5 cents per kilowatt-hour in constant 1982 dollars (excluding inflation).

systems in three regions of the United States. Under the assumptions used in Fig. 2, if 15 percent–efficient flat-plate modules can be manufactured and delivered to a desert site in the Southwest for about \$100 per square meter, a system can be built which generates electricity for the target value. To generate electricity at the same cost in Boston requires higher efficiency or a much lower delivered module cost, or both.

Concentrating PV systems require additional consideration, since they have features and components, such as sun tracking and lenses or mirrors, not found in most flat-plate systems. In concentrating systems, the "receiver," which is a packaged PV cell designed to handle and benefit from very high levels of light intensity, is likely to be much more costly per unit of cell area than cells intended for flat-plate modules. However, the receiver's contribution to the system cost per unit of array aperture is reduced in proportion to the concentration ratio. The cost of power transistors and integrated circuits is generally estimated at about \$1 per square centimeter. If sophisticated concentrating PV cells have similar costs, and if receiver packages have double this cost (about \$2 per square centimeter or \$20,000 per square meter total), and if the concentration ratio is in the range of 1000 to 500, then the receiver would add about \$20 to \$40 per square meter to the area-related portion of system cost.

Figure 3 can now be used to determine the required receiver performance. A number of detailed production and installation cost estimates have been performed for sun-tracking mirror assemblies (heliostats) in support of the central receiver solar-thermal concept. Typical estimates of installed cost are about \$120 to \$150 per square meter in mass production at levels allowing power plant construction at 100 MW per year for 5 years (*22–24*). Concentrating PV arrays are more complicated than heliostats; therefore, the achievable cost is likely to be higher. If the total area-related cost for concentrators, exclusive of the receiver, can be maintained at around \$225 per square meter, then the required receiver efficiency (at 25°C) in the desert Southwest is about 25 percent. Figure 3 also shows the required performance for other regions of the country, assuming that area-related costs can ultimately be reduced to \$175 per square meter. Outside the Southwest the required efficiency increases dramatically because concentrating PV systems respond only to the direct component of solar radiation. Consequently, significant use of these systems will probably be limited to the Southwest.

One of the most important conclusions drawn from this analysis is that high efficiency is a key attribute which will strongly determine the ultimate success of any candidate PV material.

Technology Status and Needs

Using the flat-plate and concentrator cost and efficiency targets defined in Figs. 2 and 3 as indicators of promise for widespread utility use, what PV technologies have the highest probability of success? To address this question, EPRI recently conducted a broad evaluation of the status of and outlook for PV technology. Participants in the effort included a number of technical experts, research managers, and business managers who, in aggregate, have an intimate understanding of the technical and management issues associated with this emerging technology. Many of these participants served as members of an ad hoc Photovoltaic Advisory Committee. Background for the evaluation included (i) the key research of the past decade, much of which involved the participants, and (ii) recent detailed PV assessments (*25, 26*).

Two workshops, held in December 1982 and January 1983, were central to the evaluation. The first focused on technical status and needs, and the second dealt primarily with management and business planning issues. The aim was to develop a consensus of the participating experts, rather than to assemble a quantitative summary of status and predictions for each option. The evaluation was summarized in a draft document that was reviewed by the ad hoc Photovoltaic Advisory Committee and subsequently published by EPRI (*6*).

A strong consensus emerged from the evaluation. First, the EPRI performance and cost targets for PV devices were widely accepted by representatives of the technical and business sectors of the PV community. Second, even though the targets were viewed by all as stringent, there was a strong sense that PV has a high probability of success as measured by these targets.

A particularly important issue is that of achievable conversion efficiencies. Careful consideration was given to theoretical-limit efficiencies; efficiencies already reached; and, of greater significance, practical-limit efficiencies, which are lower than theoretical limits because of (i) unavoidable losses encountered in practical cells and (ii) the potential impacts of large-scale industrial production. It is encouraging that practical-limit efficiencies for three PV technologies currently under development were judged to exceed the efficiency targets. These technologies involve high-concentration systems, tandem amorphous silicon, and crystalline silicon sheet.

The important conclusions affecting the R & D outlook for each of the major PV technology classes are listed in Table 1 with respect to eight major characteristics. Three of these characteristics are primarily technical; three are more closely associated with planning, management, and business considerations; and two are closely connected with both technical and management issues.

Concentrating systems. Photovoltaic systems with high concentration (500 to 1000 times) have a high probability of achieving the efficiency targets and a medium to high probability of achieving the reliability targets. Practical limit efficiencies for single-crystal silicon and gallium arsenide (GaAs) cells at these high concentration levels are estimated at 28 percent (*27*) and 26 percent (*28*), respectively, and efficiencies over 20 percent have been achieved with both. Testing to date indicates excellent cell stability with good prospects for 20- to 30-year lifetimes. How closely these systems approach the reliability and cost targets will be largely determined by the performance and costs achievable in their tracking and optical components.

The management-related issues, however, give rise to some concerns for this PV option. As shown in Table 1, the level of complementary development efforts is rated as medium, and the degree of commercial interest and availability of near-term markets are rated as low.

The largest technical uncertainties for concentrator systems are associated with the cells, the cell mount, and the optical and tracking components. At least one of the two candidate cells (crystalline silicon and GaAs) should achieve satisfactory cost and performance, because significant complementary research efforts on GaAs and silicon materials are under way for other semiconductor applications. However, there is relatively little complementary activity that can benefit the optical and tracking components.

Private R & D investment in addressing the technical problems of high-concentration PV systems appears to be low. Although several firms have designed such systems under federal sponsorship, the remaining technical and business risks are sufficiently high that firms seem unwilling to make major investments to commercialize concentrating PV systems. High-value, near-term markets for concentrating PV systems are not likely, since the markets are commonly in remote locations where maintenance of the tracking system, however minimal, would be difficult. Another near-term market not available to concentrators is consumer products. Nevertheless, efforts are beginning within the private sector to explore business opportunities.

It appears that concentrating PV systems should be a major focus of an R & D program directed at enhancing the prospects for utility use of PV systems. The concentrating systems have considerable promise, can be proved in the near term, and could be neglected by commercial firms which are emphasizing nonutility markets. To be most effective, such a program should (i) promote the development and testing of PV cells that meet the efficiency target of 25 to 27 percent, (ii) verify the production costs and reliability of these cells, (iii) establish device yields that are obtainable in high-volume production, and (iv) promote the design and demonstration of highly reliable tracking and optical systems capable of high concentration and with a potential for achieving the cost target.

Tandem amorphous silicon. Amorphous silicon used in tandem configurations with two or more thin (~ 1 μm), contiguous layers of material—each of which is an optically complementary alloy that responds to a different portion of the solar spectrum—has high ratings in many of the key characteristics. Because of their low material content, these devices are likely to be relatively inexpensive to produce. Single-junction, small-area (1 cm^2) amorphous silicon cells have achieved 10 percent efficiency (*29*), approaching the practical-limit estimates of 12 to 13 percent (*30*). However, the optimism about amorphous silicon stems from the practical-limit efficiency estimates for the tandem cell, which are 16 to 17 percent (*30*).

The successful development of tandem cells presents technical challenges in alloy synthesis and interface control whose resolution will probably require sustained, focused research for 10 years or more. The outlook is considered promising because adjacent amorphous layers, not constrained by the long-range order of crystalline materials, are expected to present a less formidable interface problem than tandem crystalline structures. Furthermore, there is considerable interest in amorphous materials for other electronic semiconductor applications, so that advances may come about as spin-offs of these complementary activities. Also, high-value, near-term markets are available since present-generation amorphous silicon PV devices are particularly suited to consumer products. Consistent with these positive characteristics, there is a high level of private investment, in both the United States and Japan, promising additional technical advancement.

In contrast, three of the characteristics are more problematic. Amorphous silicon is ranked as medium with respect to efficiency and reliability. While the tandem configuration is promising, research to test the performance limits of such devices is at a very early stage. Also, the material is susceptible to light-induced degradation which is not fully understood (*31*). R & D efforts should support (i) basic research in amorphous silicon materials to improve the understanding of electronic and optical properties and degradation processes and (ii) basic and applied research aimed at improving device efficiency, first for single-junction cells and later for more complex structures.

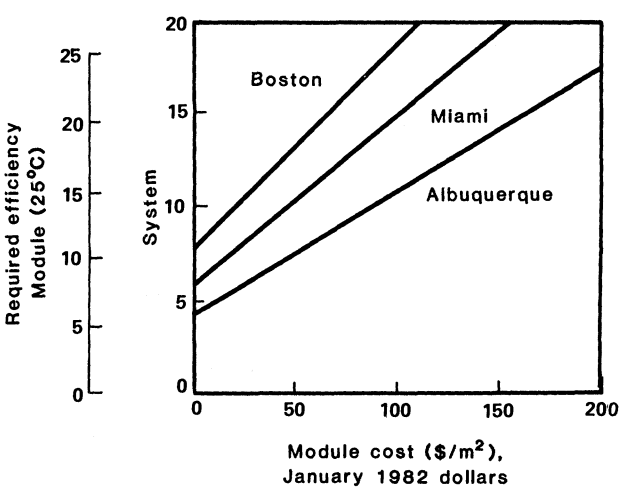
Both of these areas of investigation require basic research into the fundamental characteristics of amorphous materials. Therefore, a well-executed amorphous silicon R & D program would benefit from a strong effort to involve both universities and industrial laboratories and would place a strong emphasis on facilitating communication and interaction between these research communities.

Crystalline silicon sheets. Flat-plate PV devices made of crystalline silicon sheet material rate high in probability of meeting both efficiency and reliability targets. Indeed, most of the experience with PV cells and modules has been obtained with crystalline silicon. Extensive investigations indicate that properly encapsulated cells can be expected to operate with little degradation for decades (*32*). Practical-limit efficiencies are estimated at 20 to 21 percent (*33*), and Czochralski wafer cells roughly 80 cm^2 in area can exhibit 14 percent efficiency (*34*). However, it is generally recognized that acceptable costs will require the successful development of a silicon sheet growth technology that avoids costs associated with wafer sawing. Hence, the achievement of 15 to 17 percent efficiency in cells made from ribbon silicon crystals—a form of sheet—grown as a dendritic web is encouraging. Silicon sheet also rates high in terms of the level of complementary research efforts and the availability of near-term markets. Furthermore, it should be possible to resolve the technical uncertainties associated with crystalline silicon sheet devices for bulk-power applications in less than 10 years.

The major concern with this technology is whether it can meet the cost target for utility applications. Of the numerous alternatives to the current Czochralski-based production method, none is sufficiently advanced to be certain of achieving the cost target. Furthermore, even at

Table 1. Outlook for PV technology classes with respect to eight major technical (T) and management (M) characteristics.

Characteristic	Photovoltaic technology				
	High concentration	Tandem amorphous silicon	Crystalline silicon sheet	Poly-crystalline thin films	Novel concepts
Probability of meeting cost targets (T)	Medium	High	Medium	High	?
Probability of meeting efficiency targets (T)	High	Medium	High	Low	?
Probability of meeting reliability targets (T)	Medium/high	Medium	High	Medium	?
Margin for meeting targets (T, M)	Medium	High	Low	Low	?
Time to resolve technical uncertainties (T, M)	< 10 years	> 10 years	< 10 years	> 20 years	> 20 years
Level of complementary development efforts (M)	Medium	High	High	Low	Low
Degree of private R & D investment (M)	Low	High	Medium	Low	Low
Availability of near-term markets (M)	Low	High	High	Medium	?



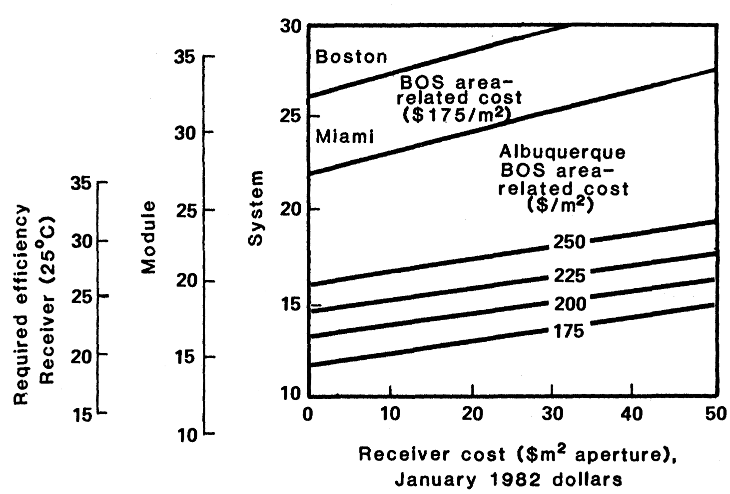


Fig. 2 (left). Required efficiency versus cost for fixed flat-plate systems in three regions of the United States. As achievable module cost (delivered to the site) increases, so does the efficiency required to meet the same levelized electricity cost target. The system efficiency scale is referenced to actual site-specific operating conditions at rated system power. The module efficiency scale removes the impact of system electrical losses, assumptions about long-term degradation, and temperature effects on module performance. Fixed parameters used for this figure are: levelized electricity cost, 15 cents per kilowatt-hour; operations and maintenance, $2 per square meter per year; indirect costs, 50 percent; BOS power-related costs, $130 per kilowatt; BOS area-related costs, $50 per square meter; and BOS efficiency, 80 percent. The SOLMET Typical Meteorological Year data base was used for performance estimation (*38*). Fig. 3 (right). Required efficiency versus cost for concentrating systems in three regions of the United States. Using $20 to $30 per square meter as a realistic receiver cost, and $225 per square meter as a likely area-related system cost, the required receiver efficiency is around 25 percent in a desert location in the Southwest (for instance, Albuquerque). To achieve the levelized electricity cost target under the insolation conditions in Miami or Boston requires higher efficiencies than are thought possible, even if area-related costs are reduced to an absolute minimum. Module (combined lens and cell) and system efficiencies are at rated power operating conditions. Fixed parameters: levelized electricity cost, operations and maintenance, and indirect costs as in Fig. 2; BOS power-related costs, $175 per kilowatt; optical efficiency, 85 percent; and BOS efficiency, 80 percent. The SOLMET Typical Meteorological Year direct normal data base was used for performance estimation (*38*).

a more advanced stage these production processes could be so costly that they meet the cost target by only a thin margin. Since the advanced processes invariably trade off efficiency for lower cost of production, it is not clear that both efficiency and cost targets can be simultaneously met. For this reason, R & D efforts should continue to focus on performance improvement and cost reduction in parallel. The research needed includes the development of processes that simultaneously achieve (i) continuous operation, (ii) a sufficiently high ribbon or sheet growth rate, and (iii) a high yield of cells with target efficiencies.

Other approaches. Polycrystalline thin-film devices generally employ micrometer-thick layers of PV material (for instance, Cu_2S/CdS, CdTe, or $CuInSe_2$) having crystalline grains with lateral dimensions of several micrometers. As with amorphous silicon, polycrystalline materials seem to be amenable to low-cost (per unit area) production processes. However, the experience to date leaves considerable uncertainty about whether the efficiency and reliability goals can be met and doubt about the potential for utility applications.

In addition to purely technical considerations, several business and institutional factors weigh against the rapid development of polycrystalline thin-film devices. Unlike the situation with silicon-based PV devices, there is no large body of ongoing industrial research in complementary areas capable of aiding the development of polycrystalline thin-film technology. Similarly, there is a low level of private investment in these technologies. Furthermore, such investment is inhibited by the difficulties private developers have encountered in commercialization efforts, primarily because of problems with device reliability.

The low level of investment (compared, for example, with investment in crystalline silicon) suggests that pioneering research will be relatively slow. It is unlikely that devices based on these materials and suited for utility applications will be developed within the next 20 years.

Nevertheless, carefully targeted research could still be beneficial and elimination of all polycrystalline thin-film work would be premature. The most important technical needs are to determine efficiency limits and to explore tandem designs, which, as in the case of amorphous silicon, might offer significant improvements in efficiency.

In addition to the more familiar PV technologies discussed in the preceding paragraphs, numerous novel, advanced PV concepts have been examined in this article. These included surface-plasmon cells, super-heterojunction cells, and semiconductor/liquid junction cells. While these concepts are not likely to evolve into bulk-power systems, they might be the source of constructive spin-off advances that can be applied to other, more promising PV options. Past experience illustrates the value of continued awareness of approaches outside the mainstream. For example, amorphous silicon and high-concentration cells began as novel approaches.

Outlook

The overall conclusion drawn from EPRI's recent evaluation and related activities over the past several years is that PV power technology offers considerable promise as a source of bulk electric power toward the turn of the century. Consequently, on behalf of and in conjunction with U.S. electric utilities, EPRI plans to conduct a focused research program on this emerging technology as a power generation alternative for electric utilities. The work of the past decade, both in the United States and abroad, has allowed the definition of activities supporting this overall aim. Many of these activities are now being pursued by the federal PV program, as outlined in the Department of Energy's most recent 5-year plan for PV (*35*).

A primary need is to seek maximum performance from PV cells, with respect to both conversion efficiency and operating lifetimes. Achieving this will require a long-term commitment to fundamental research programs. Significant progress can be expected for at least the next decade—both from basic research aimed at improved understanding of the physical, optical, and electronic properties of materials for PV cells, and from device-physics research coupling theoretical and experimental activity.

Another key need is to continue field testing activity now under way with today's technology. This activity, if maintained over extended periods, will provide the long-term experience needed as a basis for user confidence in PV, irrespective of the cost and performance levels eventually achieved. Tests now being conducted with systems as large as several megawatts will provide essential information on performance trends and operating and maintenance requirements (*36*).

Field tests also provide a proving ground for the technology advances that are important for the incremental development of the industry. Crucial to the continued growth and health of this industry is the development of near-term markets. A particularly promising market prospect in the eyes of many is village power for developing countries; another, already being served but probably smaller, is consumer products. These markets are essential to the orderly evolution of the PV industry. They are also important to electric utilities, if indirectly, because without them it is unlikely that a PV industry can grow sufficiently to serve the bulk-power market.

Good prospects for technical progress and for orderly business development point toward a bright future for PV as a source of bulk electric power. The challenge for the next decade is to push PV technology to its physical limits while simultaneously expanding markets and building user confidence.

References and Notes

1. R. Sacks for Strategies Unlimited, paper presented at the Renewable Energy Technology Symposium and International Exposition, Anaheim, Calif., 30 August 1983.
2. L. D. Cleary, "Electric utility solar energy activities: 1976 survey," *EPRI Rep. ER-321-SR* (January 1977).
3. J. R. Spelman, "Electric utility solar energy activities: 1982 survey update," *EPRI Rep. AP-2850-SR* (December 1982).
4. R. R. Ferber, *Proc. 18th Intersoc. Energy Convers. Eng. Conf.* 3, 1266 (1983).
5. Much of this work has been reported in proceeding of recent IEEE Photovoltaic Specialists Conferences (PVSC's); for example, see *Record of the 16th PVSC–1982* (IEEE 82CH1821-8, Institute of Electrical and Electronics Engineers, New York, 1982).
6. J. G. Witwer, "Photovoltaic power systems research evaluation," *EPRI Rep. AP-3351* (December 1983).
7. E. A. DeMeo and P. B. Bos, "Perspectives on utility central station photovoltaic applications," *EPRI Rep. ER-589-SR* (January 1978).
8. W. D. Marsh, "Requirements assessment of photovoltaic power plants in electric utility systems," *EPRI Rep. ER-685* (June 1978).
9. R. Neal, P. DeDuck, R. Marshall, "Assessment of distributed photovoltaic electric power systems," *EPRI Rep. AP-2687* (October 1982).
10. G. J. Bonk *et al.*, "The effects of future energy scenarios on photovoltaic energy value," *Sandia Rep. SAND83-1283* (August 1983).
11. R. Taylor, "Photovoltaic systems assessment: An integrated perspective," *EPRI Rep. AP-3176-SR* (September 1983).
12. The levelized cost is obtained by converting a series of nonuniform future payments to a uniform (level) series of payments whose present worth is equal to that of the original nonuniform series. A familiar example is the common, fixed-interest-rate home mortage loan, whose monthly payments are uniform (in current dollars) over the life of the loan even though simple interest due decreases each month.
13. Public Law 95-617, Public Utility Regulatory Policies Act of 1978, Sect. 210(d).
14. R. Moyle, H. Chernoff, T. Schweizer, "Assessment of distributed solar power systems—issues and impacts," *EPRI Rep. AP-2636* (November 1982).
15. J. B. Patton and D. Curtice, "Interconnecting dc energy systems: Responses to technical issues," *EPRI Rep. AP/EM-3124* (June 1983).
16. W. Stolte, "Photovoltaic balance-of-system assessment," *EPRI Rep. AP-2474* (June 1982).
17. ———, "Photovoltaic subsystem optimization and design tradeoff study," *Sandia Rep. SAND81-7013* (March 1982).
18. H. A. Franklin, "Integrated structure designs for photovoltaic arrays," *Sandia Rep. SAND81-7191* (April 1983).
19. D. J. Hughes, B. W. Heller, J. E. Stephenson, "Detailed conceptual designs and economic

analysis of a reference photovoltaic central power station," in *Record of the 16th PVSC–1982* (IEEE 82CH1821-8, Institute of Electrical and Electronics Engineers, New York, 1982), pp. 276–280.
20. E. J. Simburger, "Engineering design for a photovoltaic central station power plant using tracking concentrator photovoltaic arrays," in *ibid.*, pp. 164–169.
21. S. L. Levy and L. E. Stoddard, "Integrated photovoltaic central station conceptual design," *EPRI Rep. AP-3264*, in press.
22. "Second generation heliostat evaluation summary report," prepared by Sandia National Laboratories Heliostat Development Division, *Sandia Rep. SAND81-8034* (January 1982).
23. "Heliostat production evaluation and cost analysis," prepared by General Motors Corporation, *SERI Rep. SERI/TR-8052-2* (December 1979).
24. K. Drumheller, S. Schulte, R. Dilbeck, L. Long, "Heliostat manufacturing cost analysis," *SERI Rep. SERI/TR-8043-1* (October 1979).
25. J. W. Harrison, "Photovoltaic cell and module status assessment," *EPRI Rep. AP-2473* (October 1982).
26. H. Ehrenreich, *Principal Conclusions of the American Physical Society Study Group on Solar Photovoltaic Energy Conversion* (American Physical Society, New York, 1979).
27. R. M. Swanson, "Point-contact silicon solar cells," *EPRI Rep. AP-2859* (May 1983).
28. H. J. Hovel, *Semiconductors and Semimetals*, vol. 2, *Solar Cells* (Academic Press, New York, 1975), p. 80.
29. A. Catalano *et al.*, "Attainment of 10% conversion efficiency in amorphous silicon solar cells," in *Record of the 16th PVSC–1982* (IEEE 82CH1821-8, Institute of Electrical and Electronics Engineers, New York, 1982), p. 1421.
30. J. C. C. Fan and B. J. Palm, *Sol. Cells* **10**, 81 (1983).
31. D. E. Carlson, *Sol. Energy Mater.* **8**, 129 (1982).
32. Extensive evaluations of module reliability have been conducted by Jet Propulsion Laboratory for the Department of Energy. For instance, see D. T. Otth, in *Proceedings of the 21st Project Integration Meeting*, 12 and 13 January 1983 (DOE/JPL-1012-88, Department of Energy, Washington, D.C., 1983), pp. 399–406.
33. J. R. Hauser and P. M. Dunbar, *IEEE Trans. Electron Devices* **ED-24** (No. 4), 304 (1977).
34. This efficiency is inferred from manufacturers' specifications for state-of-the-art crystalline silicon modules.
35. National Photovoltaics Program, *Five Year Research Plan 1984–1988* (Department of Energy, Washington, D.C., May 1983).
36. D. J. Inglis *et al.*, "Photovoltaic field test performance assessment," Technol. Status Rep. 2, *EPRI Rep. AP-3244* (September 1983).
37. "TAG^{TM} technical assessment guide," *EPRI Rep. P-2410-SR* (May 1982).
38. *SOLMET, Hourly Solar Radiation–Surface Meteorological Observations* (Users Manual TD-9724, National Climatic Center, Asheville, N.C., 1978), vol. 1.
39. The recent EPRI evaluation of PV status and outlook involved extensive participation by some 50 members of the PV community representing industry, universities, government programs and laboratories, and utilities; 23 of the participants served on an ad hoc Photovoltaic Advisory Committee. All of these individuals contributed substantially to the evaluation. Particularly appreciated are the efforts of J. G. Witwer of Strategies Unlimited, who coordinated and documented the evaluation.

Conservation of Rice Genetic Resources: Luxury or Necessity?

T. T. Chang

Rice shares equal importance with wheat in feeding the world's population. While wheat production exceeds that of rice, rice is milled nearly exclusively as food. In the developing world, rice ranks as the principal staple. It provides about calories to sustain a larger number of persons per unit of land than other cereals in the monsoonal areas. The crop feeds and supports millions of subsistence farmers and landless workers of the humid tropics.

Summary. There is remarkably rich diversity in the cultivated rices and their wild relatives. Substantial segments of the diverse germplasm have been collected and conserved during the past two decades by national, regional, and international research centers. Multidisciplinary and interinstitutional evaluation and use have drawn substantial rewards. However, nations in the developing world that grow and consume rice still face enormous challenges to meet the continuous growth of the human population. Further conservation efforts and improved preservation measures are needed to provide security for the irreplaceable rice germplasm. Modest inputs into conservation programs are highly justified by multibillion dollar returns from the improved varieties in the past two decades.

80 percent of the calories for the 2 billion people of Asia and one-third the caloric intake of the nearly 1 billion people in Africa and Latin America. Rice is also a major source of protein for the masses of Asia. It is the only cereal that can withstand flooding, and it produces more

T. T. Chang is geneticist and head, International Rice Germplasm Center, International Rice Research Institute, Post Office Box 933, Manila, Philippines.

From 1969 to 1971 important gains in rice production and yield were realized by most of the populous countries in tropical Asia, which had faced food crises in the droughty years 1965 and 1966. Development of the semidwarf rices and wheats and the associated production technologies spurred the food production increase. The gains continued through 1982; however, per capita food production in the developing countries has lagged since the early 1970's, mainly because of high population growth rates (*1*).

If the mid-1983 world population of 4.72 billion continues to increase at the annual rate of 1.75 percent (*2*), an increase of 1.62 billion people by the year 2000 may be projected. The population will rely on increased rice production to supply nearly one-half of the caloric intake required.

Sources of Germplasm in *Oryza*

The genus *Oryza* has 20 wild species and two cultigens, *Oryza sativa* L. and *Oryza glaberrima* Steud. The full spectrum of genetic resources in the genus consists of (i) wild species, natural hybrids between the cultigen and wild relatives, and primitive cultivars of the cultigens in the areas of diversity; (ii) commercial types, obsolete varieties, minor varieties, and special-purpose types in the centers of cultivation; and (iii) pureline selections of farmers' varieties, elite varieties of hybrid origin, F_1 hybrids, breeding materials, mutants, polyploids, aneuploids, intergeneric and interspecific hybrids, composites, and cytoplasmic sources from breeding and related research programs (*3*).

The geographic distribution of the two cultigens and their close wild relatives has been described (*1, 4*). I estimate that slightly more than 100,000 cultivars of *O. sativa* may be found in the world.

Genetic Diversity in Rice Species

The cosmopolitan rice cultigen is *O. sativa*; *O. glaberrima* is grown only in Africa. The original home of the genus is