Photovoltaics Today and Tomorrow

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In the next several decades it is expected that the United States and the rest of the nations of the world will greatly expand their consumption of electricity. But many questions will accompany this expansion: Can we build enough generating capacity? Do we have enough energy resources? Can we accommodate centralized and dispersed needs, large and small applications, and the diverse requirements of all sections of the world? And can we increase consumption without increasing environmental degradation? Photovoltaics, which by means of solid-state technology turn photon energy into electricity, can make a substantial contribution toward fulfilling these energy needs. Historically, the drawbacks to photovoltaics have been cost and technological maturity. But more than a decade of research has greatly advanced the technology and has brought it to the point of entering large electricity markets. Advances in the next two decades should make it possible for photovoltaics to become one of the world's preferred technologies for generating electrical energy.

WITH THE EXCEPTION OF COLLECTOR (SOLAR CELL) costs, which continue to fall steadily, there are no remaining technical obstacles to the eventual widespread utilization of photovoltaic (PV) technology (*1*). Over the last several years, advances in PV materials coupled with innovative device designs have yielded both high-efficiency crystalline silicon and gallium arsenide solar cells with efficiencies ranging from 22.8 to 31% (*2, 3*). Significant advances in the development of low-cost PV materials, including polycrystalline silicon, amorphous silicon, copper indium diselenide, and cadmium telluride, have also occurred. At the same time, PV systems have become increasingly more reliable. PV modules are now routinely expected to last 20 years or more, and the development of automated processes has reduced manufacturing costs. Significant markets for distributed PV electrical systems have already developed worldwide.

These accomplishments mean that PV power systems should be competitive for generating central station peaking power by the late 1990s (*2*). In addition, should global warming concerns lead to governmental policies that require a rapid displacement of fossil fuels without respect to cost, that is, overriding normal "free market" processes, PV generation systems should be able to meet most of the electrical power requirements of the United States within four to five decades.

Evolution and Status of PV Technology

Edmund Becquerel first recorded the PV effect in 1839 (*4*). But the field lay fallow until the advent of improved doping techniques and a method for growing crystals in the 1940s and 1950s (*5*). Shortly thereafter (1954), Bell Telephone Laboratories made practical silicon PV cells that reached sunlight-to-electricity conversion efficiencies as high as 6% (*6*). Since 1958, PV cells have powered most U.S. satellites in space.

Because of their expense, however, PV systems were not considered for terrestrial applications until after the 1973 oil crisis, when the National Science Foundation organized a conference in Cherry Hill, New Jersey, to lay the foundation for a national R&D program in terrestrial PV systems (*7*). Since then, scores of new PV materials and many new cell designs have been explored with the objective of developing low-cost PV systems for terrestrial use. As a result, the cost of PV electricity has dropped from $15 to approximately $0.30 per kilowatt-hour. Dozens of new efficiency records have been set and reset (*2*). PV modules are now expected to last up to 20 years and more (*8*).

Manufacturing processes for PV devices are becoming automated and semicontinuous. Cell and module designs now incorporate transparent conducting oxides, flexible substrates, laser-scribed connections, microgrooved surfaces, point contacts, multijunctions, and light-capturing techniques.

Revenues for the PV industry have grown to nearly $400 million a year, a figure that includes equipment for balance of systems (*9*). Japan, European nations, China, India, and other countries have established and enlarged their PV programs. The number of organizations involved in manufacturing and R&D has grown from less than a dozen in the early 1970s to more than 200 today.

Module shipments in 1988 were 23% greater than in 1987 (*10*). Some companies are building new facilities to produce 10 MW of modules per year, a scale that could reduce the cost of PV modules to $1.15/W (*11*), which translates to approximately $0.15/kWh. Others are closing deals to provide systems for utilities (*12*).

This bodes well for the future of PV systems. By the year 2000, manufacturers will have incorporated the research advances of the 1990s into their designs. The higher efficiency modules thus achieved should help reduce the cost of PV electricity to a price competitive with baseload utility power from conventional sources (*13*).

Progress and Promise in Photovoltaic Technology

The basic technology. The basic power element of a PV system is the solar cell. Each cell has two or more specially prepared layers of semiconductor material whose atoms absorb light, freeing electrons and creating holes to carry current. Each cell has a junction between two dissimilar semiconductor materials that creates a voltage to drive electrons through a circuit (Fig. 1). Solar cells can be made from several different semiconductor materials, and these materials

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are available in a variety of physical states—single crystal, polycrystalline (many small crystals), or amorphous (noncrystalline).

Connecting many cells together into a module, the building block of PV systems, produces more power output and provides protective packaging for the cells. Modules can also be made by depositing amorphous or polycrystalline semiconductor layers over a large area and then encapsulating the layers in protective coatings. Modules fall into two broad categories: (i) flat-plate modules, which are used under ordinary sunlight, and (ii) concentrating modules, which include lenses to focus sunlight onto the solar cells. For large power needs, modules can be grouped together to form arrays.

Efficiency and cost. PV research and development is driven by the need to make PV systems cost-effective and competitive in the open market. To accomplish this there are three options: to make efficient devices, to make inexpensive ones, or to do both. In each case, modules must operate reliably for 20 to 30 years.

Device efficiency, the ratio of the electrical output power to the power of the incident sunlight, is limited by light absorption and loss mechanisms (*14*). The largest limiting factor is the inability to effectively utilize all the wavelengths in the solar spectrum (Fig. 2). Other limiting factors include the quality and type of material; carrier recombination at the junction and interfaces, the surface, the contacts, and in the bulk material; reflection of light from the surface; shading by the grid; and series and contact resistances (*15*).

The cost of a PV device is also determined by several factors. These include the kind of materials used and the amount required, the choice of substrates, device design, and fabrication processes.

Photovoltaic materials. The choice between higher efficiency and lower fabrication cost often boils down to a choice between crystalline and thin-film materials. Crystalline devices are generally more efficient, but thin-film devices cost less. Many materials are being investigated with emphasis on crystalline silicon, amorphous silicon, polycrystalline thin films, and III-V single-crystal materials.

Crystalline silicon has long been the workhorse of PV technology. It has the longest history and the largest technology base, and it still dominates the markets, especially for power modules (*16*). It is the best understood of the PV materials, and its technology continues to advance rapidly. Manufacturing techniques have become semi-automated. Methods have evolved for making pure, high-quality crystalline silicon (*17*).

New understanding of device physics has led to innovative designs. An illustrative case is the so-called "point-contact" cell that has set so many of the recent efficiency records for crystalline silicon devices (*18*) (Fig. 3). Designed by Swanson *et al.*, this cell uses a pyramidally textured top surface that scatters light into the cell at nearly random angles, which is necessary for light trapping (*19*). A back-surface mirror reflects more than 90% of the nonabsorbed photons at angles that result in total internal reflection. The design also incorporates extremely small (10 to 30 μm) point contacts that alternate between *p*-type and *n*-type in a polka-dot pattern on the back surface. Putting them on the back surface removes any shading or recombination that otherwise might have occurred by putting them at the front surface. Making them so small reduces recombination and contact resistance. As good as this and other [most notably, designs by Green *et al.* (*20*) (Fig. 4)] concepts are, designers believe that they can improve the efficiencies of cells by making them thinner, by reducing resistance, by optimizing the textured surface and the carrier lifetime, and by introducing other innovations (*21*).

The result of the recent innovations has been impressive. Whereas cells formerly required 300 to 400 μm of absorber material, efficient cells can now be made that are only 100 to 150 μm thick. Efficiency records are continually being set by both research and production devices. Research cells have reached an efficiency of 22.8% under ordinary sunlight and 28.2% under concentrated sunlight (*2*). Some claim that further materials and design improvements can increase efficiencies to as high as 30% under ordinary sunlight and 36% under concentration (*22*). But these claims are based on ideal limits that do not take into account certain losses that appear to be unavoidable in practical cells, such as band-to-band Auger recombination, some emitter recombination, and resistive voltage drops. Even with these losses, however, single-junction silicon cells could eventually reach efficiencies as high as 31% under concentration (*21*).

High efficiency is not the only road that crystalline silicon can take. Another approach is to compromise on efficiency in the interest of achieving lower production costs. The two primary methods are ribbon technology, which grows entire sheets of silicon (Fig. 5), and cast silicon, which uses simple casting processes to grow square ingots that are then sawed into wafers. Although both methods result in less efficient polycrystalline silicon, they have the potential for higher throughput and less expensive production and can use less pure, less expensive silicon. Because rectangular polycrystalline cells can be packed more densely into modules than round single-crystal cells, polycrystalline modules can be nearly as efficient as modules of flat-plate, single-crystal silicon (*23*).

In making polycrystalline silicon devices, designers use some of the same advances that have been incorporated into single-crystal silicon, such as internal reflection, back-surface reflectors, and antireflection coatings. Polycrystalline devices have also benefited from the incorporation of atomic hydrogen to reduce carrier recombination caused by defects and grain boundaries.

As a result of these and other improvements, the efficiencies of experimental cells from the dendritic web ribbon process, for example, have risen to nearly 17%, and the efficiencies of some production-size cells from this and edge-defined film-fed growth ribbon method are nearing 15% (*24*). At the same time, production rates are increasing substantially, with the dendritic web process gaining a fivefold increase in throughput since 1984 (*25*).

Ribbons of polycrystalline silicon, however, have only been produced in pilot quantities. To become commercially viable, this technology must overcome at least two related obstacles. First, the throughput of this process must be increased substantially. Second, because thin silicon ribbons can cool unevenly, thus creating stresses and crystal imperfections that can cause ribbons to buckle or crack, this can limit cell yields and performance. These obstacles are being addressed with the help of sophisticated growth models and computer-aided production that constantly samples ribbon growth and feeds the information back to the process for adjustment.

Cast silicon technology is more mature than ribbon technology. Several megawatts of modules have already been shipped to customers. Some cast-silicon production cells have efficiencies of more than 15%, and the efficiencies of large-area cells approach 14%. Industry is also exploring processes that promise to reduce the cost of solar-grade silicon by 50% or more; achieving this goal will substantially decrease the cost of polycrystalline silicon modules. Finally, by the use of light trapping and other techniques, there is the possibility of making polycrystalline cells that are as thin as 5 μm with efficiencies greater than 19% (*26*).

Hydrogenated amorphous silicon (a-Si:H) is a leading alternative to crystalline or polycrystalline silicon. That amorphous silicon exhibits high optical absorption, dopability, and photoconductivity has been known since at least 1969 (*27*). But when the first a-Si:H photovoltaic cell was made in 1973 (*28*), it had an efficiency of less than 1% and still appeared to many to be a mere curiosity. Since then, however, single-junction cells have reached an efficiency of 12%, multijunction devices have efficiencies of 13.3% (*2*), and large submodules have efficiencies that surpass 9%.

Amorphous silicon is highly light-absorbent; only 1 to 2 μm of

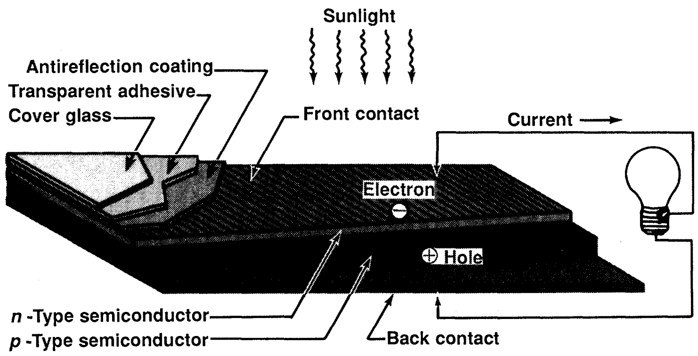

Fig. 1. In a typical PV cell, sunlight generates electron-hole pairs that are separated at the junction. This creates an internal voltage that drives current through an external circuit.

material is needed to absorb 99% of the incident light above the 1.7-eV band gap of the material. Thin amorphous layers can be deposited on a variety of inexpensive substrates such as steel, glass, or plastic.

There are two basic drawbacks to amorphous silicon. The first is that a-Si:H devices lose efficiency after initial exposure to light (*29*). The early devices lost as much as 50% of their efficiency. Since then, researchers have found that one cause of the effect is light-induced defects, known as dangling bonds, in the intrinsic layer (*30*). Therefore, some manufacturers are making modules with very thin intrinsic layers. Others use two stacked a-Si:H cells, each with an extremely thin intrinsic layer. These approaches have resulted in degradations of less than 15% for modules and 10% for cells.

The other drawback is relatively low efficiency. But by improving fabrication and design and by minimizing recombination in the intrinsic layer and the resistive effect of the transparent conductor on current, the efficiency of small area cells should reach 15% and that for large area submodules should reach between 10 and 12%.

Higher efficiencies are possible with alloys of amorphous silicon in multijunction devices. In these devices cells with different materials, and hence different band gaps, are stacked on top of each other in descending band gap order. With each cell "tuned" to a different portion of the solar spectrum, this configuration utilizes sunlight more effectively, thereby increasing the efficiencies. Although calculations of the theoretical efficiency limits of amorphous silicon multijunction devices have quite a range, the efficiency of two-junction cells should eventually reach 17% (*31*) and that of three-junction cells should reach approximately 24%. [Some believe that the theoretical efficiency limits for two- and three-junction a-Si:H cells could be as high as 29 and 34%, respectively (*32*).]

The usual method for making the a-Si partners of multijunction devices is to add carbon for high band gaps and germanium for low band gaps. This approach works well, up to a point. Adding germanium or carbon beyond a critical value degrades cell quality, causing defects and voids in the microstructure. For example, a-SiGe:H cells with band gaps above 1.5 eV are generally of high quality. But once the band gap has been lowered to between 1.4 and 1.5 eV, the quality of the material begins to deteriorate. Researchers are attempting to understand and circumvent the degradation. If they succeed, it should be possible to produce inexpensive modules with efficiencies in the 15 to 20% range.

Polycrystalline thin films, such as copper indium diselenide ($CuInSe_2$) and cadmium telluride (CdTe), offer all the advantages of amorphous silicon. They are highly absorbent, use very little material, and are amenable to automated manufacturing processes.

They have additional advantages. They do not suffer from light-induced degradation, and they can be made with promising deposition techniques. The preparation of $CuInSe_2$, for example, generally depends on variants of physical vapor deposition, methods that may be ten times as fast as the glow discharge or plasma chemical vapor deposition used for amorphous silicon. Two methods used for depositing CdTe and $CuInSe_2$, electrodeposition and spray pyrolysis, have the potential for being the most inexpensive, in terms of capital equipment, and for having very high throughput.

Polycrystalline thin films also pose problems. Cadmium telluride, for example, undergoes performance degradation because of difficulties in contacting *p*-type CdTe. Fortunately, researchers may have solved the contact problem with CdTe by using a *p*-i-*n* device structure with an *n*-type CdS window, an intrinsic CdTe layer, and a *p*-type ZnTe layer, rather than an *n*-CdS/*p*-CdTe heterostructure (which requires metallization contact to the *p*-type CdTe). This and other improvements have led to new record high efficiencies. In the past few months, the efficiency of large CdTe submodules increased to more than 7% while that of small-area cells exceeded 11% (*2*).

The low open-circuit voltage of $CuInSe_2$ has been improved by adding gallium to the compound. Cell currents have risen as well with the introduction of more transparent window materials, such as zinc oxide (ZnO) on thin cadmium sulfide (CdS). These and other advances have led to submodules that have efficiencies higher than 11% (*2*). With new cells reported as having efficiencies higher than 14%, it looks as if single-junction modules may soon break the 15% module efficiency barrier. One organization reports a 15.6% efficiency for a multijunction device that uses a-Si:H for the top cell and $CuInSe_2$ for the bottom cell (*33*). Others are working on two-junction devices that use materials related to CdTe and $CuInSe_2$, a concept with the potential to reach an efficiency higher than 20% (*34*).

The highest efficiencies may be obtained with III-V materials, most notably gallium arsenide (GaAs) and its alloys, such as aluminum gallium arsenide (AlGaAs) and indium gallium arsenide (InGaAs). To many, GaAs is the ideal PV material. It has the optimum band gap (1.45 eV) for single-junction cells, is highly absorptive, has the highest theoretical efficiency [approximately 39% for single-junction cells under the concentrated light of 1000 suns (*35*)], and can be alloyed with many different materials to alter the band gap as desired for high efficiency multijunction configurations. In addition, unlike other materials discussed here, GaAs can be used to make single-crystal thin-film cells.

This last attribute has enabled GaAs to recently set the record for thin-film cells: an efficiency of 22.4% (*36*). The device was grown on a reusable, single-crystal GaAs substrate, raising the possibility that GaAs devices can be both efficient and inexpensive. Until recently, single-crystal GaAs cells could only be grown on thick single-crystal GaAs substrates that could not be reused, which was very expensive. But now researchers are making single-crystal thin films on a reusable substrate whose lattice structure allows proper orientation for the expitaxial growth of a crystal. They can even grow GaAs on reusable germanium, which has a lattice structure very close to that of GaAs.

This is just one example of the progress in the development of GaAs-based cells. Within the last year GaAs has also set efficiency records for single-junction cells under one-sun illumination (24.3%), single-junction cells under concentrated sunlight (29.2%), and the all-time record for all cells, a GaAs/Si two-junction cell that attained an efficiency of 31.0% under concentrated sunlight (*2, 3*).

Gallium arsenide and ternary alloys based on III-V materials can be used in many promising multijunction designs. The band gap of GaAs, for example, is ideal for the middle cell in a three-junction device. The best partners would be alloys of GaAs, such as AlGaAs for high band gaps and InGaAs for low band gaps. Such a combination would match the lattice constants well and would allow monolithic fabrication while enhancing the ability to attain efficiencies in the 35 to 40% range.

However, III-V devices still face the obstacle of cost. However, the relation between efficiency and cost is not linear because of other system costs. A flat-plate module with an efficiency of 25%, for example, can cost three to four times as much as a module with an efficiency of 15% and still remain competitive in most markets (*13*). Also, high-efficiency modules may be particularly desirable in geographical locations where insolation values are not high.

PV Power Generation: Issues and Constraints

With PV costs forecast to be competitive with those of other utility power options for applications such as peaking power by the turn of the century (*13*), the potential exists for PV power to displace conventional power generation worldwide as the primary source of electricity by the end of the 21st century. The solar resource could easily support this level of penetration (*37*). However, a number of important issues, including cost, land-area requirements, utility grid compatibility, solar resource intermittency, and storage, will influence the rate and degree of PV market penetration over the next several decades. These issues are crucial in assessing the potential for photovoltaics to produce intermediate and baseload power for central utilities.

Although there are areas of the world where distributed, grid-connected PV systems consisting of small arrays will make significant contributions, it appears likely that PV power systems will make their most significant impact on the U.S. energy supply by way of large, multimegawatt (50 MW to 1 GW) installations dedicated to generating power for sale by utilities to consumers. To be economically viable, the cost of this power must be competitive with that of power generated from other sources.

Cost. Over the past decade, research and development have reduced the costs of PV-generated power 40-fold, to about $0.30/kWh without storage (*38*). This is within the range of prices currently paid by some utilities for peaking power on very hot summer days (*38, 39*). Current technical objectives of the Department of Energy (DOE) National Photovoltaics Program are designed to support industry efforts to achieve price reductions that will make PV power competitive in the open market with today's baseload generating costs by 2000 (*13*). Given the program and industry's success in meeting and often surpassing their technical and cost goals for the previous 10 years, the likelihood of continued price reductions is high.

In addition, PV power offers environmental benefits to society, which are not accounted for in traditional economic analyses (*40*). In an analysis where such environmental factors are accounted for, current market prices for utility-scale PV systems are estimated to be competitive with conventionally generated electricity (*41*). PV power also offers the diversity in energy supply needed for long-term energy security independent of international oil markets.

Cost considerations for dispersed, grid-connected PV systems, which include rooftop-mounted, fixed flat-plate power systems in the range of tens to several hundred kilowatts, vary from those for central power generation. Recent studies suggest that design standardization coupled with economies of scale can keep residential PV costs below those of comparable larger systems (*38*). Because the residential sector represents a large electricity market (about one-third of the U.S. total consumption), this option should be seriously considered. Fostering significant growth in the residential use of photovoltaics, however, may require adjustments in government policy, in methods for setting typical utility rates, and in those state regulations that currently preclude utility financing of customer generation systems.

Space. PV power plants will require large land areas for solar arrays. Early evaluations of land requirements estimated that PV plants would require five to ten times the land area needed for coal-fired or nuclear power plants (*42*). A recent analysis, however, shows that land requirements for PV power are comparable to those of conventional technologies when mining, transportation, and waste disposal are considered. PV power generation has been estimated to require 0.080 acre/GWh; coal, 0.090 acre/GWh; and nuclear, 0.083 acre/GWh (*43, 44*). Photovoltaics does not necessarily require acreage dedicated solely to power generation. Utilizing the space available as roadside rights-of-way and rooftops could conceivably meet the space requirements necessary to generate all the electric power needed in the United States.

Grid interface issues. Large PV generation centers and dispersed, grid-connected power systems share two problem areas relative to their interconnection and interaction with a utility grid network. The first problem area is intrinsic to the technology (and is thus relatively easily addressed by design strategies) (*45–47*); the second is related to the intermittency of the solar resource. The first problem encompasses basic requirements for maintaining the quality of electric power, for protecting the safety of personnel and disribution lines, and for shielding the PV system from faults and abnormal voltages in distribution lines. The second includes sudden changes in power output resulting from changes in cloud cover as well as the inability of PV systems to generate power at night or their reduced ability during periods of extended cloud cover.

Photovoltaic arrays require inverters and sophisticated control systems to change dc voltages into high-quality ac outputs for grid connection and distribution. The newest power inverters not only produce suitable power outputs but also incorporate control systems that maintain system security during lightning storms or circuit switching interruptions (*45*). Safety issues involving maintenance personnel, arising from circumstances in which electricity could be delivered from either side of the meter, or interface, are expected to be addressed through development of new safety standards, techniques, and education.

The intermittency of the solar resource is a more challenging problem. To avoid serious power generation control and dispatching problems, utilities using substantial PV power must plan for power variations caused by changes in cloud cover. This can be accomplished by adding extra spinning reserves or better load-following generation, or by using better weather forecasting methods to allow plant operators to manage PV output in response to the effect of intermittent cloud cover. Even so, without provision for some kind of short-term (2 hours or less) storage, a recent study suggests that using more than 13% PV power could lead to severe problems with operating mismatches (*48*). In addition, longer term storage may also be necessary to assure reliable service during periods of extended cloud cover.

Storage. Beyond the problem of the cost of PV modules, the major limitation on widespread baseload PV power usage is the lack of low-cost systems for storage of the electrical energy generated during sunlit periods. Without storage, PV power production will be limited to daytime energy displacement and peaking power, which accounts for about 17% (120 GW) of today's installed capacity (*42, 49*). Fortunately, PV power output is well matched to utility peaking demands, especially in summer when periods of intense sunlight correspond to maximum customer demands for air-conditioning (*50*).

However, there are significant environmental and energy security benefits associated with the use of solar energy to generate baseload power. Therefore, research, development, and demonstration efforts are under way to develop cost-effective, PV-compatible short- and long-term storage technologies. The leading near-term contenders

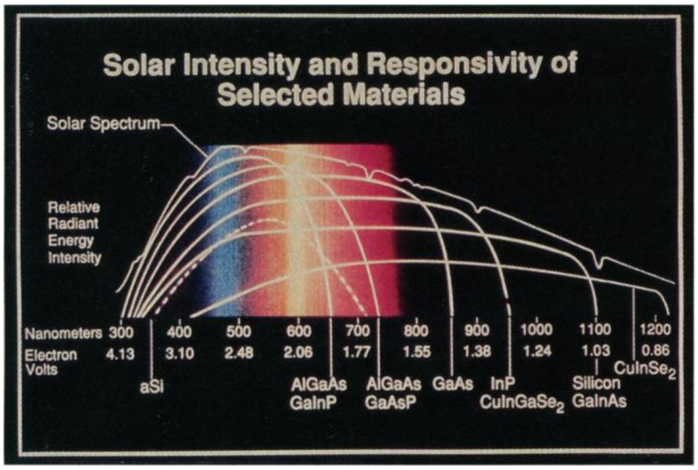

Fig. 2. The characteristic band gap of a semiconductor material is the energy level at which light of a particular wavelength, or shorter, interacts with the electrons in atoms of the material to produce electron-hole pairs, the onset of PV activity.

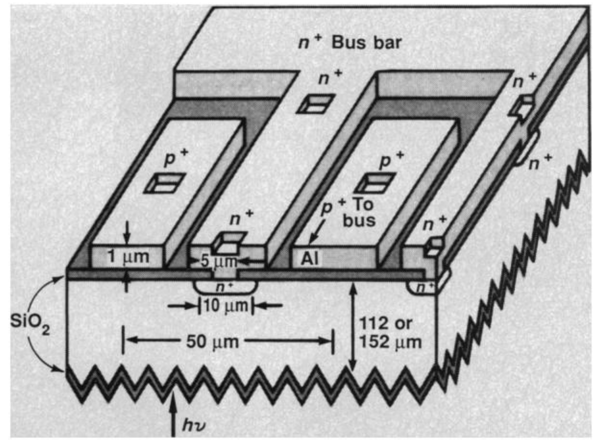

Fig. 3. Stanford University's innovative point-contact cell, which has exceeded all existing efficiency records for silicon cells. The device uses a textured front surface, oxide layers at the front and back surfaces, a highly reflective back surface, and an array of small, point-diffused emitter regions on the back of the cell. [Adapted from (*80*) with permission of the Institute of Electrical and Electronic Engineers, Inc., New York]

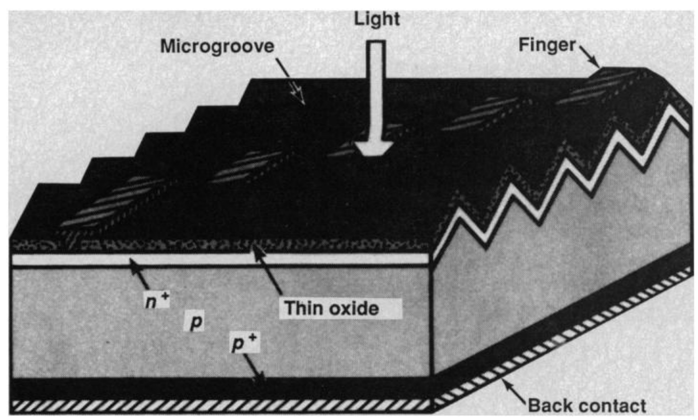

Fig. 4. Design of a new silicon cell devised at the University of New South Wales, Australia, that is expected to substantially improve silicon concentrator modules. The cell uses a microgrooved texture for the front surface, a thin layer of oxide to reduce recombination, and front and back contacts that allow the cell to be easily mounted in concentrator modules. [Adapted from (*80*) with permission of the Institute of Electrical and Electronic Engineers, Inc., New York]

appear to be utility-scale lead-acid battery storage (*51*), pumped hydro (*52*), and utility-scale compressed air storage (*53*). In the future, fuel cells, electrically generated hydrogen production (*54–57*), and superconducting magnetic energy storage (*58, 59*) are likely to be of great interest.

The latter two systems, although technically very challenging, offer unique advantages as storage systems. Solar hydrogen systems offer the possibility of generating noncarbonaceous transportation fuels in addition to providing electrical energy storage (*57*). Superconducting magnetic energy storage would provide both short- and long-term electromagnetic energy storage and storage efficiencies well over 90%, much higher than the efficiencies of other systems that rely on mechanical, chemical, or thermal storage (*59*). With hydrogen or superconducting magnetic energy storage systems, PV power systems could completely displace conventional electricity-generating systems. Hydrogen storage coupled with hydrogen-oxygen fuel cells or appropriately modified direct combustion engines could also provide energy for transportation as well as residential and commercial electricity.

PV Power Systems: Current Markets and Future Trends

Stand-alone and distributed, grid-connected PV power systems appear to represent the best power options available to remote regions not yet committed to fossil-fuel or nuclear technologies (*60–65*). Tens of thousands of PV systems are already providing power for a variety of applications, including vaccine refrigeration, cathodic protection, irrigation pumping, battery charging, lighting and home power, grain grinding, potable water pumping, and bulk power. A study of more than 2700 remote, stand-alone systems in 45 countries showed them to be well accepted by their users for their reliability, low maintenance, and independence from fuel (*66*). In addition, military experience with PV power systems has shown them to be the technology of choice for numerous land-based and offshore applications (*67*).

In inaccessible locations, stand-alone PV systems are the only viable alternative for such applications as remote lighting, telecommunications, or security systems. Even when diesel alternatives do exist, PV systems frequently prove to be more reliable and more cost-effective on a total lifetime cost/benefit basis, when loads are small and operation and maintenance are important (*38*).

Despite their apparent economic viability, markets for remote, stand-alone PV systems are not growing as rapidly as anticipated. Several factors may be responsible (*61*). Because market penetration is still quite low, the costs of distribution, service, and sales remain high, particularly in the remote areas these systems are designed to serve. In addition, PV technology is unfamiliar to many potential users, and there is a need for substantial education and marketing efforts. Finally, although the need for energy in remote, less developed regions of the world is acute, the inhabitants of these regions are not able to pay for this energy (*68*). Obtaining financing for such projects can be a lengthy and complex process involving local governments, the World Bank, and international development agencies. However, as PV system costs continue to fall and the PV industry grows in response to increasing utility involvement, the prospects for growth in the remote, stand-alone markets should improve as well.

Studies and demonstration projects for dispersed, grid-connected power systems are currently under way in the United States, Europe, and Japan (*38, 46, 62*). In the United States, the Northeast, Southwest, and Southeast Residential Experiment Stations have established that there are no serious operating problems with

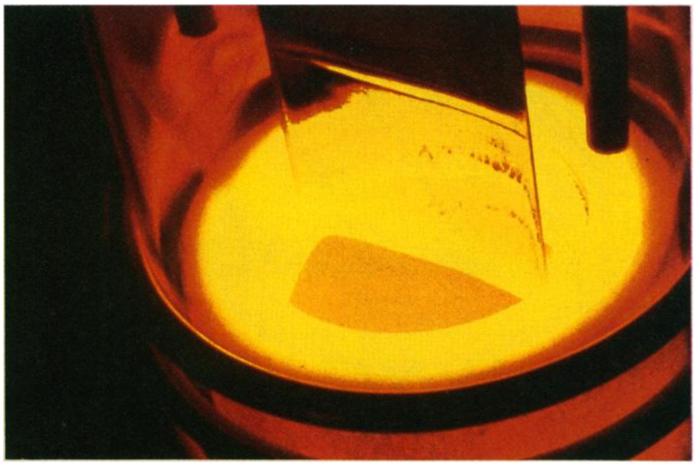

Fig. 5. One technique for making polycrystalline silicon PV cells is edge-supported pulling. With this process silicon sheets are crystallized from a liquid silicon meniscus, which is formed and stabilized between two parallel vertical graphite filaments immersed in the liquid.

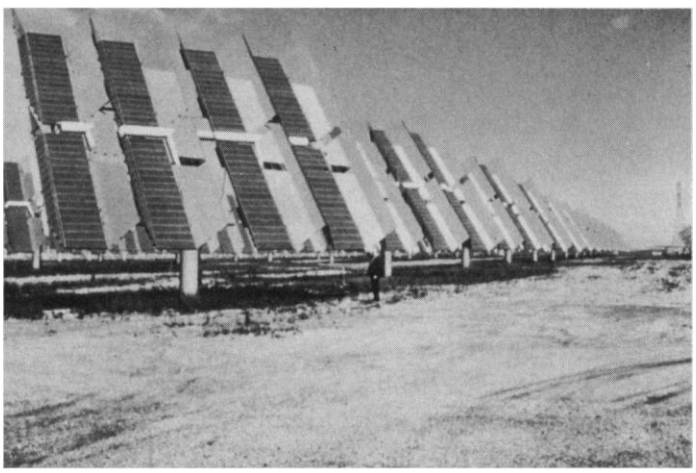

Fig. 6. ARCO Solar's 6.5-MW PV plant on Carissa Plains in California is the largest PV facility in the world. The arrays use mirrors to augment the sunlight impinging on the cells. [Courtesy of ARCO Solar, Inc.]

residential PV system technology. Such systems now offer promising solutions for rural electrification in such diverse locations as less developed countries (*61, 64*), northern California (*65*), the Greek islands, and sparsely populated areas of Spain, France, and Australia. In Europe, such systems are expected to comprise the major penetration of PV power in this century (*60*). Distributed PV systems are also expected to be important in Japan, where space constraints favor residential, distributed PV power systems over land-intensive central facilities (*46, 60, 62, 69, 70*).

As with stand-alone and residential systems, the system technology for large power plants is well known (*1*). The installation of terrestrial PV systems over 10 kW, the smallest size practical for studying potential utility-scale applications, began in 1976. Since then, Europe and Japan have made slow, steady progress in demonstrating this technology. More than 20 systems, ranging in size from 30 to 300 kW (with total power greater than 1 MW), have been installed in Europe, and in 1985 the Japanese completed a 1-MW plant in Saijo City (*71*).

During the same period, the United States has established itself as a world leader in the development and demonstration of utility-scale PV power. Supported by American industry, which currently leads the world in the production of power modules, dozens of U.S. PV systems have progressed through several generations of improved design and performance. One example of this effort, Alabama Power's 100-kW amorphous silicon power plant (completed in 1986) is the only demonstration of its kind for utility-scale applications of thin-film, amorphous silicon technology.

ARCO Solar and Pacific Gas and Electric's 6.5-MW Carissa Plains, California, facility (completed in 1985) is the world's largest PV power plant (Figs. 6 and 7). Experience with the Carissa Plains facility has shown that solar electric generators are highly reliable and easy to install and operate (*72*). This demonstration and others have shown PV power to be a potential source of incremental, peaking electric energy with minimal environmental impact. In addition, experience with Carissa Plains suggests that to be competitive with future electric generation options, PV modules must exhibit efficiencies in excess of 15% at costs somewhere between \$0.06 and \$0.12 per kilowatt-hour. Such costs and efficiencies are consistent with technological improvements anticipated by the mid-1990s (*1, 72*).

A new industry-government initiative, the Photovoltaics for Utility Scale Applications (PVUSA) project, could well demonstrate efficiencies at these levels by the time the project is completed in 1992. This project will use a series of 20-kW arrays to compare and evaluate current and emerging technologies, including crystalline silicon, amorphous silicon, and new thin-film materials; assess operation and maintenance costs within an electric utility; compare the most promising technologies in differing geographic areas (within different utilities); and provide U.S. utilities with hands-on experience in installation and operation of utility PV power-generation systems (*73*). Tests of the first set of emerging technologies at Pacific Gas and Electric's Davis, California, test site should begin in March 1989, and the first utility-scale demonstrations, 200-kW and 400-kW turnkey systems, should be built by the end of 1989. The project is expected to generate substantial utility interest in photovoltaics.

So, too, will the September 1988 agreement between Chronar Corporation and SeaWest Power Systems, of San Diego, to jointly develop a 50-MW, amorphous silicon PV power station to be completed in 1992 (*74*). If the completed project realizes its ambitious cost and efficiency goals, PV experts agree it will be the beginning of a new era in the development of PV technology that will make possible competitive, central utility power generation.

Future Trends

In a rapidly changing field such as photovoltaics, speculating about the future carries a certain amount of risk. Nevertheless, it appears that actively pursuing policies that focus on industry-government collaboration on technology and market development of photovoltaics could result in a total PV deployment in the United States of more than 1 GW by the year 2000 without unreasonable capital and R&D investments (*9*).

How rapidly could PV power deployment proceed? Photovoltaics has the advantage of a relatively short time period (1 to 2 years) required to bring a large (1-GW) power plant on-line. In light of this, researchers at Chronar Corporation have optimistically estimated that with an investment of approximately \$20 billion over the period from 1990 to 1995, approximately 10 GW per year of PV manufacturing capability could be in place by 1995, leading to 40-GW installed PV generating capacity by 2000 (*75*). An effort of this magnitude is likely to be handicapped by limitations in the availability of materials and processing equipment (*76, 77*), which would limit the industrial capability to bring manufacturing capacity on-line.

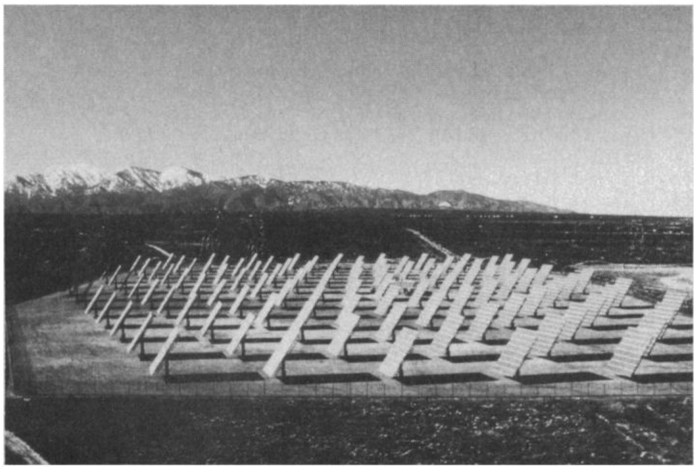

Fig. 7. The 1-MW PV plant on Hesperia Plains in California, built by ARCO Solar, Inc., in less than 1 year from inception. [Courtesy of ARCO Solar, Inc.]

Ten years of research has put PV technology for terrestrial power applications on a solid footing. Progress in the theoretical understanding of PV semiconductor materials and in the identification and development of candidate cell materials has presented cell designers with a wide array of choices, offering them the opportunity to tailor cells and modules to specific applications and markets. There is little doubt that the scientific and technological knowledge base necessary in order for photovoltaics to play its expected role, that of a major supplier of electrical power, is here. But continued research is necessary to optimize cell materials, cell designs, and PV systems.

There is also little doubt that there is a significant market for PV systems today and that over the next several decades it will become a multibillion dollar global market. There is strong international competition to determine who will supply that market. Currently the United States and Japan are leading, with Europe close behind. Japan leads in supplying cells for consumer products, whereas the United States leads in shipments of power modules. With the exception of the United States, leading PV-producing countries have maintained or increased government expenditures on PV research in the last 2 years. Germany and Japan now invest more in PV research than the United States, and by 1989 Italy's investment may also exceed that of the United States (*8*).

For the past decade most of the PV research in the United States has been conducted through or coordinated with the National Photovoltaic Program, planned and managed by DOE in collaboration with industry. The work is conducted in industrial and university laboratories as well as in DOE's support laboratories, the Solar Energy Research Institute and Sandia National Laboratory. The program has been a model of effective collaboration between industry and government (*78*).

The program has two major strategies in place to deliver economical electrical power to utility grids: (i) the development of concentrator and flat-plate PV systems based on high-efficiency crystalline cell and module concepts and (ii) the development of flat-plate systems based on thin-film cell and module technologies with emphasis on low material and processing costs (*79*). These strategies will be supplemented by directed basic research in solid-state materials, the development of advanced characterization techniques, and continued characterization of the solar radiation source. These efforts will be closely coupled to industry's own proprietary development progress and perceptions of market requirements.

The rate of penetration of PV power systems can be increased by a strong continued R&D effort but will be determined primarily by economic and policy considerations. It is clear that photovoltaics will soon offer U.S. utilities a realistic alternate peaking electricity-generation source with minimal environmental impacts and relatively short construction times. Global warming considerations may accelerate the rate of PV utilization for both peaking and base utility requirements. Consumer markets for PV-powered devices are expected to continue to grow. And PV power systems are likely to find favor in developing countries not yet committed to national grid networks. Underlying all of this development is the fact that, once installed, photovoltaics is a power system with low operation and maintenance costs that is immune to supply disruptions and fuel cost escalations. It has a bright future.

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81. I acknowledge the contributions of G. Cook and J. Phillips in the preparation of the manuscript. I also thank the members of the Solar Energy Research Institute staff for their valiant efforts to educate me. However, the article represents my personal viewpoint and I accept full responsibility for the content.