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Photovoltaic Power Systems: A Tour Through the Alternatives

A family of new technologies, rich in ideas, may provide the basis for many useful energy systems.

Henry Kelly

We probably know only slightly more about generating energy from photovoltaic devices than James Watt knew about producing mechanical energy from steam. Like Watt, we know that the technology works, we know something about the principles which govern it, and we can dare to speculate about a promising future. Indeed, it is very likely that photovoltaic arrays will be a common sight in less-well-developed nations and in remote parts of the developed world during the coming decade. With only a little more courage, we can envision photovoltaic-generating equipment becoming a major part of new U.S. generating capacity by the turn of the century. These promises, however, are clouded by a host of distressingly relevant questions.

In particular, we have only recently begun to think seriously about designing practical photovoltaic systems and about how these systems can best be integrated into national patterns of energy supply and demand. The number of alternative approaches turns out to be enormous, and the analytical basis for choosing between them surprisingly primitive. We do not know, for example, what the optimum size for such systems will be, we do not know whether we should emphasize the development of low-cost devices (which could perhaps eventually be used as integral parts of buildings) or the development of tracking apparatus or both, and we do not know whether cogeneration or total energy systems should be attempted.

It will be difficult to improve the present photovoltaic development program without answers to these questions. Criteria for components, for example, cannot be established without a clear understanding of the ways in which these components can contribute to integrated systems meeting real loads in real operating environments. Taking advantage of the opportunities presented by the torrents of emerging ideas will require a great deal of imagination and flexibility.

The most immediate barrier for all photovoltaic systems, of course, is the present high cost of the devices. In its latest procurement, the federal government was able to purchase flat plate arrays in quantities of tens of kilowatts for about \$11 per peak watt of output (*1*); electricity from systems using such cells costs \$1 to \$2 per kilowatt-hour.

Developmental work to reduce the cost of photovoltaic energy can be divided into three general categories: (i) reducing the cost of manufacturing the single crystal silicon cells that are now on the market; (ii) developing techniques for mass producing and increasing the performance of cells made from thin films of materials such as CdS/Cu_2S or amorphous silicon, and (iii) developing high-efficiency cells which can be installed at the focus of magnifying optical systems.

There is little doubt that it is technically possible to use any of these approaches to reduce costs to \$1 to \$2 per peak watt (electricity costing \$0.10 to \$0.40 per kilowatt-hour) during the next 3 to 5 years. Further cost reductions are almost certainly possible without any fundamental innovations, but costs below \$1 to \$2 per watt will, at a minimum, require a considerable amount of engineering development. Progress in any of a number of current research programs would give us greater confidence about meeting the lower cost goals.

A set of goals for reducing the cost of silicon photovoltaic devices was established somewhat arbitrarily during the crash "Project Independence" studies conducted in 1973. Officials in the Department of Energy believe that, with some relatively minor adjustments, these goals are achievable and are using them for planning purposes. The present goals for flat plate arrays (with 20-year+ life expectancies) are \$2 per watt by 1982, \$0.50 per watt by 1986, and \$0.10 to \$0.30 per watt in the 1990's (*2*).

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Markets

The level of private interest in manufacturing photovoltaic equipment will clearly be based primarily on perceptions about the commercial markets available at different prices. Photovoltaic sales are difficult to predict, however, because the market differs substantially from the market for other types of electricity-generating equipment. Since this equipment can provide power in remote areas where conventional alternatives are extremely expensive, a demand for photovoltaic devices exists at a large range of prices. The unique features of the equipment may lead to the discovery of markets for energy where no market now exists. The large price elasticity of markets, coupled with the fact that individual installations can be very small, has allowed an evolutionary growth in sales and a gradual reduction in cell prices.

The free world market for photovoltaic cells at 1976 prices was about 380 kilowatts (*3*), of which about 280 kW were sold by U.S. manufacturers. The U.S. government during this period purchased about 108 kW, of which about 50 kW were used in satellites (*4*). Major commercial markets have appeared in communications equipment (68 kW), corrosion protection for bridges, pipelines, and like applications (28 kW), and aids to navigation (20 kW) (*4*). Sales during 1977 were about twice those of 1976.

Several market surveys for photovoltaic equipment have been completed during the past several years, and some of these are summarized in Table 1. The considerable differences in the forecasts reflect differing judgments about the future cost of conventional energy and other forms of solar energy, about the rate at which an industrial infrastructure capable of supporting large-scale production can be established, and about the potential costs of support equipment (storage, controls, and other types of equipment) and installation. Some manufacturers, for example, have been skeptical about the high forecasts for small remote applications since many of these applications require a considerable amount of expensive marketing and engineering.

One point on which the surveys seem to agree, however, is that a significant fraction of sales during the next few years will occur in developing countries. Photovoltaic equipment is ideally suited to places where no utility grid is available and where labor for installing the equipment is relatively inexpensive. Consumers in the capital cities of many developing nations now pay as much as \$0.20 to \$0.25 per kilowatt-hour for electricity, and prices in more remote areas are often higher (if power is available at all) (*5*). The modular nature of photovoltaic equipment has the additional advantage of allowing functioning power sources to be installed quickly and in sizes appropriate for each application. Moreover, an investment in the photovoltaic power source does not commit a nation to finding a reliable source of fuel or to maintaining a highly trained group of operators.

Table 1. Market forecasts for photovoltaic devices at different prices (in megawatts of annual sales). Some of these projections include estimates of delays from an inability of the industry to grow rapidly enough to meet demands and an inability of the market to react to cost-effective applications as soon as they are theoretically available. The estimates are therefore not fully complete without a careful analysis of the impacts of these assumptions. Abbreviations: FEA, Federal Energy Administration; DOD, Department of Defense; DOE, Department of Energy.

Marketing study	Array prices in dollars per peak watt					Reference
	10	3	1	0.5	0.1–0.3	
BDM/FEA						
DOD market	10	75	100			(*6*)
Worldwide commercial market	1.5	20	70	100		(*3*)
Intertechnology Corporation	0.5	13	126	270		(*4*)
Motorola	1.5	20–30				(*52*)
Texas Instruments	0.4	2.6	30	100	20,000	(*53*)
RCA	0.8	13	200	2,000	100,000	(*53*)
Westinghouse					96,000	(*7*)
DOE planning objectives	1.0	8	75	500	5,000	

Other possible areas where sales of photovoltaic equipment may increase rapidly during the next few years include applications in the U.S. Department of Defense (where large purchases may be possible) (*6*) and the armed forces of other nations; the agricultural sector, for irrigation and other pumping applications; and the transportation industry, for markers and lighting (*3, 4*).

If prices fall below about \$0.50 per watt, an explosive growth in sales could occur since at this price photovoltaic equipment might be able to provide electricity which is competitive with residential and commercial electricity rates in many parts of the United States (*7, 8*). By the time prices fall to \$0.10 to \$0.30 per watt, photovoltaic electricity may be competitive with electricity sold at bulk rates to large industrial consumers. Estimating sales at these levels is extremely speculative since generating large amounts of power from photovoltaic devices would require a fundamental change in the ways in which this country now supplies and consumes electric energy. Moreover, when prices of photovoltaic arrays reach these low levels, the overall cost and attractiveness of photovoltaic systems are likely to be dominated by factors other than the cost of the cells themselves. Before turning to an analysis of integrated systems, however, it will be useful to examine the costs and capabilities of the assortment of photovoltaic devices which are or may be available in the near future.

Photovoltaic Cells

All photovoltaic installations will consist of arrays of small, individual generating units—the photovoltaic cell. Individual cells will probably range in size from a few millimeters to a meter in linear dimension. A surprising variety of such cells is available or is in advanced development since only during the last 5 years has serious attention been given to designing cells for use in anything other than spacecraft. Devices are available with a wide range of efficiencies, voltages, tolerance to high temperatures and high light intensities, and other characteristics. The variety should not be taken to suggest that this is an area where large amounts of private or public research funding has been directed; indeed, many of the projects that I will describe are being conducted by one- or two-man research teams in laboratories where one is likely to find the inventor hunched over a table soldering leads to his latest cell design.

The photovoltaic equivalent of power engineering is something of an anomaly in the power-generating industry since it involves manipulations in the miniature world of semiconductor physics instead of steam tables, gears, and turbine blades. The following discussion can provide only a very brief excursion through a complex field; more complete discussions of the topics covered can be found in several recent publications (*9–12*). The state of theoretical work in the field is quite uneven. Some areas have been examined extensively; in others, important effects remain to be explained.

The energy in light is transferred to electrons in a semiconductor material when a light photon collides with an atom in the material with enough energy to dislodge an electron from a fixed position in the material (that is, from the "valence band"), giving it enough energy to move freely in the material (that is, into the "conduction band"). A vacant electron position or "hole" is left behind at the site of this collision; such holes can "move" if a neighboring electron leaves its site to fill the former hole site. A current is created if these pairs of electrons and holes (the holes act as positive charges) are separated by an intrinsic voltage in the cell material. Creating and controlling this intrinsic voltage is the trick which has made semiconductor electronics possible. The most common technique for producing such a voltage is to create an abrupt discontinuity in the conductivity of the cell material (typically silicon in contemporary solid-state components) by adding small amounts of impurities or "dopants" to the pure material (this is called a "homojunction"). An intrinsic voltage can also be developed by the joining of two dissimilar semiconductor materials (such as CdS and Cu_2S) creating a "heterojunction" or by the joining of a semiconductor to a metal (for example, amorphous silicon to platinum) creating a "Schottky junction."

A fundamental limit on the performance of all of these devices results from the fact that light photons lacking the energy required to lift electrons from the valence to the conduction bands (the "band gap" energy) cannot contribute to photovoltaic current and from the fact that the energy given to electrons which exceeds the minimum excitation threshold cannot be recovered as useful electrical current. Most of the photon energy not recovered as electricity is converted to thermal energy in the cell.

The bulk of the solar energy reaching the earth's surface falls in the visible spectrum where photon energies vary from 1.8 electron volts (deep red) to 3 eV (violet). In silicon only about 1.1 eV is required to produce a photovoltaic electron, and in GaAs about 1.4 eV. Choosing a material with a higher energy threshold results in the capture of a larger fraction of the energy in higher energy photons but the loss of a larger fraction of lower energy photons. The theoretical efficiency peaks at about 1.5 eV, but it remains within 80 percent of this maximum for materials with band gap energies between 1 and 2.2 eV (*13*).

Electrons actually leave cells with energies below the excitation voltage because of losses attributable to internal resistance and other effects, not all of which are understood (*14*). (An electron leaves a typical silicon cell with a useful energy of about 0.5 eV.)

The same kinds of fundamental limits apply to photochemical reactions in which a light photon with energy about some fixed excitation threshold is able to produce a chemical reaction or a structural change which can be assigned a fixed energy. The theoretical limit to the performance of several types of cell designs are shown in Table 2.

The performance of real cells (also listed in Table 2) falls below the theoretical maximum for a number of reasons. One obvious problem is reflection of light from the cell surface (which can be reduced with special coating and texturing) (*15*) and reflection from the electrical contacts on the front surface of the cell (which can be reduced with careful design of the contacts). Losses also result from the fact that the photogenerated electrons and holes which fail to reach the region in the cell where they can be separated by the intrinsic voltage cannot contribute to useful currents. Photogenerated charges can be lost because of imperfections in the crystal structure of the cell, defects caused by impurities, surface effects, and other types of imperfections. Losses are minimized if a perfect crystal of a very pure semiconductor material is used, but producing such a crystal can be extremely expensive. Manufacturing costs can probably be greatly reduced if cells consisting of a number of small crystal "grains" can be made to operate with acceptable efficiencies. The size of the grains that can be tolerated depends on the light-absorbing properties of the cell material. If absorptivity is high, photovoltaic electron-hole pairs will be created close to the cell junction where the voltages exist and relatively small grain sizes can be tolerated since the charges need only drift a short distance before being sorted by the field. It is important that the grains be oriented

Table 2. Photovoltaic cell efficiencies. Techniques for reporting efficiencies differ. Wherever possible, efficiencies were chosen which assume air mass 1 and include losses due to reflection and contact shading.

Device	Probable maximum achievable efficiency	Maximum measured efficiency	Performance of commercial cells	Reference
	Silicon devices			
Single crystal homojunction	20–22	19	10–13	(*9, 54*)
Single crystal Schottky with indium-tin oxide	20	12		(*55*)
Polycrystalline homojunction	?	7–14 (?)		(*18, 19*)
Amorphous Schottky with platinum	15	5.6		(*22, 23*)
	Thin films			
CdS/Cu_2S (chemical vapor deposit process)(heterojunction)	15	8.6	2–3	(*12, 56*)
CdS/Cu_2S (spray process) (heterojunction)	8–10	5.6		(*40*)
$(Cd/Zn)S/Cu_2S$ (heterojunction)	15	6.3		(*56*)
$CdS/CuInSe_2$ (single crystal) (heterojunction)	24	12		(*57*)
$CdS/CuInSe_2$ (thin film) (heterojunction)	15	6.9		(*58*)
GaAs (homojunction)	25–28	15		(*9, 59*)
	Cells for use in concentrated sunlight			
Optimized silicon cell (single crystal homojunction), 200 times concentration	22	18	12.5	(*26, 29, 60*)
Interdigitated back-contact silicon, single crystal homojunction, 100 times concentration	26–27	15 (20?)		(*27*)
Thermophotovoltaic	30–50	13		(*31*)
$Ga_xAl_{1-x}As/GaAs$ (200 times)	25–26	24.5		(*61*)
$Ga_xAl_{1-x}As/GaAs$ (1700 times)		19		(*32*)
Multicolor cell (GaAs/Si/Ge)	40			(*35*)
Vertical multijunction (silicon)	31	9.6		(*62*)

with the grain boundaries perpendicular to the cell junction so that charge carriers can reach the junction without crossing a grain boundary.

Because silicon is a relatively poor absorber of light, silicon cells must be 100 to 200 micrometers thick to capture an acceptable fraction of the incident light (*16*). This limitation places rather rigorous limits on the sizes of crystal grains which can be tolerated, and all current commercial silicon cells are manufactured from single crystals of silicon. Some investigators believe that, if polycrystalline silicon is to be used, individual crystal grains must be at least 100 μm on a side if efficiencies as high as 10 percent are to be achieved (*17*). A number of research projects are under way to develop inexpensive techniques for growing such polycrystalline materials (*18–20*) and for minimizing the impact of the grain boundaries (*21*). Efficiencies as high as 6 to 7 percent have been reported for vapor-deposited polycrystalline silicon cells with grains about 20 to 30 μm on a side (*18*), and a proprietary process capable of producing grains nearly a millimeter on a side reportedly can be used to produce cells with efficiencies as high as 14 percent (*19*). Work is under way to improve crystal-growing techniques and to enlarge grains with lasers and electron beams.

Perhaps the most intriguing recent development is the discovery that an amorphous silicon–hydrogen "alloy" can be used to construct photovoltaic cells with useful efficiencies. Efficiencies of 5.5 percent have been measured (*22*), and 15 percent efficiency may be possible (*23*). The hydrogen apparently attaches to "dangling" silicon bonds, minimizing the losses that would otherwise result at these sites. Acceptable performance is possible in spite of the large number of remaining defects because the amorphous material is an extremely good absorber of light; test cells are typically 1 μm or less thick (*24*). The properties of this complex material are not well understood.

Cells made from GaAs or CdS/Cu_2S are also much better absorbers of light than crystalline silicon; cells made from these materials can also be thinner and smaller crystal grains can be tolerated than is possible with crystalline silicon. Commercial CdS/Cu_2S cells will probably be 6 to 30 μm thick (*12, 25*), and the crystal structure produced with a relatively simple spray or vapor deposit process is large enough to prevent grain structure from significantly affecting cell performance. The primary drawback of most of the "thin film" cells is that their efficiencies are quite low. Research is proceeding rapidly in a number of areas, however, and a number of thin film cells may be able to achieve efficiencies greater than 10 percent.

Enthusiasm about cells based on materials other than silicon must be tempered to some extent by uncertainties about the health hazards that they may present and about the domestic and world supplies of component materials. Both CdS and GaAs contain toxic materials, and, although it may be possible to reduce the hazards they present to manageable proportions, it clearly will be necessary to examine this issue with some care before their widespread use can be contemplated. Domestic supplies of cadmium will be sufficient to supply annual production rates in excess of several thousand megawatts a year, but production beyond this level could tax domestic supplies (*12*). Gallium supplies will probably not present problems since GaAs devices are likely to be used primarily in concentrating collectors. Silicon, of course, is nontoxic and plentiful.

Cells Designed for Use in Concentrated Sunlight

Achieving high cell efficiencies is important to reducing the cost of photovoltaic systems, since many of the costs of producing and installing the cells are related to cell area instead of power and high efficiencies reduce the land or building areas required for a given level of output. High efficiencies are, however, particularly important for cells used in concentrated sunlight since an increase in cell performance leads directly to a reduction in the area which must be covered with the magnifying optical equipment which is the most costly aspect of the system. Devices designed to optimize performance in concentrated sunlight are not inherently more expensive than ordinary cells, but high-intensity devices are always likely to be somewhat more expensive per unit of cell area because production rates will be lower and because more care will be taken in manufacturing them. Since the cells cover only a fraction of the receiving area, of course, much more can be spent on any individual cell.

The current from a photovoltaic cell increases almost linearly with increasing sunlight intensity, and the voltage increases slightly faster than the logarithm of the intensity. These effects would lead to an increase in overall cell efficiency except for the fact that the increased current densities in the cell lead to increased resistive losses and other effects. The design of standard silicon cells can be optimized for operation in intense sunlight if one carefully designs the wires used to draw current from the cells, optimizes the resistivity of the cell material, changes the thickness of the cell junction, and otherwise takes pains in cell manufacture. Efficiencies as high as 18 percent have been reported for silicon cells operating in sunlight concentrated about 300 times (*26*).

Several ingenious techniques have been suggested for improving the performance of silicon devices used in intense sunlight with novel designs. An "interdigitated back-contact" cell exposes an unobstructed wafer of pure silicon crystal directly to the sunlight. The junctions that produce the cell voltages, and that are attached to electrical leads, are entirely on the back of the cell. An efficiency of 15 percent at a sunlight concentration of 400 times has been reported for a preliminary version of this cell. It is believed that straightforward design improvements will result in cells that have an efficiency of at least 20 percent (*27*).

The resistance losses of cells operating in high concentrations can be reduced if one connects a number of silicon homojunctions in series (thereby reducing the current produced at a given power output) and illuminates the resultant multijunction device from a direction parallel to the plane of the junction (*28*). Designs for horizontal multijunction devices have also been proposed (*29*). Although in theory these devices should have high efficiencies, very little experimental work has been done. The highest efficiency measured to date is 9.6 percent (*29, 30*).

The "thermophotovoltaic" cells may be able to achieve efficiencies as high as 30 to 50 percent by shifting the spectrum of light reaching the cell to a range where most of the photons are close to the minimum excitation threshold for silicon cells. The sun's energy is used to heat a thermal mass to 1800°C (the effective blackbody temperature of the sun is about 5700°C). A large fraction of the surface area of this mass radiates energy to a silicon photovoltaic device. (Reradiation to the environment can occur only from the small aperture through which the sunlight enters.) A surface behind the photovoltaic cells reflects unabsorbed photons back to the radiating mass, thus preserving this energy in the system (*31*).

High efficiencies in intense radiation can also be achieved with GaAs cells, particularly if these cells are covered with a layer of $Ga_xAl_{1-x}As$, which has the effect of reducing surface and contact losses (9, p. 195). Efficiencies as high as 24.5 percent have been measured for such devices operating in sunlight concentrated more than 200 times (32).

Loferski has suggested that cell efficiencies could be increased if a number of cell junctions were used, each sensitive to a different color (33). An ingenious scheme for producing such a multicolor device has been recently proposed which uses a series of dyes capable of absorbing sunlight and reradiating the energy in a narrow frequency band matched to the band gap of each of a series of cell junctions (34).

Manufacturing Problems

With this background in some of the fundamentals of cell design, it will be possible to understand some of the difficulties faced in reducing the cost of manufacturing photovoltaic devices on a commercial scale.

Silicon. The vast majority of the photovoltaic cells now being sold are single-crystal silicon devices; the bulk of federal funding to reduce the cost of cells is being directed to silicon technology. The federal low-cost silicon project, managed by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology, has made a careful analysis of the component costs of each step in the manufacturing process and is systematically examining techniques for reducing costs in four major areas: (i) production of the pure silicon feedstock; (ii) preparation of a thin sheet of single crystal silicon; (iii) fabrication of cells; and (iv) arrangement of the cells in a weatherproof array.

The purified polycrystalline silicon used as the raw material in commercial cell manufacture now costs about $65 per kilogram. Estimates from JPL indicate that, if the goal of $0.50 per watt is to be reached, the cost of the silicon material must be reduced to about $10 per kilogram and the amount of silicon wasted in the manufacturing process considerably reduced (35). Perhaps even more important, present techniques for manufacturing silicon are extremely inefficient in their use of energy; approximately 7000 kWh of energy is required to manufacture a cell with a peak output of 1 kW (assuming that cells are 100 μm thick and 82 percent of the silicon entering the manufacturing process is wasted) (36). This means that the device must operate in an average climate for about 4 years before it produces as much energy as was consumed in manufacturing the component silicon.

Several promising techniques for improving the purification and reducing silicon wastage have been experimentally verified. It should be possible to develop devices capable of producing all the energy used in their manufacture in 3 to 4 months (36). A significant amount of chemical engineering and process development is needed, however, to demonstrate that these laboratory experiments can be scaled up by many orders of magnitude to form the basis of a commercial facility.

Silicon costs probably represent the single greatest technical barrier to meeting JPL's cost goals for nonconcentrating arrays in the early 1980's. This is so because plants capable of manufacturing silicon in quantities large enough to achieve the required cost reductions would need to be established very quickly—probably within the next year—and the investments required will be large, compared to previous spending in photovoltaic manufacturing. New plants are likely to require more capital investment per unit of cell production than any other stage in the cell production process, between $20 million and $40 million for a single plant. There is no incentive to invest in such equipment on this magnitude solely for the purpose of selling silicon to the semiconductor industry because material costs for these devices are already a small part of the device cost. Silicon prices, therefore, are unlikely to fall by 1982 unless the government takes some action. Development of an amorphous silicon cell with adequate performance would dramatically reduce silicon requirements in cells since these cells will probably require less than 1 percent of the silicon used in commercial cells. Silicon requirements can also be greatly reduced if concentrator devices are used.

Growing pure silicon crystals and sawing them into thin wafers now represents about 25 percent of the price of the arrays (37). There are a number of active programs for improving the batch processes in which crystal ingots are currently being produced and sawed (38); techniques have also been designed for drawing single crystal sheets or ribbons directly from molten silicon, but a considerable amount of engineering work must be done before a commercial process is available (35, pp. 71–72). Development of an ingot technique adequate to meet the cost goal of $1 to $2 per watt appears to be assured, and improved ingot techniques may even be adequate to meet the 1986 cost goal. The technological problems remaining appear to be largely ones of improving mechanical designs; this is another area where the program could be accelerated by the government. Although crystal-growing equipment is relatively expensive, unsubsidized commercial interest in this kind of equipment in the next few years is likely to be greater than commercial interest in advanced silicon refinement processes. Research progress which makes it possible to use polycrystalline or amorphous materials would substantially reduce the cost of this step in the production cycle.

The process of converting silicon sheets into an operating photovoltaic cell involves a number of individual steps which now require hours of hand labor (about 35 percent of the price of arrays). Processes include the creation of the photovoltaic junction, the addition of electrical contacts, and the application of antireflective coatings. Studies of mass production techniques conducted for JPL by Motorola, Texas Instruments, and RCA all indicate that this cost could be reduced to between $0.40 and $0.60 per watt (35, pp. 71–72) with existing production apparatus if plants capable of producing about 5 to 30 megawatts (electric) annually could be constructed. Projecting further price reductions, however, requires a fair amount of optimism. However, cell prices must fall to $1 to $3 per watt before there will be markets large enough to support several competing fabrication plants of the size envisioned in the JPL studies (Table 1). It is likely that manufacturers will show greater desire to invest in cell fabrication equipment than in the more capital-intensive devices required to manufacture silicon wafers because of the smaller investments required and because it is much less likely that fabricating plants would become obsolete even if breakthroughs dramatically reduce the cost of manufacturing wafers.

Finally, the cost of the process to connect cells together into arrays and encapsulate them to protect them from the weather must be reduced by a factor of 10 to about $0.02 per watt (35). A variety of techniques have been proposed and the cost reduction seems feasible, but the exact technique that will be used is not yet clear.

Thin films. The thin film technologies which show the greatest potential for reaching the cost goals early in the 1980's are all based on CdS/Cu_2S heterojunction cells. Photon Power, Inc., of El

Paso, Texas, is now completing a pilot plant which should begin making such cells in the near future. If the process works as well in large-scale production as it has in laboratory tests, the facility will be expanded into a small manufacturing plant which, it is hoped, will be able to produce arrays which can be sold for \$2 to \$5 per watt by 1980 (*39*). Low costs are possible because all of the processes in cell manufacturing (cell growth, junction formation, the application of contacts, and encapsulation) involve spraying a series of chemical layers onto hot glass moving through the plant on a continuous conveyor. Laboratory devices produced by a similar process have yielded efficiencies of 5.6 percent, and cells with efficiencies of 8 to 10 percent appear possible (*40*). Even higher efficiencies may be possible if the promising results of experiments in which zinc is mixed with cadmium can be integrated into the process.

Photon Power, Inc., is working with Libby-Owens-Ford (a part owner of the company) to design a process which can be attached to a float glass plant. It may be possible to produce cells for as little as \$0.05 to \$0.15 per watt in such a facility (*41*). The major technical challenge in increasing output will be finding a way to increase the speed of the spray application process from 2 centimeters per minute (which will be achieved in a pilot plant) by about an order of magnitude to match the rate at which glass is produced from a float glass facility (*39*). The SES Corporation (a Shell Oil subsidiary) has also been developing a CdS cell.

A number of other thin film technologies are now being examined. Many of these may eventually compete with CdS/Cu_2S but are now only laboratory processes.

Concentrator systems. The contribution of the cost of photovoltaic cells to the overall cost of an installed photovoltaic system can be greatly reduced if an optical system is used to concentrate sunlight on the cell. If such systems are used, problems of reducing cell fabrication costs are replaced with problems in designing low-cost mechanical equipment.

Concentrator designs can vary from a simple booster system consisting of an inexpensive reflecting surface placed adjacent to a flat plate array to massive devices that look like radar dishes. Concepts are emerging at an astonishing pace.

Most concentrating systems must move to follow or track the sun, but a design called the compound parabolic collector has been developed which can achieve concentration ratios of 9 to 10 for at least 7 hours each day with only ten position adjustments per year. The mirror shape developed for this design can also be used at the focus of other concentrating systems to reduce the requirement for high tracking precision (*42*).

A concentrator system based on use of a plastic doped with fluorescent dyes has recently been suggested which may be able to achieve concentrations on the order of 100 times with no tracking at all (*34, 43*). The dye molecules reradiate light that they absorb at a random angle. The reradiated light striking the receiving surface at an angle greater than the angle of total internal reflection and continues to be reflected until it reaches the edge of the sheet covered with the receiver. (The frequency of the reradiated light can be selected to optimize photovoltaic cell performance.) If the dyes have zero absorptivity at the reradiated frequencies, collection efficiencies as high as 60 to 75 percent are theoretically possible in 1- to 2-meter plexiglass cells (*44*).

In most other types of concentrators thin acrylic Fresnel lenses or inexpensive parabolic mirrors are used to achieve the needed concentration. Continuous mirrored surfaces or a series of segmented surfaces may be used. These surfaces can either be rigidly mounted together or rotated separately. In some tracking systems line-focusing optics are used to bring about rotation about a single axis (this axis can be the polar axis or it can be an east-west or north-south line normal to the zenith at the collector location).

The technology of concentrating systems is too primitive to permit any confident judgments about the cost goals that can ultimately be achieved. In principle, system costs can be quite low since the bulk of the receiving area of such devices need only be covered with a thin mirror or lens surface which may cost as little as \$5 to \$20 per square meter. Tracking system costs can also be quite low, particularly if many units can be driven from a single tracking motor. Wear on moving parts should not present a major problem since a system that would follow the sun for 30 years would only need to rotate 11,000 times. A major part of the cost of current structures results from the need to steady the equipment against strong winds.

One can obtain some feeling for the current state of the art by examining the concentrating devices now on the market for use with solar air-conditioning systems or with other solar thermal installations. Northrop Inc. is marketing a one-axis Fresnel device which costs (F.O.B.) \$130 to \$180 per square meter, and the Acurex Corporation sells an east-west single-axis tracking mirror system for about \$150 per square meter (F.O.B.) in large quantities. The Albuquerque-Western Company sells a one-axis tracking device for about \$50 per square meter (F.O.B.). Sunpower Systems sells a two-axis tracking unit for \$150 per square meter.

There is clearly much room for imagination and development work in collector design, and it is impossible to estimate future costs with any confidence. Projected collector costs (F.O.B.) on the order of \$50 to \$80 per square meter are optimistic but probably not unreasonable.

Assuming that concentrating systems cost 50 percent more than flat arrays to install and three times as much to operate on an annual basis, concentrator systems would be competitive with flat plate arrays costing \$500 per kilowatt-hour and having an efficiency of 15 percent if the concentrating collector costs about \$70 per square meter and concentrating cells had an efficiency of 20 percent. The concentrator could cost about \$180 per square meter if concentrating cells had an efficiency of 40 percent. (In this calculation I have assumed that the optical efficiency of the concentrators is 80 percent and that the concentration ratio is at least ten times the ratio of the cost of the concentrator cell to the cost of flat plate arrays.)

Most types of tracking collectors can only use light from areas of the sky close to the sun's disk; they cannot use diffuse sunlight scattered from clouds or atmospheric turbidity. They compensate for this deficiency to some extent by maintaining a better angle between the collector and the sun through the day. As a result, in many parts of the country there is no great difference between the amount of energy reaching a stationary flat plate system and the amount reaching a focusing device. In Albuquerque, for instance, a fully tracking collector with perfect optics would receive about 13 percent more energy annually than a perfect stationary collector tilted at an optimum orientation; in Boston or Omaha the tracking system would receive 6 to 8 percent less energy than the flat plate system.

Very little operating experience with tracking systems has been accumulated: information about maintenance costs (particularly in adverse climates), cleaning difficulties, and life expectancies is inadequate to permit confident judgments about the practical potential of the systems. The devices may not be appropriate in the remote, unattended installations that will probably constitute the bulk of U.S. installations during the next few years, but they may have applications in developing nations since their repair and cleaning would not require any special skill. The devices have the disadvantage of being rather ugly and ungainly, so that a great deal of imagination would be required to integrate them gracefully into a building or landscape. They clearly have enough potential, however, to be considered serious candidates for photovoltaic applications both in the near future and in the long term. Their importance could increase if it proves difficult to meet cost goals with flat plate arrays.

Although the cost of mounting cells on tracking collectors is clearly a major concern, there is also cause for concern about the cost of mounting flat plate arrays. If array prices fall below \$300 to \$500 per kilowatt, the cost of supporting and installing the arrays will begin to exceed the cost of the arrays themselves. General Electric has proposed a design for a photovoltaic shingle which it may be possible to substitute for roofing material (*44*). If costs reach \$100 to \$300 per kilowatt, it may become practical to use photovoltaic sheets as a part of a wall surface. In most locations in the United States, the output of a collector mounted vertically on a wall facing south, east, or west is 40 to 60 percent lower than the output of a collector fixed at an optimum orientation. There have also been proposals for lifting flat plate arrays into synchronous orbit (*45*).

Cogeneration

Thus far I have considered only the electrical output of collector systems, but the attractiveness of photovoltaic devices can be increased significantly if effective use can be made of the thermal energy carried away by water pumped over the back surfaces of collecting cells. Such systems are the photovoltaic analogs of cogeneration systems, and such devices have advantages similar to those of conventional systems. In both cases the net efficiency of the systems can only be understood if one examines the combined demands for electricity and thermal energy in each proposed situation. There are clearly many useful applications for thermal energy with temperatures of 60° to 170°C, which can be extracted from photovoltaic cogeneration devices: the heat which can be provided by such systems can be used for space heating, domestic hot water heating, and operation of absorption air-conditioners. About 2.6 percent of the industrial process heat used by U.S. industry is applied at temperatures below 100°C, and about 40 percent is applied at temperatures below 175°C (*46*).

With photovoltaic systems the critical question is whether the electricity-generating efficiency that is lost because of the high-temperature operation of the cells needed for a cogeneration application can be compensated by the value of the thermal energy produced. Cell performance degrades almost linearly with temperature at temperatures in the range from 50° to 200°C, primarily because of a drop in the operating voltage of the cell (at high temperatures, thermally excited electrons begin to dominate the electrical properties of the semiconductor device). High-efficiency cells such as GaAs cells are less affected by high-temperature operation than silicon devices (*9*, p. 166). A commercial silicon cell operating with an efficiency of 12 percent at 27°C has an efficiency of only about 8 percent if operated at 100°C (*47*), whereas a GaAs cell with an efficiency of 18.5 percent at 28°C can operate with 16 percent efficiency at 100°C and about 12 percent efficiency at 200°C (*48*). In most cases, if a use for low-temperature thermal energy exists, it is preferable to accept these losses of efficiency and to use the thermal output from cells directly rather than to maximize cell performance and attempt to use a heat pump to produce thermal energy.

It is possible to operate flat plate collectors at elevated temperatures, but cogeneration will probably be easier to justify for concentrating systems. Care must be taken to cool concentrator cells even if waste heat is not used, and much less area needs to be covered with cooling apparatus. The long-term prospects for concentrator systems may be significantly improved if photovoltaic cogeneration proves to be attractive.

Backup Power

Selecting an optimum approach to providing backup power for photovoltaic equipment is in some ways the most subtle and difficult problem that must be confronted in analyzing different photovoltaic system designs since it involves institutional as well as technical issues. The problem is particularly complex when photovoltaic systems are integrated with a conventional electric utility.

A utility connection makes it necessary to evaluate the performance of the photovoltaic apparatus as a part of an integrated system which includes a variety of types of generating and storage devices. The problem is not simplified if the photovoltaic equipment is owned by individuals or organizations other than the utility since the costs of less than optimum systems will be communicated to these owners through higher rates for backup electricity purchased and lower rates for any energy sold to the utility.

If the photovoltaic equipment is tied into an electric utility, charging storage equipment from photovoltaic generators seems almost always to be a mistake. A photovoltaic system without a grid backup would charge batteries during the day when utility loads peak and when a utility would be discharging storage, and photovoltaic energy would be withdrawn from storage at night when utility energy is least expensive and when utility storage is being charged. There will be some overlap between the two operating strategies since both types of storage would be discharging near sunset and during cloudy days. It is clear, however, that storage equipment can be used to best effect if it is controlled by the utility. The use of photovoltaic electricity to serve daytime utility loads directly has the additional advantage that smaller amounts of the energy generated would need to be cycled through storage devices which typically have an efficiency of only 75 percent. Design of the storage systems by the utility is also preferable because the utility has access to a greater range of storage opportunities than are available to a small photovoltaic system. Pumped hydroelectric facilities, for example, can be used to provide economical storage when sites are available. If low-cost batteries are developed, utilities may choose to locate battery storage installations at many small load-leveling centers in order to minimize transmission and distribution losses, but the small centers would still be best operated in coordination with the utility as a whole. This logic would apply even if a very large fraction of the utility's energy were derived from solar sources, although in this case the strategy of operating individual storage systems would closely parallel the operation of utility storage.

There are several exceptions to this general line of logic. Photovoltaic cogenerating equipment will almost certainly be designed with on-site storage of thermal energy since energy stored in the form of hot water costs much less than electric storage. There may also be instances where on-site cogenerating devices based on the use of fossil fuels would be less expensive than utility backup power in spite of the poor load factors inherent in backup allocations or if photovoltaic systems capable of providing 100 percent of the energy needs of a building or region can be constructed which provide power less expensively than devices integrated with utility equipment. (Uneven load factors are usually not serious problems for gas utilities or oil delivery systems where storage costs are relatively low.)

The argument in favor of connections between photovoltaic systems and electric utilities clearly does not apply if regulatory procedures or other regulatory distortions prevent the utilities from constructing a rate schedule which accurately reflects the cost of backup power at different times or which accurately reflects the value of power sold back to the utility.

The fact that solar energy is available primarily during periods of utility peak demands means that utilities will not necessarily need to maintain generating equipment sufficient to provide 100 percent of the installed photovoltaic capacity as backup. A study conducted by General Electric has indicated that a utility in Phoenix would only need to maintain a backup capacity equal to between 40 and 65 percent of the peak capacity of the photovoltaic devices installed in a utility in that region, whereas a utility in Washington, D.C., would need to maintain 70 to 80 percent of the photovoltaic capacity as backup (*44*, p. 34). The need to maintain backup generating capacity decreases the value of photovoltaic equipment to a utility, and thus reduces the price which it would be willing to pay for photovoltaic electricity when it is available. One of the conclusions of the General Electric study was that the value of photovoltaic equipment to a utility in Phoenix would be on the order of \$350 to \$500 per watt, with equipment in Washington, D.C., valued about 1/3 less (*44*, p. 33). The value was reduced if photovoltaic equipment represented more than a small fraction of the utility load. Development of low-cost storage of any kind would clearly make photovoltaic equipment somewhat more attractive to utilities. There are a number of advanced battery systems under development which may be able to reduce the cost of storage to \$10 to \$40 per kilowatt-hour (*49*).

The problem of developing an optimum integration of photovoltaic systems of differing sizes into existing electric utilities is an extremely complex one and will clearly require considerably more thought. There is unlikely to be a single clearly preferred relationship since utility costs are very sensitive to climate, the types of equipment owned by the utility, the design of the photovoltaic system and the strategy with which the system operates, and the amount of photovoltaic power produced in a utility service area. However, although the widely fluctuating backup loads required by photovoltaic power systems are far from ideal from the perspective of electric utilities, many types of on-site energy-consuming equipment (such as air-conditioners and heat pumps) also im-

Table 3. A comparison of the performance of several photovoltaic systems associated with an apartment building in Omaha, Nebraska (*30*). The following assumptions were made: that utilities will purchase excess on-site energy at 50 percent of their sale price and that utility power will be purchased at prevailing rates (including demand charge); that thermal storage costs \$0.50 per kilowatt-hour; and that two-axis tracking collectors cost \$140 per square meter installed. Details of other assumptions can be found in (*8*). For case 1, the cost of nonsolar energy is assumed to increase only with inflation (5.5 percent); for case 2, nonsolar energy prices increase 40 percent by the year 2000 and solar devices are given a 20 percent investment tax credit. Low-cost arrays are associated with lower cost installation and support equipment.

Equipment used	Cell efficiency (%)	Collector area (m²)	Percentage of annual building energy requirements met with solar energy	Case 1*		Case 2	
				Effective cost of solar energy† (¢/kWh)	Levelized monthly cost to consumer (\$/month)	Effective cost of solar energy† (¢/kWh)	Levelized monthly cost to consumer (\$/month)
Conventional all-electric system				3.9§	81– 87‡	4.9§	107–114‡
\$100/kW thin film (on vertical south wall)	10	2,000	5.2	3.3– 8.3	79– 84	2.3	103
Thin film on racks							
\$300/kW	8	4,000	11.5	9.7–15.2	91–101	6.7	109
\$100/kW	10	4,000	14.8	6.2– 9.9	86– 95	4.3	104
Flat plate silicon on racks							
\$1000/kW arrays	14	4,000	19.2	16.3–23.6	120–143	11.2	126
\$500/kW arrays	14	4,000	19.2	9.2–13.7	97–112	6.3	110
\$500/kW arrays with (3000 kWh of batteries at \$37/kWh)	14	4,000	18.4	11.6–16.7	103–119	8.3	115
Two-axis tracking							
Silicon cells (cogeneration)	20	2,500	43	3.7–6.0	86–103	2.6	94
High efficiency cells	40	2,500	49	3.9–6.1	90–108	3.0	105
Two-axis tracking with seasonal thermal storage (1.1×10^6 kWh), GaAs cells	22	2,756‖	74.1	5.0– 7.8	102–138	3.3	88
Two-axis tracking, GaAs, seasonal thermal storage (0.6×10^6 kWh) and seasonal electric storage (3.3×10^4 kWh at \$11/kWh)	22	11,500‖	100	8.6–12.4	166–231	6.1	123

*Lower cost assumes that the solar device was financed with the apartment building; higher cost assumes utility ownership. †The effective cost of solar energy is computed by dividing the difference in electricity purchased by the difference in capital and operating expenses for buildings operating with and without solar equipment. ‡Range reflects different types of heating equipment. §Levelized cost of conventional energy (cost levelized over 30 years). ‖Collector arrays (including required spacing) will not fit on parking lot and roof.

pose extremely erratic loads. The real costs of meeting these loads are also difficult to evaluate.

Analysis of Integrated Systems

Having looked at the problems and benefits of a number of different aspects of photovoltaic power, it is now possible to review the performance of several representative system designs. Table 3 compares the performance of a number of systems designed to meet the energy requirements of a typical 10-story, 196-unit high-rise apartment building located in Omaha, Nebraska. With the exceptions noted in the table, all of the systems listed can be located on the roof or over the parking area associated with the building (assumed to be 4300 m^2). Omaha is a particularly unfavorable location for photovoltaic apparatus because it receives relatively little sunlight and its electricity costs are relatively low. The cost of photovoltaic energy in sunny regions of the United States would be 30 to 40 percent less expensive than the costs shown. In computing costs, actual utility rates in Omaha were used (including demand charges) and it was assumed that utilities purchased excess on-site energy at 50 percent of the sales price. Photovoltaic costs in Table 3 are compared with commercial electric rates and not with the higher marginal costs of electricity from new generating plants.

The great value of cogenerating equipment can clearly be seen in this example. In this particular application, the value of the high-efficiency cells is not exploited since the ratio of electric to thermal output from the device is too high. The high-efficiency cell would be much more attractive in an installation where the ratio of electric to thermal demand was higher. The relatively low cost for the cogeneration devices holds, even though tracking devices are assumed to cost \$135 per square meter (installed).

The advantage of using the low-cost photovoltaic equipment as a building material can be clearly seen from Table 3 since this application produces the lowest cost energy of any system shown. The apartment building chosen for this study is not well suited to this application, however, since it has a small roof area in relation to the available floor space and the south wall can only provide about 5 percent of the energy needs of the building. The cost of racks and mounting represents a significant fraction of the costs of the other flat plate systems (\$45 to \$60 per square meter).

The fraction of a building's energy requirements that can be met from any given collector area depends most critically on the extent to which attention is paid to conserving energy in the building; high-efficiency collectors require about as much land area as lower efficiency flat plate devices since tracking collectors must be spaced so that they do not shadow each other. Storage requirements could be reduced if occupants were willing to defer energy-consuming activities during cloudy periods. (The best strategy for shifting loads will, of course, depend on the pricing relationship with the utility that is providing backup power.)

The analysis of the system shown in Table 3, which is entirely independent of the utility, postulated successful development of the iron redox battery, being developed for the photovoltaic demonstration project at Mississippi County Community College in Arkansas. This battery can store energy inexpensively by means of a tank of iron chloride. The battery system (installed) was assumed to cost \$11 per kilowatt-hour (*50*).

Economies of Scale

Apart from the possibility that large purchasers might obtain some discount in purchasing equipment, it is difficult to find clear economies of scale in photovoltaic systems. In fact, smaller systems enjoy a number of advantages. (i) They can be built more rapidly than larger systems, thus reducing the interest paid during construction and reducing the lead time over which the demand for new generating equipment must be forecast. (ii) They can be more effectively tailored to the requirements of the individual load being served (in particular, it is much easier to use the thermal energy produced when collectors are close to the buildings that will use the thermal energy). (iii) Locating systems on the roofs or walls of buildings reduces the requirement for land. (iv) Locating the generating equipment close to the buildings which will ultimately use most of the energy produced reduces the demand for transmission and distribution equipment. (v) The small equipment can be built by local building contractors and local labor much like the conventional heating and cooling systems for new buildings.

Many types of buildings in densely populated urban areas may not be able to utilize the photovoltaic equipment effectively, however, because they are shaded during much of the day. These problems can be minimized in carefully designed new communities, but they represent a major barrier in retrofitting.

It should be understood, however, that the utilization of small photovoltaic systems does not necessarily imply non-utility ownership. There is reason to believe that utilities, which will compare the cost of photovoltaic energy with the marginal and not the average cost of electricity, may find photovoltaic equipment economically attractive before other types of users.

What Happens Next?

In spite of the promising potential of the technology, commercial interest in photovoltaics could grow rather slowly over the next few decades. Prospective manufacturers are likely to be conservative about investments in the area for several reasons. First, there is concern that markets may not prove adequate to support the production volumes required to significantly reduce the prices of photovoltaic cells—market projects are necessarily speculative since photovoltaic devices have no established record in many areas where markets will need to be found. Second, there is concern about investing in manufacturing equipment that may become obsolete before the end of its productive life as a result of progress in manufacturing technology. (It is ironic that the technology is almost paralyzed by the number of alternatives available; prices cannot be reduced rapidly without a large investment in a single approach.) Finally, there is considerable confusion about the commitment of the federal government to photovoltaic technology and about the continuity of federal support. The increased funding for photovoltaic purchases for federal installations that has now passed both houses of Congress in some form will provide some continuity to federal interest in the area, but time will be required to measure industry's response.

The fears leading to hesitation in the private sector are also affecting federal planning since there is concern that a premature decision to support a particular photovoltaic approach may leave the government financing an obsolescent technology. It is becoming increasingly apparent, however, that without a major federal commitment to a specific process for manufacturing silicon devices, the cost goals for the early and mid-1980's are unlikely to be met. But how much should the government be willing to invest in a single approach when it is unlikely that the energy produced from experimental equipment will be able to compete in ordinary commercial markets? One basis for comparison is provided by the proposal to spend about $2 billion in federal funds for the Clinch River breeder reactor design. This project will produce subsidized electricity for Tennessee utility customers with a capital cost of about $5 per peak watt or about $10 per average watt (assuming a 50 percent load factor) (*51*). A substantially smaller federal outlay would almost certainly result in the development of a process for producing photovoltaic arrays for $1 per peak watt (or less) which could be installed in remote areas with all necessary supporting equipment costing about $10 per average watt.

Although the technology of photovoltaics must be viewed as a potentially major energy source in the future, confident predictions cannot be made. Perhaps the greatest uncertainty arises from the fact that there is no reliable way to forecast the future cost of energy from conventional sources or for determining how much society may be willing to pay for the social and environmental benefits of solar energy.

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