Photovoltaics: The Semiconductor Revolution Comes to Solar

If there is a dream solar technology it is probably photovoltaics—solar cells. These devices convert sunlight to electricity directly, bypassing thermodynamic cycles and mechanical generators altogether. They have no moving parts and are consequently quiet, extremely reliable, and easy to operate. Photovoltaic cells are a space age electronic marvel, at once the most sophisticated solar technology and the simplest, most environmentally benign source of electricity yet conceived.

The federal solar research program, however, has not sought aggressively to realize the photovoltaic dream. Despite growing evidence that such devices could become a competitive source of on-site power within a decade, the Energy Research and Development Administration (ERDA) characterizes photovoltaics as a long-range option with significance only in the next century. The agency's current budget allots $59 million for photovoltaic research—less than one-seventh of that being spent on fusion—and the proposed budget for fiscal year '78 would cut even that modest amount somewhat. Agency officials are considering reorienting the program to give additional emphasis to large, utility-scale applications.

This is the third in a series of Research News articles examining recent developments in solar energy research.

The skepticism of federal energy planners regarding photovoltaics is understandable, because these devices are the most expensive source of solar power now available. Prices must drop 20- to 40-fold before photovoltaic cells could come into general use as a source of on-site power, and further reductions are needed before central power stations would be feasible. The manufacturing processes applicable to photovoltaic cells and related semiconductor devices are an unfamiliar art to those outside the industry, and officials whose experience is primarily with conventional mechanical or nuclear energy systems find the possibility of such staggering cost reductions hard to believe. Their skepticism is widely shared within the electric utility industry. On the other hand, semiconductor manufacturers and observers familiar with the even larger cost reductions routinely achieved for electronic devices based on semiconductors contemplate the problems facing solar cells with equanimity or even optimism.

Private Efforts Accelerate

Ironically, the federal photovoltaic research effort is credited by many observers as being perhaps the best conceived and most successful of the government solar programs. Despite its designation as a long-term option, the program has an ambitious set of goals that would make photovoltaic power widely available by 1986. Not only is it achieving improvements in the efficiency and reductions in the cost of silicon solar cells at a more rapid rate than that projected by its plan, but it also appears to have stimulated private industry into activity. Researchers at several major semiconductor manufacturers say that the ERDA program has attracted the attention of corporate management to the potential for near-term markets and resulted in the establishment or upgrading of proprietary development efforts. Private efforts have accelerated in the past year, and there are even indications that the smart money is betting on photovoltaics—oil companies, including at least four major firms, have concentrated their solar investments in photovoltaic technologies.

The prospects for photovoltaic power depend more on the application of mass production methods to known techniques than on fundamental breakthroughs or new concepts. Solar cells already exist and have for years reliably powered most space satellites. Modern photovoltaic devices were developed at Bell Laboratories in the early 1950's, not long after a related semiconductor device, the transistor. Unlike the transistor, however, there was at the time no prospect of a mass market and the emphasis in developmental work for space applications was on reducing weight, not cost. Even now, cells manufactured for terrestrial applications (and sold for prices 50 times lower than those that prevailed a few years ago in the space market) require between 10 and 100 man-hours of handwork per kilowatt of generating capacity. Complete automation has yet to be achieved.

Several different photovoltaic approaches are being pursued in the attempt to reduce manufacturing costs. The bulk of the federal program is based on cells cut from huge crystals of silicon, the dominant commercial technology. Both stand-alone, "flat plate" arrays of cells and those designed for use with a solar collector that concentrates the sunlight are being pursued. But conventional silicon faces stiff competition on both fronts. Many investigators believe that thin films of cadmium sulfide, amorphous silicon, or other materials offer a less expensive approach for flat plate arrays. And for concentrating systems, where the cost of the cells themselves is less crucial than high efficiency, designs based on gallium arsenide are attracting increasing attention. Other, novel approaches that may permit conversion efficiencies as high as 50 percent are being considered. Events are proceeding so rapidly that there is no consensus yet as to which approach is most likely to prove successful.

There is general agreement that concentrating systems are likely to accelerate the cost-cutting process. Arrays of silicon cells now cost about $15 per watt of generating capacity in full sunlight. Reduction to about $1 per watt—a cost that is expected to make feasible a broad range of specialized applications—is widely anticipated as early as 1980, particularly for concentrating systems. Cells designed for energy densities of 100 suns (100-fold concentration), for example, do not cost appreciably more than those designed for 1 sun, but generate 100 times as much power, so that the cost of the concentrating system rapidly becomes the limiting factor. A recent report* by the congressional Office of Technology Assessment (OTA) finds that "concentrating systems can be developed which provide photovoltaic electricity in the next few years costing no more than $1200 per peak kilowatt."

Below $1 per peak watt, however, things get more difficult, and many observers believe that only flat plate arrays will be able to achieve further price reductions. The ERDA goal is $0.50 per peak watt for flat plate arrays of silicon cells by 1986—a figure that program officials acknowledge was chosen as a ballpark one which would be necessary before on-site photovoltaic power could be generally competitive. Despite this, there is growing evidence that it is an attainable goal. Within the last year, according to observers familiar with the

**Application of Solar Technology to Today's Energy Needs* (Office of Technology Assessment, Washington, D.C., June 1977).

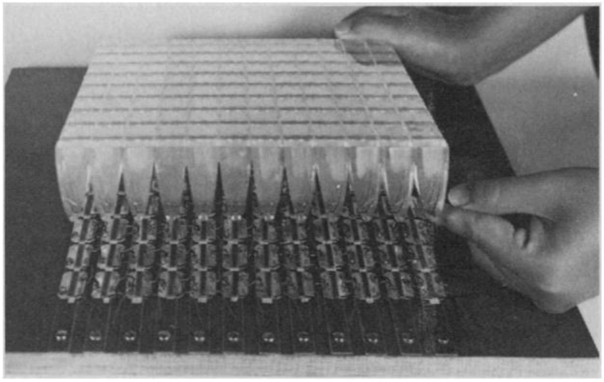

Fig. 1. A concentrating collector being put in place on top of an array of silicon photovoltaic cells. The concentrator is of a type known as a compound parabolic collector; this one, made of acrylic, concentrates sunlight by a factor of 10. The design has the unusual feature for concentrating systems that it can be used like a flat plate, without sun-tracking equipment. [Source: Argonne National Laboratory]

semiconductor industry, several of the major companies that are analyzing possible production methods for the ERDA program have convinced themselves that $0.50 per watt can be achieved, without any breakthroughs, by simply extending and automating present procedures. Paul Rappaport, the new head of the Solar Energy Research Institute and a recognized photovoltaic authority, says that the cost goal "is doable" if dedicated processing plants large enough to turn out 50 megawatts of generating capacity a year are built. The OTA study, comparing the ERDA cost goals to historic learning curves that describe how prices have declined as production volumes increased for other semiconductor devices, characterizes them as "optimistic but not impossible," provided near-term markets for solar cells can be found.

Much of the optimism regarding low-cost silicon cells stems from recent systems studies and laboratory work done for the Jet Propulsion Laboratory (JPL), which is managing the flat plate silicon program for ERDA. Although the effort has so far generated more paper than cells, it is credited with having tapped some of the best industrial talent in the country. One key area is material costs—the extremely pure semiconductor grade of silicon now used to make cells costs $65 per ton and is a substantial component in the cost of the final product. Moreover, cells made with present techniques would have to operate about 12 years to recoup the energy expended in their manufacture, in part because the raw silicon is melted and remelted so many times during purification and crystal growth that it is among the most energy-intensive commercial materials in the world. But studies by Dow Corning and Union Carbide, among others, indicate that a sixfold decrease in the cost and a tenfold or greater reduction in the manufacturing energy for solar-grade silicon are feasible. Another major problem with present techniques is waste. About 80 percent of the purified silicon is left as scrap in the crucibles used to grow large cylinders of the material in crystalline form, or ends up as sawdust when the thin wafers used to make cells are cut from the cylinder. Methods of growing larger cylinders, of recharging the crucibles, and of sawing thinner slices—for example, by a new laser slicing technique being developed by Texas Instruments—are expected to reduce this waste by at least half.

The bulk of the cost of a silicon cell, however, comes from the many mechanical steps required to convert the raw wafer into a commercially useful product. Controlled amounts of impurities are diffused into the silicon to create a *p-n* junction—which creates a kind of internal electric field that propels positive charges in one direction and negative charges in the other. (Pairs of such charges are created when sunlight is absorbed in the cell.) A grid of metal contacts must be attached to the front and rear of the cell to collect the charges that migrate there and thus create a flow of current. Finally, individual cells must be assembled into an array and encapsulated to protect against deterioration.

Much of this is now done by hand, but studies by RCA, Texas Instruments, and Motorola have indicated that the cell manufacture and assembly steps can be streamlined and largely automated with substantial reductions in cost. Beyond that, improvements that are well established but not now used in solar cell manufacture are being considered—such as the use of ion implantation techniques for introducing impurities during cell manufacture. Apparently such studies have convinced these companies, experienced in assessing and manufacturing semiconductor products, that silicon cells have a future. Motorola recently announced that it is entering the solar cell business, and the others are known to be studying the prospect closely.

Still further cost reductions in silicon could come if the necessity to grow and slice large cylinders of silicon could be avoided. Development work for JPL on a process for growing continuous ribbons of crystalline silicon is going on at Mobil-Tyco and IBM. Efficiencies as high as 11 percent have been demonstrated with cells made from the ribbon, but the process introduces unwanted impurities into the silicon and is not yet as rapid as the traditional method. Several other processes for producing sheets of silicon are also being studied, but all of the ribbon and sheet processes are still regarded as uncertain by most observers and the current optimism is not based on their prospects.

Within the last year there has also been a surge of enthusiasm for concentrating photovoltaic systems based on what appear to be very attractive economics—at least for the short run. The systems under consideration are designed to operate at a range of concentrations from tenfold to well over 1000-fold. At high concentrations most collectors will require active cooling, because the performance of photovoltaic devices degrades as temperatures increase; this prospect has stimulated consideration of photovoltaic total energy systems that would produce low-temperature heat as well as electricity. A variety of innovative concentrating collectors have been designed, and some of them are being tested at ERDA's Sandia Laboratories. With one exception (Fig. 1), the concentrating photovoltaic systems under development will be sun-tracking, which may limit their use in some applications.

Most observers believe that high efficiency will prove to be the overriding requirement for photovoltaic cells to be used with concentrating systems. This accounts for a growing interest in gallium arsenide cells, despite the fact that they are now as much as ten times as expensive as silicon. Varian Corporation has demonstrated an experimental system that operated with 19 percent efficiency at a concentration of 1735 suns—sufficient to produce electricity at a density of 0.24 megawatt per square meter of cell area. IBM recently announced that experimental gallium arsenide cells made with a novel and potentially inexpensive epitaxial growth technique showed an efficiency of 22 percent. An additional advantage of gallium arsenide cells is that they can tolerate higher temperatures than silicon, up to 200°C with only modest losses in efficiency—high enough for many solar thermal and total energy applications.

Still higher efficiencies may be possible. Texas Instruments has announced a new high-efficiency design for silicon cells based on two superimposed p-n junctions in the same cell. Varian researchers are also working on multiple junction cells that would consist of two or more cells, using different parts of the solar spectrum, stacked one on top of the other; the theoretical efficiencies for such cells approach 40 percent. An even more provocative idea, being pursued by Richard Swanson at Stanford, is to convert the solar spectrum to a form in which photovoltaic cells can make better use of it. This approach, known as thermophotovoltaics, makes use of a complicated geometry and a refractory radiator; light that passes through a photovoltaic cell unused is absorbed and reradiated to the cell by the refractory material, in the process lowering its wavelength. In effect, the device recycles light until 30 to 50 percent of it is converted to electricity, according to Swanson's calculations with computer models. He is now fabricating experimental devices, and a Stanford engineering group is preparing to launch a major effort to develop the concept.

The Varian and the Stanford researchers, among others, believe that high-efficiency concentrating systems are the best approach for photovoltaics, and they doubt that flat plate arrays will ever be cheap enough for widespread use. At the other extreme are those who believe that flat plate arrays made from thin films of polycrystalline or amorphous semiconductor materials can be made so cheaply that they are inevitably the way of the future, despite the low efficiencies in present devices. Rappaport, for example, says that "the technology of thin films is still in its infancy" and that they may ultimately prove a major competitor not only of concentrating systems but also of conventional crystalline silicon cells. One indicator that buttresses this point of view is the degree of private investment in thin film techniques and manufacturing facilities.

Optimism about the possibility of dramatic cost reductions with thin film techniques is based on savings in both material and manufacturing effort. Large areas of photovoltaic material can, in principle, be quickly formed by chemical deposition or spray techniques, eliminating the need to grow crystals; these techniques also lend themselves to the incorporation of additional processing steps in the same operation, and thinner cells, typically a few micrometers or less in thickness, can be formed. The only thin film cell now commercially available is based on cadmium sulfide, for which the efficiency of arrays of commercial cells is less than 5 percent, necessitating substantially more cell area than would be required to produce the same power from silicon.

Despite this disadvantage, two firms are now gearing up to produce these cells in large quantities. Solar Energy Systems of Newark, Delaware, a subsidiary of Shell Oil, already markets cells made with a batch, vacuum-deposition process at prices competitive with those for silicon cells. Photon Power of El Paso, Texas—originally a subsidiary of the D. H. Baldwin Co. but now primarily owned by the French national oil company—is developing a chemical spray technique in which solar cells are formed directly on hot float-glass. Observers familiar with both processes speculate that cells could be produced in large quantities with either method for prices of about $2 per watt or less—possibly much less if the Photon Power approach can be made to work in a combined facility that would produce both glass and cells.

Thin Films Are Promising

Still other potentially inexpensive thin film materials are being developed. At RCA, for example, investigators are experimenting with an alloy of amorphous silicon and hydrogen. The hydrogen, which can be added in varying amounts up to about a one-to-one atomic ratio, acts to increase the absorption of light in the film and to improve its photovoltaic properties. The RCA group has made cells with efficiencies of 6 percent and expects to reach as high as 10 percent within a few years. Other investigators are studying cells analogous to cadmium sulfide cells, but in which indium phosphide or copper indium selenide is also used, which have shown laboratory efficiencies of 12 percent.

The basic unit for photovoltaic power systems is an array of cells producing up to a few tens of kilowatts. Even large central power stations, if they were constructed, would be built up from units of this size. Thus photovoltaic systems are inherently modular, perhaps more so than any other solar technology. Engineering studies conducted for ERDA's Sandia Laboratories indicate that there is a substantial residential market for photovoltaics, for example, and that there is no technical reason why they cannot compete with other sources of electricity on all scales. Nonetheless, the dominant line of thought within the ERDA program is that photovoltaics can have a major impact only if large, utility-scale applications can be found. "My view," says Henry Marvin, director of ERDA's solar energy division, "is that the only way to get the cost down is to service some large installations—megawatt size." One knowledgeable critic describes this approach as "a misapprehension; distributed applications have to be the way of the future." Because photovoltaic technology is so modular, however, the agency's centralized bias does not yet appear to have affected the technical choices made within the program to the extent evident in other solar programs.

There already exists a market for terrestrial photovoltaic power systems. Silicon cells with a capacity of about 350 kilowatts were sold in 1976, in part to the government program but also for such applications as protection of pipelines against corrosion and power supplies for remote Forest Service watchtowers. A recent study done by the Department of Defense for the Federal Energy Administration forecasts a substantial near-term market, eventually as large as 100 megawatts per year, at remote military installations and says that photovoltaic systems for such applications are competitive even at current prices.

One major on-site application now being actively studied by industry is in electrochemical plants, for which the low-voltage, direct current produced by photovoltaic cells is ideal; because the plant could adjust production to changes in the amount of sunlight available, storage of electricity would not be necessary. Observers familiar with the electrochemical industry say that this market could amount to several thousand megawatts. Given a market, many observers believe that one or more manufacturing plants, each capable of producing as much as 100 megawatts of photovoltaic capacity per year, could be built within 2 years.

Photovoltaic technology is advancing at an explosive rate, and the richness of the technical options already under investigation is a strong argument that one or more of the approaches to reducing costs will work out. Knowledgeable observers of the semiconductor industry such as John Linvill, chairman of the Stanford Electrical Engineering Department, and Lester Hogan, vice-chairman of the board of Fairchild, say in a recent article that "we believe that photoelectric conversion of solar energy can be made viable as a source of power for terrestrial use within a decade." But ERDA, in casting photovoltaics as strictly a long-term option and severely restricting its funding, appears intent on ignoring both the stated objectives of its own subprogram and the signs of dynamism in private industry.

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