Solar photovoltaic energy

The study conducted for The American Physical Society investigated general systems questions, solar cell technologies and directions for future research.

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John H. Martin

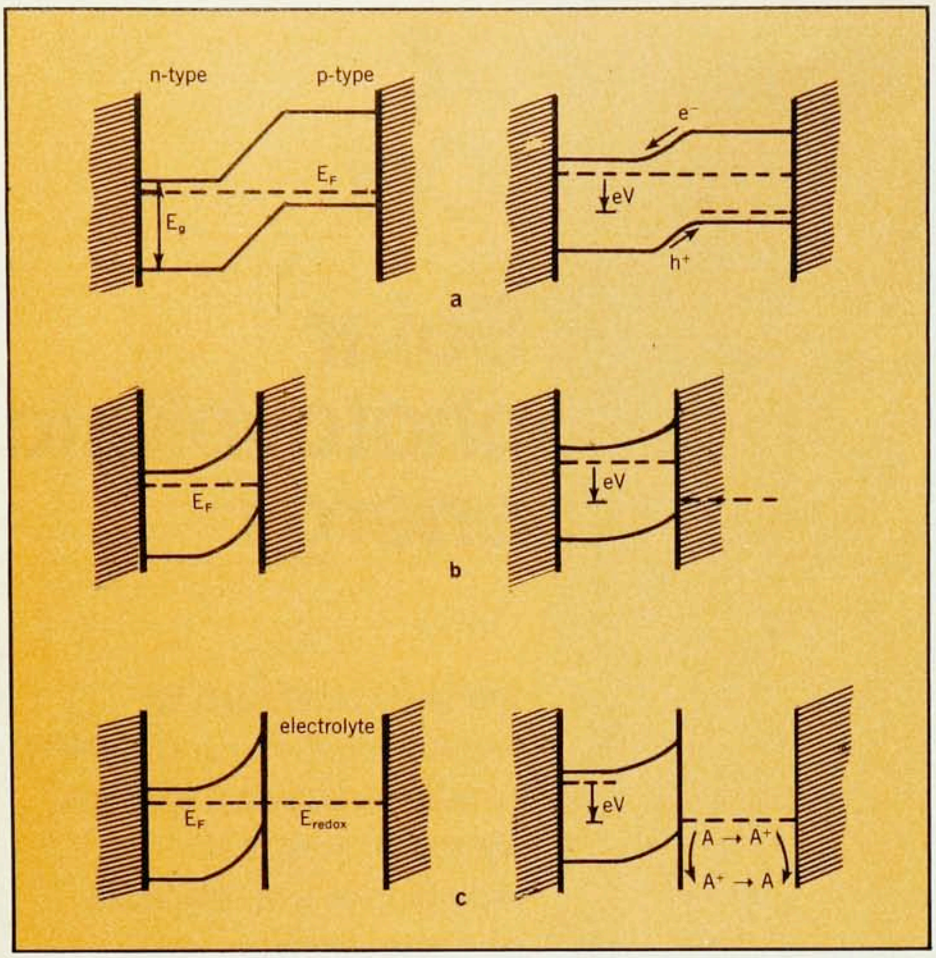
Although the Sun is frequently labeled as an "alternative" energy source, it has in fact produced almost all of man's energy throughout history. The world's energy economy now runs primarily on fossil fuels, a form of "solar capital" saved over geological time scales. Because this capital is apparently rather modest in amount and is not being renewed by nature at a rate comparable to our demands, we may eventually exhaust it. We will therefore be forced to turn either to the use of larger non-solar capital stocks such as primordial methane (if it exists), uranium-238 and deuterium, or to the use of regular "solar income" derived from the Sun's daily radiation.

The solar income is about 200 W/m^2, averaged over time, on a ground-level surface tilted to the latitude, and peaks at about 1000 W/m^2 near noon on clear days. It can be used in two ways: directly (for example, heating, photovoltaic conversion and photochemical conversion) or indirectly (for example, wind, hydroelectricity, ocean thermal gradients and biomass). These techniques have a number of advantages:

- They are based on an inexhaustible source of energy
- Sunlight and its effects, such as wind and rain, are free and ubiquitous. (Although the distribution of direct and indirect solar resources is not uniform on the Earth's surface, it is far more even than the distribution of mineral resources such as coal, oil and uranium.)
- The solar income is large. The US consumes about 80 Quads of primary energy annually (1 Quad = 10^{15} Btu, 1 Btu = 1054 J). The insolation (the energy carried by the light flux from the Sun) on the US is about 5×10^4 Q per year. Accordingly, trapping and converting incoming solar radiation with about 10% end-use efficiency on about one percent of US land would satisfy our energy demands.
- Solar-income technologies are flexible and varied. Energy end-use can be matched to a supply of equal quality. For example, a house can be heated by a low-temperature solar collector rather than electricity. The effect of this is an increased national "second-law efficiency",[1] in which low entropic energy forms, for example those resulting from photovoltaic and photochemical conversion, would be used only for appropriate tasks.
- Most of these technologies have no major *inherent* ecological drawbacks. They do have environmental effects, as do all energy technologies, and some of the consequences may be quite serious—firewood in the Third World is a particular problem at present—but these effects can be controlled by wise choice and application of the appropriate form of solar energy.

Some solar-income energy-technologies, such as hydroelectricity, are already in wide use. Others, such as wind power, were once important but have been eclipsed, at least temporarily, in the era of cheap fossil fuel. There are also new technologies, such as photovoltaics (figure 1) and ocean thermal energy conversion, which are now being developed in the laboratory or being deployed for special

A large concentrator array. The photograph above shows the space between the Fresnel lenses on the right and the solar cells on the left. (Sandia Laboratories) Figure 1



Types of solar cell. We show schematic plots of the energy of the bottom of the conduction band and the top of the valence band across the junction in **(a)** a p–n junction cell, **(b)** a Schottky-barrier cell and **(c)** a semiconductor–liquid junction cell. Plots on the left are for the cells in the dark; on the right we show the situation for illuminated cells. Shading indicates metal electrodes, and the Fermi levels are labelled E_F. Illuminating the cell with sufficiently energetic photons ($h\nu > E_g$) produces a photovoltage V when the cell is in an open circuit. Figure 2

purposes. These last are so costly that they do not yet represent a significant entry on the US or world energy balance sheet.

The APS Study

The US, through the Department of Energy and its antecedents, has recently increased sharply its efforts to develop and commercialize new energy technologies, including the solar-income technologies, because of the clear necessity to move away from our heavy dependence on oil. The funding level for solar energy in the Department of Energy, for example, has been increased about 25% in the fiscal year 1980 budget and is more than ten times the total government budget for solar energy in 1974. It is gratifying to note that The American Physical Society Study on Solar Photovoltaic Energy Conversion is contributing to the climate that is shaping such changes in our energy policy. By and large these developments are proceeding in technically sound and carefully considered steps despite the politically based urgings of polemicists.

The American Physical Society's study on photovoltaics was begun in 1977. The White House Office of Science and Technology Policy asked Herman Feshbach, chairman of the MIT physics department and at that time chairman of the Panel on Public Affairs of The American Physical Society, to form a group to study the promises and problems of solar photovoltaic energy conversion as a significant source for electrical energy generation in the United States and, in particular, to delineate an optimal program of research and development. To obtain conclusions that would be substantially free of preconceived opinions, the study group was to be chosen primarily from scientists who possessed appropriate disciplinary backgrounds but were not involved in photovoltaics in a major way. This condition posed no particular problems because the semiconductor field is broad and interdisciplinary.

After he was selected to be Chairman of the panel, Henry Ehrenreich and Feshbach began to select the Study Group and the equally important Review Committee that would assess the progress of the study and review its conclusions. Our ability to obtain distinguished scientists who were willing to devote substantial time and effort to this task was principally due to its importance in national energy problems. The Department of Energy's program for photovoltaic research, development, demonstration, and commercialization was entering a period involving major decisions regarding its future directions and budget. Everyone recognized that many factors would combine to determine the ultimate direction and funding level of the program, but it was also apparent that as a group we might have a substantial opportunity to influence the development of photovoltaic technology constructively.

The first phase of the study lasted somewhat over one year, from November 1977 to January 1979. During the months preceding the summer of 1978, the Study Group met at length with more than forty experts in photovoltaic science, technology and manufacturing methods to inform itself about key issues. The group also talked extensively with economists concerned with the evaluation of energy technologies. Finally it had the opportunity of meeting with various members of the Department of Energy, the Solar Energy Research Institute, and the Office of Science and Technology Policy, who posed questions, supplied perspective and background, and freely shared their own expertise.

These discussions, backed by literature researches, particularly of directly relevant previous studies, formed the background for a month's session during the summer of 1978 at which the issues were discussed and preliminary position papers were drafted.

The remainder of the fall was devoted to refining the drafts and assembling them into a document, the *Principal Conclusions of The American Physical Society Study Group on Solar Photovoltaic Energy Conversion.* After extensive review by the Review Committee, the Panel on Public Affairs and the APS Executive Council, this report was published in February 1979. Another report emphasizing the scientific and technological opportunities for research and development is in preparation. Its intent is to stimulate greater interest in photovoltaic science on the part of the scientific community. This article will be published in due course in *Reviews of Modern Physics.*

The study was restricted to the problem of terrestrial photovoltaic energy conversion. Because the study's charter was limited to photovoltaics and because it became apparent that just doing justice to the subject of terrestrial photovoltaics would require all the time available to the

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group, the panel did not address related options such as photothermal generation, wind power, biomass, oceanic thermal energy conversion and the space power satellite. While there are some allusions to funding formats, particularly for long-range research programs with no prospective near-term pay-off, the Study Group felt it inappropriate to comment in any way on the management of DOE or to make specific recommendations concerning funding levels.

Photovoltaic basics

A photovoltaic device absorbs photons by the production of electronic excitations that result in electron–hole pairs. An electric field gradient is built into the device to separate these pairs. The separated carriers can then be used to produce a current through an external circuit because part of the energy absorbed remains as potential energy of the separated carriers. There are several ways to produce this field, among them:

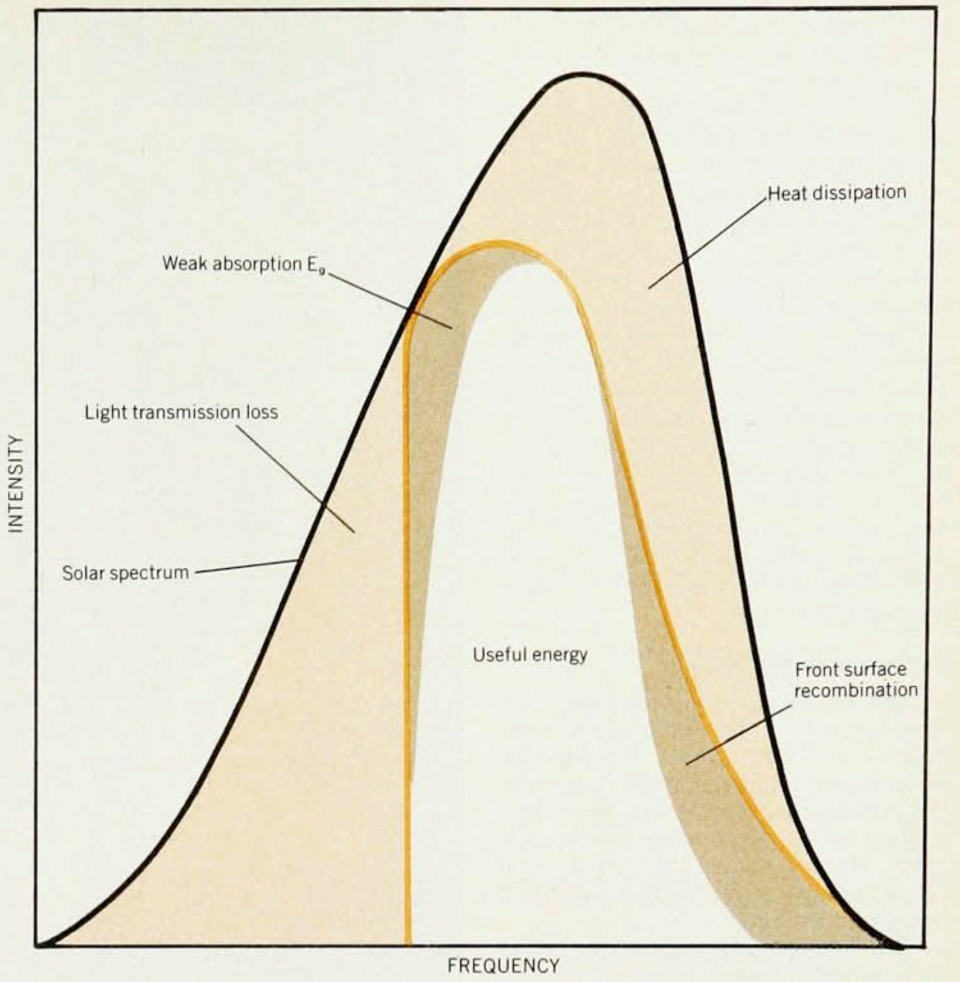
- p–n junctions
- Schottky barriers
- semiconductor–liquid-electrolyte interfaces

These mechanisms are shown schematically in figure 2.

In a p–n junction (figure 2a) a slab of semiconductor is doped to make one side into p-type material and the other into n-type material. The Fermi levels on the two sides must be equal, and this requires that electrons in the conduction band on the p side have a higher potential energy than on the n side. The resultant electric field is located in the junction, or "depletion," region. The thickness of this region depends on the doping. In solar cells it is usually a few microns.

A Schottky barrier (figure 2b) can arise from the transfer of electrons from a n-type semiconductor (or holes from a p-type) to a metal layer deposited on it; the effect is mostly seen in junctions between n-type semiconductors and high-work-function metals. When a metal–semiconductor sandwich containing such a barrier is illuminated, electrons flow into the semiconductor and holes into the metal, producing a photovoltage—or a current in an external circuit.

The same situation prevails in semiconductor–liquid-electrolyte interfaces (figure 2c), in which electrolytes play very much the same role as metals do in Schottky barriers. The holes and electrons transferred into the electrolyte produce chemical reactions, and for appropriate combinations of semiconductors and electrolytes, these reactions can be used to produce fuels directly. This feature represents one of the most attractive incentives for the further development of this type of system, because liquid fuels are difficult to replace in many uses, such as transportation, and relatively difficult to obtain from sources other than oil.



Solar-cell collection efficiency. The outer curve represents the solar power as a function of frequency (or, equivalently, the number of photons as a function of their energy). The light-colored region represents inherent losses in any solar cell based on a semiconductor with bandgap energy E_g, so that the colored curve marks the performance of an ideal single-junction cell. The darker colored region represents two further loss mechanisms present in any real cell. The white area in the center is the remaining useful energy available from the cell. Figure 3

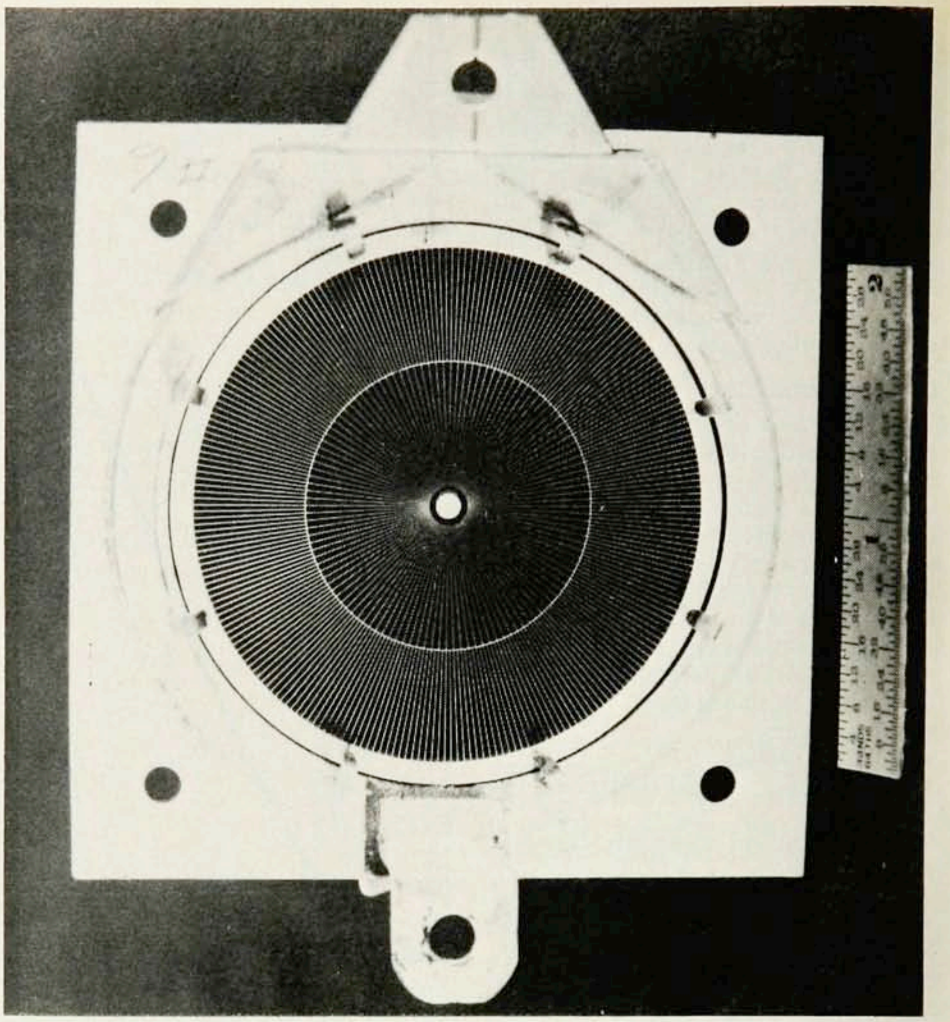
The theoretical solar efficiency of a single junction photocell is significantly less than 100%. (See figure 3.) Much of the solar spectrum cannot be used by any given cell: Photons whose energy is less than the band gap of the semiconductor are not absorbed, and while photons whose energy is considerably higher than the band gap are absorbed efficiently in the junction region, a significant portion of the absorbed energy is dissipated by conversion into phonons or heat as the electron and hole dribble respectively to the conduction and valence band edges. In practical devices, moreover, light just above the absorption edge is absorbed only weakly while photons well above the band gap are absorbed so near the surface that the electron–hole pairs often recombine. These opposing effects result in an optimum band gap (1.2–1.4 eV at room temperature) for which a semiconductor is best matched to the solar spectrum. In silicon (band gap of 1.1 eV) the ideal efficiency is 29%. In gallium arsenide (band gap about 1.4 eV) the ideal efficiency is about 36%.

Some of the effects that limit the efficiency of a single-junction cell can be minimized by using a more complex cell design. For example, multijunction cells can be made of layers of materials with different band gaps connected in series, with the material of the largest band gap facing the incident light. Such cells can in principle make more efficient use of the solar spectrum—the theoretical efficiencies can be greater than 50% in cells with three or more layers. Cells of this type are just beginning to be developed in the laboratory. It is too soon to tell whether stable cells of high efficiency can be made this way. There are however a variety of designs of this and other types that hold considerable promise for improvements in cell efficiency.

Currently cell performance is limited not by the theoretical efficiency but rather by cell imperfections such as those associated with the metal grid (figure 4) and surfaces that produce recombination of the light-produced electron–hole pairs. These difficulties have been most nearly surmounted for silicon and gallium arsenide. Certain cell designs eliminate the front surface gridding entirely, but at some increase in complexity. Recombination at the front and back surfaces is often reduced by building into the cell electric fields to reflect the carriers—the use of GaAlAs layers on GaAs cell surfaces is an example.

Reflection of light by the solar cell can be minimized, but not eliminated entirely, through the use of antireflection coatings and textured surfaces. Texturing the surface can also help to increase efficiency by causing light to traverse the cell obliquely, so the absorption path length for a cell of given thickness increases.

Clearly, GaAlAs–GaAs and other more sophisticated cell designs that require elaborate fabrication procedures or rare materials are likely to be expensive (for that reason they are called "jewel cells") and as such they are intended primarily for use in concentrator systems, such as those shown in figures 1 and 5, where the premium on efficiency is particularly high and cell cost is effectively reduced by the concentration ratio.



In this solar cell the front (illuminated) surface is covered with a network of metallic electrodes to collect the current produced by the cell. Figure 4

Rationale for the Study

The Study Group delineated the question of the future value of photovoltaics in the following way: What are the technical problems, and do their solutions lie within the capabilities of present technology? Given this information, what are the nature, magnitude, and proper priority of the technical issues that require attention?

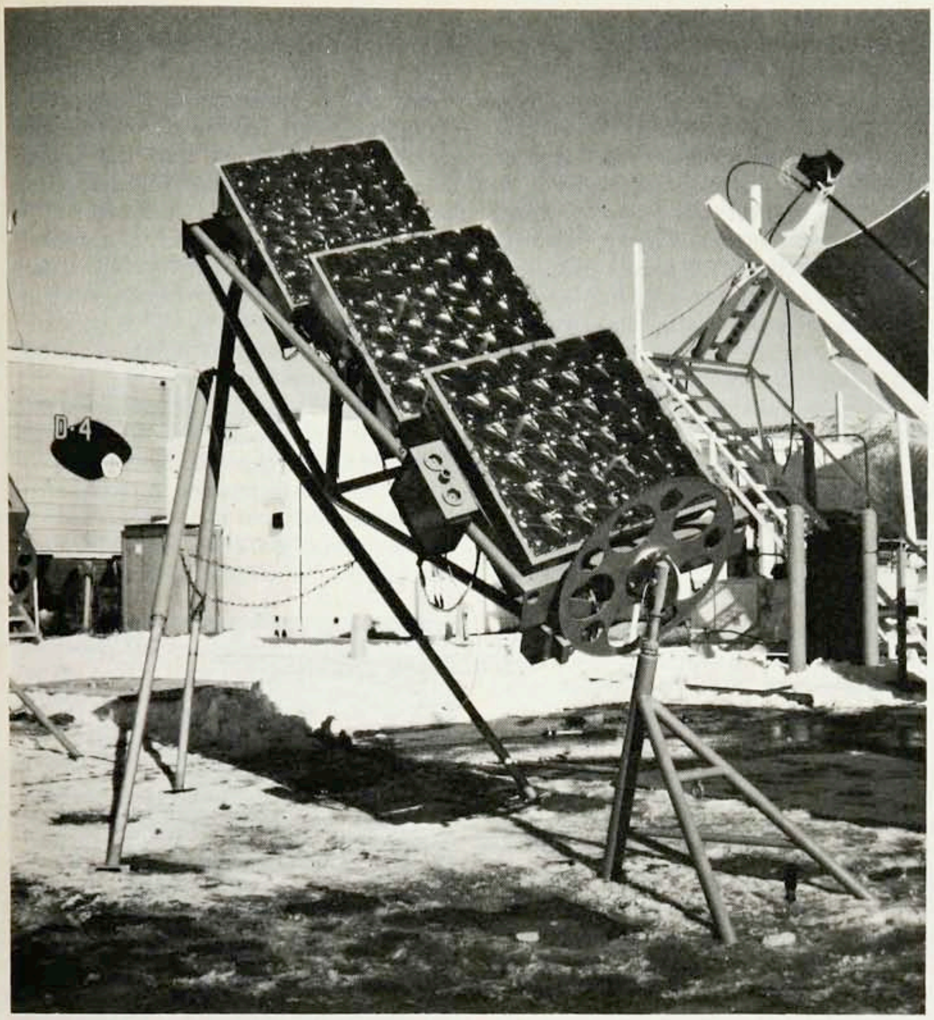
The sequence of questions can be put more specifically as follows: First, what price and performance goals need to be achieved by a photovoltaic technology that can contribute in a major way to the country's future energy mix? Second, what is achievable on the basis of optimistic but realistic extensions of current technological practice? Third, are these technological improvements without substantial modification likely to yield an economically competitive technology within a specified time? Finally, what steps are necessary to achieve a photovoltaic technology producing significant amounts of power in a way that is both time and cost effective?

Cost goals

The description of the setting implied by the answer to the first question requires some form of economic assessment based on a definition of an economically competitive technology. It quickly became apparent to the Study Group that the technical conclusions would be relatively insensitive to the details of the economic assumptions because the required cost reduction turned out to be something of the order of a factor of twenty. This requirement is sufficiently stringent as to require major technical advances, if not breakthroughs, before extensive deployment can become a reasonable course of action. We estimated that module costs would have to be reduced to something like 10–40¢/W_p in 1975 dollars (the subscript denotes the "peak" wattage resulting from an insolation of 1000 W/m^2) in order to become economically competitive. The estimate of the costs of a photovoltaic system was based on information obtained from several systems-design studies of central power systems. The basis for comparison is the projected cost of coal-generated central-station electrical production in the period 2000–2030, using systems analyses of the likely future capital and operating costs of such plants.

Because our use of the term "central power" in this context has led to a great deal of misunderstanding, a caveat concerning it is in order. "Central power" is used here to mean that the generating capacity is utility-owned and is part of the electrical grid that is the present basis of US electrical distribution. It is not implied that any photovoltaic generation facility would be comparable in size to the largest conventional plants now in use. A typical large coal or nuclear unit is on the order of 1000 MW in capacity; it is probable that insurance costs against damage from local storms, as well as other considerations, will limit photovoltaic plant sizes to at most 100 MW_p or so. In fact, most of the economies of scale associated with installation, maintenance, power conditioning (that is, conversion of dc to regulated ac), and the like can probably be realized for installations of a few MW_p, which is on the scale of the electric power needs of a small community.

The much debated issue of whether in the long term photovoltaic systems should be deployed in utility-owned central stations or in a purely residential fashion should be regarded as one having low priority at this time. Studies of central power and residential deployment[2] arrive at quite similar allowed costs for the year 2000 assuming consistent energy price escalation rates and balance of systems costs. Even though small-scale residential applications may constitute one of the early uses of solar cells in this country, the primary present problem is to lower the cost of photovoltaic modules by an order of magnitude or more. While exploration of the technical issues involved in all applications via systems tests is necessary to ensure that all necessary parts of the eventual solar–electric systems are being developed, no choice needs to be made now. This is so since photovoltaic arrays can, by and large, be deployed in any fashion. (High-concentration-ratio systems may form an exception.) Thus the use of a central power model in the study



A solar-concentrator array of three units mounted on a tracking device to maintain orientation with the Sun. (This photograph and that of figure 4 are by Sandia Laboratories.) Figure 5

to establish cost targets does not imply any determination on the Study Group's part concerning the ultimate mode of deployment.

The detailed systems studies have been in general agreement that the economics for residential photovoltaic systems is best when there is no residential energy storage, and excess power from the photovoltaic array is sold back to the utility at about half the price paid for the electricity bought. Combined photovoltaic–thermal flat-plate arrays do not appear to possess any advantage over side-by-side electric and thermal solar arrays. This makes the residential system just a very small version of a central power station that may not differ appreciably from its larger counterpart.

The existing electric generation system and the reluctance of homeowners to incur high capital expenses, particularly in a period of rapidly rising house prices, favor the use of photovoltaic systems in central power generation, but local conditions may exist that make purely residential deployment advantageous.

Systems issues

In the *Principal Conclusions* the Study Group addressed five areas of importance. The first concerns systems questions. Several significant points emerged from this discussion besides those concerning cost goals. One of the more controversial of these was that photovoltaic systems are unlikely to exceed 1% of US electrical energy production in the year 2000. This number represents an order-of-magnitude estimate: Under the most favorable circumstances—high continuing demand for electricity, rapid technological progress, and a national decision to maximize the use of photovoltaic systems by, for example, offering substantial incentives and subsidies—it might be increased to several percent. For photovoltaics to provide more than about 5% of the total electric power would be extremely difficult because storage and other systems problems require resolution at about that level of deployment. (These numbers represent averages for the country as a whole. The Southwest and the Northeast are, respectively, the areas of highest insolation and highest energy cost, so the fraction of solar-electric power in these two areas would be expected to be much higher than the national average.)

It is instructive to examine the kind of commitment of capital and materials that is required to produce a 1% deployment during a ten-year period extending say from 1990 to the year 2000. One would expect, on the basis of the present rate of progress and the Department of Energy's projections as outlined in its present program plan, that a satisfactory technology might well be ready for commercialization and large-scale deployment at about that time. A build-up at a uniform rate to the 1% level in ten years would require producing photovoltaic systems at a rate of 2000 MW_p per year, more than 1000 times our present level of production.

One percent of total generation corresponds to 5×10^{10} kWh (assuming that electricity demand roughly doubles by 2000; in the energy future of reduced electricity consumption envisioned by Amory Lovins and others, new electricity sources are less important). The thermal fuel displacement would be about 1/2 Quad per year at a thermal-to-electric conversion efficiency of one third after completion of the total deployment. The total capital investment at $\$1/W_p$ system cost is about twenty billion dollars (in 1975 dollars).

Assuming 10% conversion efficiency from sunlight to electricity leads to an array area of 200 km^2. If the arrays were all built as ground structures for central power or intermediate-sized installations, the total land area required including access roads would be about 400–600 m^2, a relatively modest amount. If the arrays were put on rooftops, about two million houses would be required with a 10-kW_p array on each house.

The materials requirements are more demanding. For example, the steel and concrete used each year to build the structures needed to support ground-based flat-plate solar-cell arrays of a typical recent design would amount to roughly 5 and 17% respectively of the 1974 US annual production of these materials. The use of lightweight concentrators made of novel materials such as plastics would reduce such requirements significantly. Materials savings also result when flat-plate arrays are installed on rooftops if the arrays do not need to be tilted with respect to the roof. Because electrical generation consumes about 20% of all private capital investment, large materials demands may be supportable without major dislocations. Materials usage will have to be considered carefully in system design, however.

The amount of active cell material required may also pose significant limitations. For example, the amount of silicon required to produce 1% of the US electricity in this way would be roughly the same as the present total production of metallurgical (not semiconductor) silicon. Because of the abundance of a high-grade silicon ore (sand) this level of production poses no intrinsic problems, although there is the necessity of building the requisite facilities for low-cost production of high-purity material. This situation is somewhat different for materials like gallium arsenide or cadmium sulfide, which use elements with present production levels far below those required for large-scale use in photovoltaic systems. The present annual production of gallium, for example, is about 7 tons, which is about an order of magnitude less than would be required to use a GaAs concentrator system as the basis for the model deployment above. The gallium problem is one of cost—gallium is abundant in the Earth's crust but there is no source of concentrated ore. Substantial amounts could be recovered as by-products in zinc and aluminum ore processing, but the cost might be prohibitive.

These rather substantial numbers should serve to illustrate that a 1% penetration, corresponding to roughly 0.1% of the 1975 total US energy demand, is far from being insignificant. This point is illustrated more vividly by noting that the amount of electrical power in question is equivalent to the power that would be produced by using 1/3 of the output of the Alaska pipeline to generate electricity. The total capital investment over 10 years equals roughly 2/3 of total 1975 US automobile factory sales. Thus, even this seemingly modest electrical energy source requires build-up of a very substantial industry. While there is nothing that limits in any absolute sense our ability to achieve these goals, or perhaps even goals two or three times as large, the scale of the required effort must not be underestimated.

What of the times required to pay back the amount of energy consumed in creating this industry? Because the production of electricity by other means also involves capital investment of the same general magnitude as photovoltaic systems, the most useful measure is probably the energy payback time of the solar cell itself. This can be estimated to be about one year for silicon cells, which are more highly energy-intensive than most other cells. Out of a projected lifetime of twenty to thirty years, this appears to be quite reasonable and is in line with the payback times estimated for present electrical power plants.

An economically competitive photovoltaic industry would require sufficiently cheap cells, cell encapsulants, support structures and other system components (power conditioning, installation, and so forth). The premium on cell efficiency is particularly high. The cost of energy from a photovoltaic system decreases about 40% for an efficiency increase from 10 to 20% if the area-related system costs (including cell cost) remain constant. Because of costs other than those due to the cells, "free" cells of less than 10% efficiency are likely to be uneconomical in grid-competitive applications.

Before the grid-connected US applications become competitive, it is highly probable that significant intermediate markets involving export and a number of specialized US uses in remote locations will develop. However, a premature entry into large-scale US deployment before the technology has reached fruition might lock us into an overly costly technology. Indeed the national interest may well be served optimally by an emphasis on research and development accompanied by measured and technologically appropriate progress in Government-assisted commercialization. The naive impatience of some solar advocates to deploy solar cells immediately and on a large scale appears to be associated with an inadequate appreciation of the technical problem.

Silicon

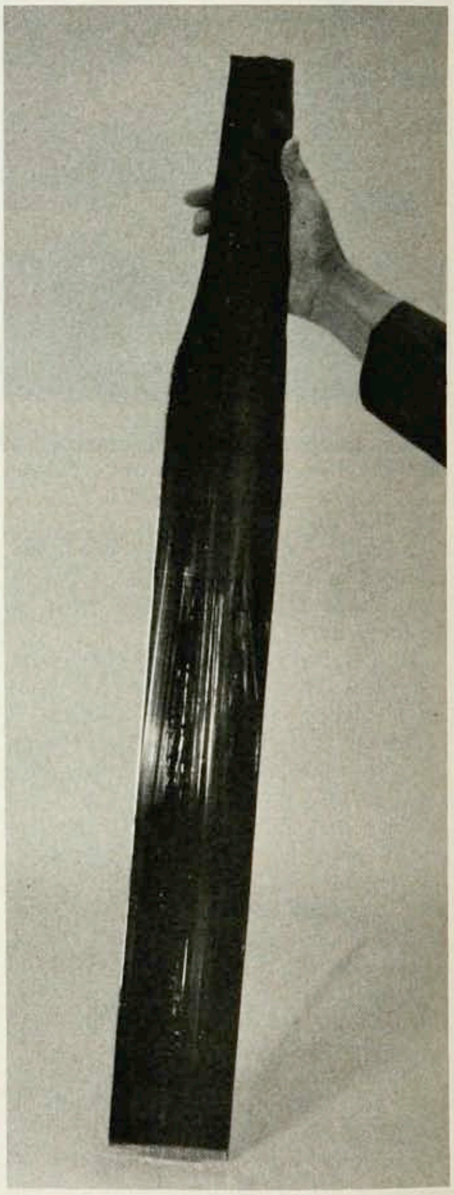
The second area discussed in the *Principal Conclusions* concerns crystalline-silicon-based photovoltaics. This is an established and proven technology because of its long and successful use in space vehicles. It thus serves as a standard of reference for the field. However, currently manufactured cells are far too expensive for most terrestrial uses. Because it is the best understood technology, it represents the best short-term hope for a reliable system of at least moderately low cost. For this reason there has been a vigorous development effort by the Jet Propulsion Laboratory and other organizations, largely under the auspices of the Department of Energy.

Crystal-silicon devices are capable of high efficiency and reliable performance, but the rather elaborate manufacturing technology makes the ultimately attainable price per watt difficult to estimate.

The need to understand the demands that cost requirements place on the manufacturing technology has led to some very detailed analyses of the steps in solar cell fabrication. In order to reach the neighborhood of the price goal of 50¢/W_p (in 1975 dollars), which DOE has set itself for 1986, it is necessary to design and build factories that are essentially totally automated. Two stages of manufacturing are involved, the first producing purified solar-grade polycrystalline silicon from sand, and the second utilizing that output to fabricate finished solar cell modules with minimal labor cost and a near-perfect yield of functional finished cells.

Some feeling for the procedure is conveyed by considering the steps and their pricing in one approach to fabricating modules from the starting polycrystalline silicon material. In the single-crystal cell technology, the polycrystalline silicon must first be converted into a single crystal material. There are many ways of doing this, the most popular at the present being the Czochralski technique, which grows a cylindrical single crystal of at least several kg from a crucible of molten silicon. According to the estimates analyzed in the APS report this can be accomplished at a projected cost of about 10¢/W_p for a module of 16% efficiency. The single crystal boule then must be sliced. While this sounds like an entirely straightforward procedure (one popular writer has suggested that the Italian marble industry has had this art well in hand for many years!), it is in fact a difficult technical problem to find a method for producing about 20 acceptable wafers per centimeter of silicon crystal at a projected cost of 12 ¢/W_p (20 ¢ per cut). Saws under development cut up to 1000 wafers simultaneously.

The slices then must be converted into solar cells by doping and other procedures, which are expected to cost 13¢/W_p. Finally these cells must be interconnected and assembled into modules containing on the order of 100 cells, at an additional cost of 18¢/W_p. The total projected cost



A silicon ribbon. The usual process for making solar cells involves sawing cells from cylindrical ingots of single-crystal silicon, which wastes much purified silicon. This single-crystal ribbon was grown for experiments to test other, less wasteful, manufacturing processes. (IBM Fishkill Laboratory) Figure 6 for the module and cells is 62¢/W_p, somewhat higher than the DOE goal. Other methods for producing silicon-cell modules (figure 6, for example, shows a single-crystal ribbon) involve process steps that are lower in cost per unit area but result in less efficient modules, so that the final costs in our estimates turn out somewhat higher per watt. We regard these numbers as optimistic projections that will be difficult to surpass in the absence of major technological advances, but JPL, which manages DOE's highly effective silicon research and development effort, has produced lower cost estimates for some of these processes on the basis of somewhat different assumptions.

Major advances in silicon-cell design have been made in recent years. For example, electron–hole recombination losses at the rear surface of the cell have been reduced by building into the cell a back-surface field that repels minority carriers. Light-reflection losses have been nearly eliminated by anti-reflection surface texturing to trap the incident radiation. Losses associated with the heavily doped layer that forms the front surface have been reduced by decreasing the thickness of this layer, as in the "violet cell." The development of other junction configurations, such as the vertical multijunction and interdigitated back contact structure, has been pushed forward rapidly. Indeed, silicon technology is sufficiently advanced that it should be possible to demonstrate with suitable cleverness the achievement of designs yielding nearly 100% of theoretical efficiency under manufacturing conditions. Because of the premium on achieving high efficiencies, this avenue is being actively explored.

Concentrators and thin films

The third area is concerned with concentrator systems that present solar cells with focused sunlight. Concentrators are attractive in principle because they substitute large areas of simple devices such as mirrors and lenses for the large areas of sophisticated electronic devices required by flat plates. However, the savings realized by this strategy must be balanced against the cost for devices that focus and track the sunlight. Structural stability under wind loading is a more severe problem for trackable arrays than for flat plates, and most early concentrator designs were so massive that materials use was prohibitive. Some designs that are much more materials-conservative have recently appeared, but they are still in the early stages of development. Cells with efficiency greater than 20% have been demonstrated in the laboratory (in fact, a device using two cells and a beamsplitter has achieved 28%). Development of practical devices with an efficiency this high would give a strong impetus to the concentrator program.

The fourth area is concerned with thin-film devices or, in a more general sense, with novel active materials other than single-crystal silicon. Most of these have higher absorption coefficients and hence require smaller thicknesses. This is a double advantage: Little material is used and its purity becomes less critical because charge carriers travel shorter distances before macroscopic separation occurs at the barrier or junction. There are many candidate materials, relatively few of which have yet been investigated with any thoroughness. This field offers many research opportunities, some of which are outlined in the *Principal Conclusions*.

Cells with an efficiency of 5–10% can be made from disordered, impure, thin layers of active material. Two common examples are the heterojunction cells made from Cu_2S and CdS and cells made from doped hydrogenated amorphous silicon. The advantages of such systems are that they use little active material, that their band gaps can be well-matched to the solar spectrum, and that their absorption coefficients can be much higher than that of crystal silicon. However, there are also disadvantages. Thin films tend to be mechanically fragile, they may undergo chemical degradation with time, and they are often difficult to make reproducibly.

Nonetheless, the variety of thin-film materials that could be useful in solar cells is very large indeed. Many promising systems have not yet been explored and characterized using well-known semiconductor techniques. Our knowledge of semiconductors is probably sufficiently extensive at this point to permit an intelligent choice of such systems. The potential payoff would be immense if a truly inexpensive technology based on a thin-film system were to be developed.

The members of the panel

The members of the Study Group, their scientific interests, and their affiliations are:

David DeWitt—semiconductor manufacturing and engineering, IBM San Jose

Jerry P. Gollub—physics of turbulence and superconductivity, Haverford College

Robert N. Hall—semiconductor-device science, General Electric Research and Development

Charles H. Henry—semiconductor physics, Bell Laboratories

John J. Hopfield—condensed-matter theory and biophysics, Princeton University and Bell Laboratories

Thomas C. McGill—semiconductor physics, Caltech

Albert Rose—semiconductor-device science, Boston University and University of Delaware

Jan Tauc—semiconductor and metal physics, Brown University

Robb M. Thomson—materials science and metal physics, National Bureau of Standards

Mark S. Wrighton—photo and electrochemistry, MIT

The Review Committee was chaired by Herman Feshbach; its other members were:

N. Bruce Hannay, Vice President and Director of Research, Bell Laboratories

Robert N. Noyce, Vice Chairman of the Board, Intel Corporation

J. Robert Schrieffer, Mary Amanda Wood Professor of Physics at the University of Pennsylvania and Nobel Laureate

Peter A. Wolff, Professor of Physics and Director of the Research Laboratory of Electronics at MIT

Basic research

The final area concerns the fundamental, long-term research programs that are necessary for the development of a significant photovoltaic or photochemical energy technology. The problems are numerous and their scope usually multidisciplinary. Significant contributions to these programs will be made by a variety of disciplines, including solid-state physics and chemistry, materials science, surface physics, inorganic and organic chemistry, electrochemistry, and biophysics. We can only give a flavor of the types of appropriate activities here.

The photovoltaic process is in principle closely related to the photosynthetic process. One of the most intriguing questions concerns the possibility of man-made photosynthesis with an efficiency of 10 to 30%, more than ten times higher than that typical of natural photosynthesis. Programs in molecular science, directed toward characterizing and synthesizing molecules capable of producing fuel directly from sunlight, and in biophysics, examining natural photosynthesis with a view towards creating artificial analogs, would represent useful beginnings.

Another relevant problem area concerns the properties of interfaces. Despite the crucial importance of interfaces in all aspects of semiconductor electronics this area is only now beginning to receive the attention it deserves. For example, despite the great practical importance of silicon devices, little is yet known about why the SiO_2–Si interface is electrically inactive and stable. Equally to the point is the question of why we have been unable to use our empirical knowledge of this system to find appropriate passivation layers for other semiconductors such as the group III–group V compounds.

There are many materials suitable for photovoltaic systems, and in consequence there are many types of interfacial structures. The atomic and chemical structures of interfaces will have to be characterized and perhaps modified using the approaches and techniques of materials science. The investigation of the associated electronic properties will involve electrical engineering and physics. Because different methods of materials preparation strongly affect the character of the interface, solid-state chemistry and crystal-growth science must contribute to this research.

Many interesting problems arise, such as the energetics and kinetics of semiconductor–liquid interfaces, the structural and electronic properties of amorphous semiconductors containing hydrogen and other additives, and the electronic properties of polycrystalline materials. These problems are sufficient to keep condensed-matter scientists happily and fruitfully occupied for some time. Solutions or insight would obviously be of great value in the development of solar photovoltaic energy.

General observations

The time required for photovoltaics to become a mature component of the US energy mix is likely to be some 30 years or more. This assessment is based on the time scale that has been associated historically with the transfer from one dominant energy technology to another (for example, wood to coal and coal to oil) and on the time necessary to build a large industry and a large market. There are many worthwhile shorter-range applications for photovoltaics, some of which we have mentioned in this article. Nonetheless, in the formulation of a program that will best serve the national needs, the central emphasis must be on the eventual establishment of photovoltaics as a major energy technology.

Even though the implementation of a photovoltaic technology that will contribute appreciably to the nation's energy mix may be a long-term proposition, the ultimate prospects for photovoltaic energy conversion are bright in view of the current ferment and rapid rate of progress in both the science and technology relevant to the field. None of the present photovoltaic technologies (with the possible exception of silicon) represents a clearcut choice, because the price of solar cells needs to be reduced by more than an order of magnitude in order to become competitive with the cost of generating electricity by conventional means. These technical problems need to be resolved before the appropriate photovoltaic technology can be determined.

It is in fact not at all clear that the winner will be a single technology based on a single type of cell made from one specific set of materials. During the past year silicon technology has made rapid progress both in the area of materials preparation and cell design. The Cu/CdS system is also undergoing rapid commercialization: At least two US manufacturers, and possibly several others here and abroad, are exploring the commercial fabrication of these systems.

In these somewhat tentative attempts to forecast the development of a new energy technology, it is important to realize that there are no scientific barriers to the success of photovoltaics. While some major technological advances in the next few decades are needed in order to make the technology economically competitive, there is also little doubt that the necessary technological ingenuity to accomplish this is available.

However, it is necessary to ensure that highly talented scientists be attracted to the field. This may require some examination and revision of DOE funding formats: The management styles and funding formats planned for the photovoltaic research and development program must take into account that parts of the program are intrinsically long-range and that there is a real need to compete with other condensed-matter research fields for the talent essential to a successful program. The program must use diverse approaches addressing both near and long-range goals. On the one hand, the candidate technologies available now should be developed at an optimal rate; on the other hand due attention must also be given to the kind of fundamental research leading to new ways in which the Sun's energy may be used efficiently. We have already mentioned the idea of man-made photosynthesis in this regard.

Because none of the present photovoltaic options has shown sufficient promise that its price is reducible to the range needed for grid-connected applications, large-scale deployment or major Federal procurement plans appear to be premature. Certainly something would be learned from such guaranteed buys, and perhaps the large expense may even be justified in view of the prevailing energy crisis. However, the danger that a too primitive technology becomes frozen into the industrial system prematurely is one that is far more serious.

As a result of these considerations, the *Principal Conclusions* emphasizes that an intensive, imaginative, well-funded, and well-managed program of research and development offers the greatest hope for the long-term success of photovoltaic technology as a way of effectively utilizing our solar income.

References

Much of the material of this article is drawn from the *Principal Conclusions of the APS Study Group on Solar Photovoltaic Energy Conversion*, which is available for $5.00 postpaid from The American Physical Society, 335 E. 45th St., New York, N.Y. 10017.

1. *Efficient Use of Energy*, APS Studies on the More Efficient Use of Energy, edited by K. W. Ford et al. (New York, A.I.P. 1975)
2. In addition to the references given in Section 1 of the *Principal Conclusions*, see: (a) Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems, Final Report, GE Space Division for Sandia Laboratories, DOE report #SAND78-7039 (2 vols., 1979) and (b) Application of Solar Technology to Today's Energy Needs, Office of Technology Assessment reports OTA-E-66 (vol. 1) and OTA-E-77 (1978). □