

Chapter X

**ENERGY CONVERSION WITH
PHOTOVOLTAICS**

Chapter X.—ENERGY CONVERSION WITH PHOTOVOLTAICS

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Energy Conversion With Photovoltaics

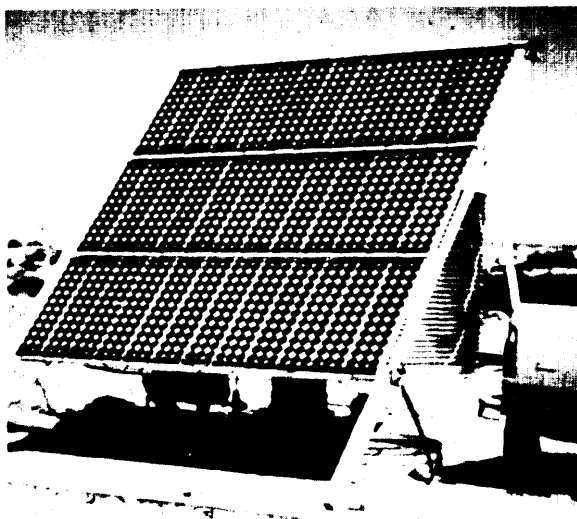
INTRODUCTION

Photovoltaic cells (often called "solar cells") are semiconductor devices which are capable of converting sunlight directly into electricity. Generating electricity in this way has obvious advantages. The photovoltaic cells have no moving parts, and they do not require high-temperature or high-pressure fluids. Since they are extremely reliable, quiet, safe, and easy to operate, they are ideally suited to onsite applications. Photovoltaic energy production is unlimited by scarce materials, since cells can be manufactured from silicon, one of the Earth's most abundant elements.

There is no doubt as to the technical feasibility of generating electricity from photovoltaic devices. The units have been used for many years in the space program and to provide power in remote terrestrial sites. The array of silicon cells shown in figure X-1 provides power to pump water in a remote location in Arizona.

The most immediate barrier faced by all photovoltaic systems is the present high cost of the devices. Photovoltaic arrays could be purchased in large quantities in late 1977 for about \$11 per peak watt of output. * Electricity from systems using such cells costs \$1.50 to \$2.00/kWh.

Figure X-1.—Array of Silicon Photovoltaic Cells Providing Power to Pump Water



SOURCE Solar Technology International

Development work to reduce the cost of photovoltaic energy can be divided into three general categories:

1. Reducing the cost of manufacturing the single-crystal silicon cells which are now on the market;
2. Developing techniques for mass producing and increasing the performance of cells made from thin films of materials such as CdS/Cu₂S or amorphous silicon, and
3. Developing high-efficiency cells which can be installed at the focus of magnifying optical systems,

It is technically possible to use any of these approaches to reduce costs to \$1 to \$2

* Photovoltaic prices throughout this paper refer to the selling price of arrays of cells encapsulated to protect them from the weather, for the manufacturing facility in 1975 dollars. The peak output of a cell refers to the output which would be obtained if the cell were exposed to the Sun at the zenith on a clear day.

per peak watt (electricity costing \$0.10 to \$0.40/kWh) during the next 3 to 5 years. The achievement of costs below \$1 to \$2 per watt will require a considerable amount of engineering development work. Progress in any of a number of current research programs would give us considerably more confidence about the prospects for achieving substantially lower costs.

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. The Department of Energy (DOE) believes that, with some relatively minor adjustments, these goals are achievable and is using them for planning purposes. The present goals are: \$1 to \$2 per watt by 1980-82, \$0.50/watt by 1986, and \$0.10 to \$0.30/watt by 1990. Current goals are shown in table

X-1. The lower cost goals appear to be optimistic but not impossible.

The DOE price goals assume that the arrays will last approximately 20 years. (Presently, terrestrial arrays are guaranteed for 1 year.) This seems to be an attainable objective, although more data is required on the degradation rate for arrays exposed to the environment for long periods of time. Silicon cells apparently fail only when the material used for encapsulation cracks or leaks. Structural failures and corrosion have occurred in improperly encapsulated devices, and most clear plastics darken with prolonged exposure to sunlight, cutting down the light reaching the cells. Glass or acrylic encapsulation should, however, be able to prevent these problems.

¹A Johnson (M ITRE Corporation), private communication, 1977.

Table X-1

a) Key Milestones for National Photovoltaic Conversion Program

	Array price in 1975, dollars per peak watt	Production rate, peak megawatts per year
1. End of FY 1977	11	
2. End of FY 1978	7	
3. End of FY 1982	1-2	20
4. End of FY 1986	0.50	500
5. End of FY 1990	0.1-0.3	50,000

SOURCE Photovoltaic program summary January 1978, U S Department of Energy, Division of Solar Technology

b) Goals for Concentrator Systems Using Silicon Cells

	Technical feasibility*		Commercial equipment* •	
	1975 dollars per peak watt (entire system)	Silicon cell efficiency	1975 dollars per peak watt (entire system)	Silicon cell efficiency
1. End of FY 78. . .	2	16%	15	13.5%
2. End of FY 80. . .	1	180/0	2.75	16%
3. End of FY 82. . .	0.50	200/0	1.60	180/0

* Laboratory proof of concept + reasonable estimate of cost of commercial system based on concept

** F o.b. price of production technology.

SOURCE Annual Operation Plan, Systems Definition Project (FY 1978), Sandia Laboratory

PHOTOVOLTAIC CELLS

All photovoltaic installations will consist 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 it has only been in the past 5 years that serious attention has been given to designing cells for use in anything other than spacecraft. Devices are available with a large range of efficiencies and voltages. Some cells are designed to withstand high solar intensities and high operating temperatures, while others are designed to minimize manufacturing costs. The variety should not give the mistaken impression that this is an area where large amounts of private or public research funding have been directed; indeed, many of the projects described here are being conducted by small research laboratories.

The photovoltaic equivalent of power engineering is something of an anomaly in the generating industry since it involves manipulations in the miniature and silent world of semiconductor physics instead of steam tables, gears, and turbine blades. The following discussion provides only a very brief excursion through this complex field. More complete discussions of the topics covered can be found in several recent publications.²³⁴⁵ All that can be done here is to outline some of the major effects influencing cell cost and performance.

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 mater-

ial (i. e., from the valence band), giving it enough energy to move freely in the material (i. e., 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 (which 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” cell. A typical homojunction device is shown in figure x-2.

An intrinsic voltage can also be created by joining two dissimilar semiconductor materials (such as CdS and Cu₂S), creating a “heterojunction,” or by joining a semiconductor to a metal (e.g., amorphous silicon to palladium) creating a “Schottky” barrier junction.

A fundamental limit on the performance of all of these devices results from the fact that (1) 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 (2) the energy given to electrons which exceeds the minimum excitation threshold cannot be recovered as useful electrical current. Most of the unrecovered photon energy is dissipated by heating 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 eV (deep red) to 3 eV (violet). In silicon, only

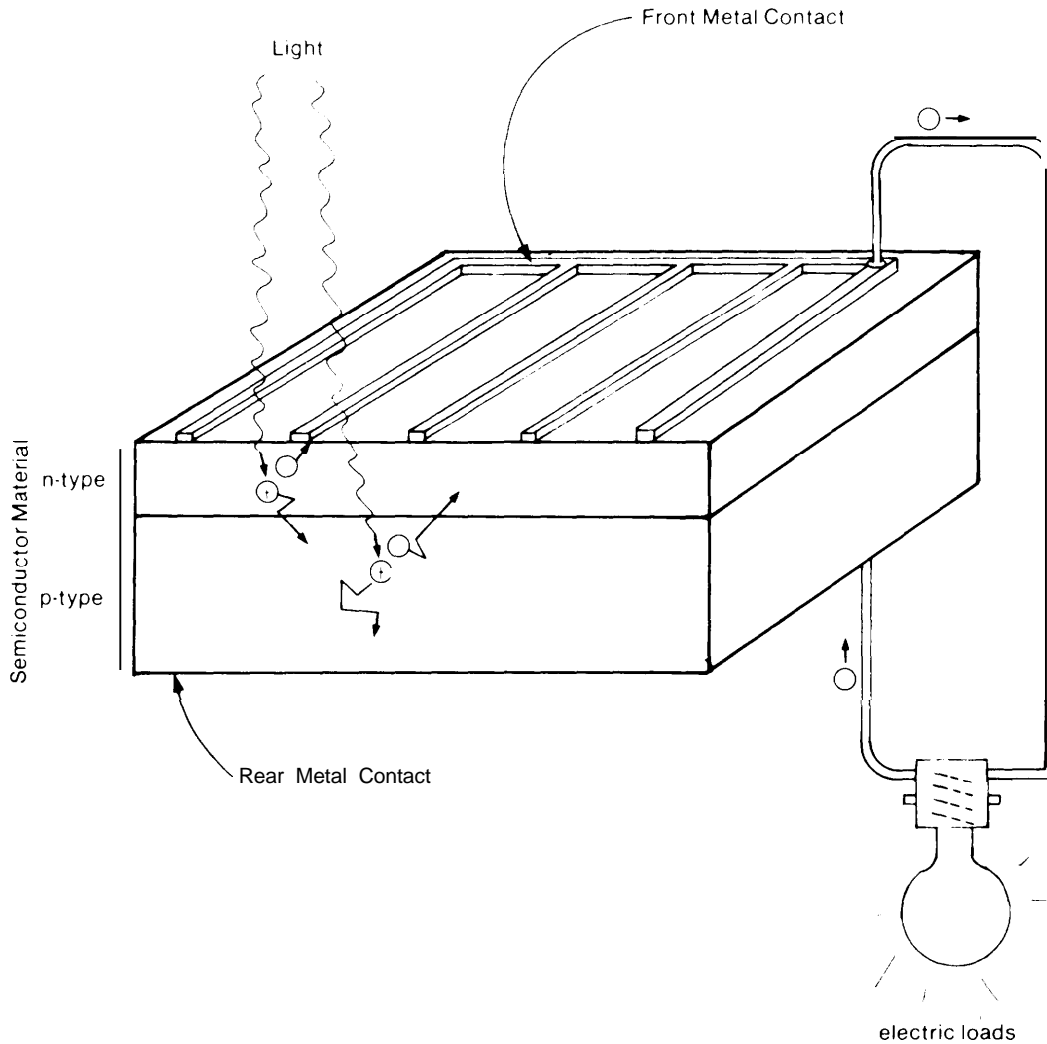
²H. J. Hovel, *Semiconductors and Semimetals*, Volume II, Solar Cells, Academic Press, New York, 1975

³C. E. Bacus, (ed.), *Solar Cells*, I E E E Press, New York, 1976

⁴A. Rothwarf and K. W. Boer, *Prog. in Solid State Chem.*, 10(2), p 77 (1975)

⁵K. W. Boer and A. Rothwarf, *Ann. Rev. Mat. Sci.* (6), p 303 (1976)

Figure X-2.— A Typical Photovoltaic Device



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 capturing a larger fraction of the energy in higher energy photons but losing a larger fraction of lower energy photons. The theoretical efficiency peaks at about 1.5 eV, but the theoretical efficiency remains within 80 percent of this maximum for materials with band gap energies between 1 and 2.2 eV.⁶⁷

⁶M. Wolf, *Energy Conversion*, 11, 63(1 971).

⁷Joseph J. Loferski, "Principles of Photovoltaic Solar Energy Conversion," *25th Annual Proceedings, Power Sources Conference*, May 1972.

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. ⁸(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 above some fixed

⁸M. Wolf, University of Pennsylvania, "Recent Improvements and Investigations of Silicon Solar Cell Efficiency," U.S./U.S.S.R. *Joint Solar Energy Workshop*, Ashkhabad, U. S. S. R., September 1977.

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 is shown in table X-2.

The performance of real cells (also shown in table X-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) and reflection from the electrical contacts on the front surface of the cell (which can be reduced with careful contact design). Losses also result from the fact that the photo-generated 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.

Photo-generated charges can be lost because of imperfections in the cell crystal structure, 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 which can be tolerated depends on the light absorbing properties of the cell material. If absorption is high, photovoltaic electron-hole pairs will be created close to the cell junction where the voltages exist; relatively small grain sizes can be tolerated since the charges need drift only a short distance before being sorted by the field.

Silicon is a relatively poor absorber of light and, as a result, cells must be 50 to 200 microns thick to capture an acceptable fraction of the incident light. This places rather rigorous standards on the sizes of

crystal grains which can be tolerated, and all commercial silicon cells are now manufactured from single crystals of silicon. It is believed that if polycrystalline silicon is to be used, individual crystal grains must be at least 100 microns on a side if efficiencies as high as 10 percent are to be achieved.^{11,12} It is important that the grains be oriented with the grain boundaries perpendicular to the cell junction so that charge carriers can reach the junction without crossing a grain boundary. A number of research projects are underway to develop inexpensive techniques for growing such polycrystalline materials^{13,14,15} and for minimizing the impact of the grain boundaries. Efficiencies as high as 6.7 percent have been reported for vapor-deposited polycrystalline silicon cells with grains about 20 to 30 microns on a side⁷ 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. Work is underway 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 con-

¹¹A. R. Kirkpatrick, et al., Proceedings of the ERDA Semiannual Photovoltaic Advanced Materials Program Review Meeting, Washington, D. C., Mar 22-23, 1977

¹²A. Baghdadi, et al., ERDA Semiannual Photovoltaic Advanced Materials Program Review Meeting

¹³T. L. Chu, et al., *IEEE Transactions on Electron Devices*, ED-24 (4), 1977, pp. 442-445.

¹⁴H. Fischer and W. Pschunder, (AEG-Telefunken), "Low-Cost Solar Cells Based on Large-Area Unconventional Silicon," *IEEE Transactions on Electron Devices*, ED-24(4), 1977, pp. 438-441

¹⁵L. D. Crossman, *Research and Development of Low-Cost Processes for Integrated Solar Arrays*, (Third quarterly progress report, ERDA EC (11-1)-2721, Energy Research and Development Administration, Washington, DC., 1975), p. 38

¹⁶T. H. Distefano and J. J. Cuomo, IBM, "Enhancement of Carrier Lifetime in Polycrystalline Silicon," *Proceedings*, National Workshop on Low-Cost Polycrystalline Silicon Solar Cells, Dallas, Tex., May 18-19, 1976.

¹⁷T. L. Chu, et al., op. cit pp 442-445

¹⁸H. Fischer and W. Pschunder, op. cit, p 438

⁹J. Lindmayer and J. F. Allison, *Comsat Tech.* #3, 1973, p 1

¹⁰J. R. Hauser and P. M. Dunbar, *IEEE Transactions on Electron Devices*, ED-24 (4), 1977, p 305

Table X-2.—Photovoltaic Cell Efficiencies

Device	Probable maximum achievable efficiency	Maximum measured efficiency	Performance of commercial cells	Reference
<i>Silicon devices</i>				
Single crystal homojunction	20-22	19	10-15	(1,2)
Polycrystalline homojunction	?	7-14(?)	—	(4,5)
Amorphous Schottky with platinum	15	5.6	—	(6,7)
<i>Thin films</i>				
CdS/Cu ₂ S (chemical vapor deposit process) (heterojunction)	15	8.6	2-3	(8,9)
CdS/Cu ₂ S (spray process) (heterojunction)	8-10	5.6	—	(10)
(Cd/Zn)S/Cu ₂ S (heterojunction)	15	6.3	—	(9)
CdS/CuInSe ₂ (single crystal) (heterojunction)	24	12	—	(11)
CdS/CuInSe ₂ (thin film) (heterojunction)	15	6.9	—	(12)
GaAs (Schottky AMOS)	25-28	14	—	(1,13)
Single crystal Schottky with indium-tin oxide	20	12	—	(3)
<i>Cells for use in concentrated sunlight</i>				
Optimized silicon cell (single-crystal homojunction), 200 times concentration	22	18	12.5	(14,15,16)
Interdigitated back-contact silicon, single-crystal homojunction, 100 times concentration	26-27	15(20?)	—	(17)
Thermophotovoltaic	30-50	13	—	(18)
Ga _x Al _{1-x} As/GaAs (180 times)	25-26	24.5	—	(19)
Ga _x Al _{1-x} As/GaAs (1,700 times)		19	—	(20)
Multicolor cell (GaAs/Si/Ge)	40	—	—	(21)
Vertical multijunction (silicon)	30	9.6	—	(22)

● Techniques for reporting efficiencies differ. Wherever Possible, efficiencies were chosen which assume air mass 1 and include losses due to reflection and contact shading.

- H. J. Hovel, *Semiconductors and Semimetals, Vol. 2: Solar Cells* (Academic Press, New York, 1975).
- J. Lindmayer and C. Y. Wrigley, "Development of a 20 Percent Efficient Solar Cell," (NSF-43090, National Science Foundation, Washington, D. C., 1975).
- J. V. DeBow, paper presented as part of the *Proceedings of the Energy Research and Development Administration Semiannual Photovoltaic Advanced Materials Program Review Meeting*, Washington, D. C., Mar. 22-23, 1977.
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- D. E. Carlson, *IEEE Transactions on Electron Devices, ED-24 (No. 4) 449 (1977)*.
- D. E. Carlson and C. R. Wronski, *Appl. Phys. Lett.* 28, 671 (1976).
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20. L. W. James and R. L. Moon (Varian Associates). "GaAs Concentrator Solar Cells" *The Conference Record of the Eleventh IEEE Photovoltaic Specialists Conference*, Scottsdale, Ariz., May 1975, pp. 402-408.
21. J. J. Loferski (Brown University), "Tandem Photovoltaic Solar Cells and Increased Solar Energy Conversion Efficiency," *The Conference Record of the Twelfth IEEE Photovoltaic Specialists Conference-1976, Baton Rouge, La., November 1976*, pp. 957-961.
22. H. J. Hovel (IBM). "Novel Materials and Devices for Sunlight Concentrating Systems," *IBM Journal of Research and Development*. Vol. 22, No. 2, Mar 1978, T. T. Rule, et. a/. (Arizona State University). "The Testing of Specially Designed Silicon Solar Cells Under High Sunlight Illumination," *Twelfth IEEE- 1976*. pp. 744-750.

struct photovoltaic cells with useful efficiencies. Efficiencies of 5.5 percent have been measured" and 15 percent efficiency may be possible. 20 The hydrogen apparently attaches to "dangling" silicon bonds, minimizing the losses that would otherwise result at these sites. Acceptable performance is possible, despite the large number of remaining defects, because the amorphous material is an extremely good absorber of light; test cells are typically 1 micron or less in thickness.²¹ The properties of this complex material are not well understood.

GaAs or CdS/Cu₂S are also much better absorbers of light than crystalline silicon, so cells made from these materials can be thinner and tolerate smaller crystal grains than was possible with the crystalline silicon. Commercial CdS/Cu₂S cells will probably be 6 to 30 microns thick,^{22, 23} 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 their low efficiencies. 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.

Older designs of cadmium cells degraded and failed relatively rapidly, but accelerated lifetime tests on modern designs appear to indicate that cells hermetically sealed in glass with proper electrical loading could have a useful life of decades.^{24 25 26}

Research is also underway on a number of other materials which may be used to manufacture inexpensive thin film cells. Experimental cells have been constructed which substitute iridium phosphide or copper iridium selenide for the copper sulfide in the CdS/Cu₂S heterojunction, and efficiencies greater than 10 percent have been demonstrated in single-crystal laboratory cells made with these materials. 2728

It is also possible to convert light energy directly into electricity by exposing electrodes immersed in chemicals to sunlight. If the materials are properly chosen, a current can be produced without any net chemical change in the materials used. Conversion ef-

¹⁹DE Carlson, RCA Laboratories, "Amorphous Silicon Solar Cells," *IEEE Transactions on Electron Devices*, ED-24(4), 1977, pp 449-452

²⁰_____ and C R Wronski, *App Phys.Lett.* 28, 1976, p 671

²¹A R Moore, *Electron and Hole Drift Mobility in Amorphous Silicon* (to be published)

²²Boer, op cit , p 319

²³J Jordan, Photon Power, Inc., El Paso, Tex , private communication, February 10, 1977

²⁴J. Besson, et al , "Evaluation of CdS Solar Cells as Future Contender for Large Scale Electricity Production," *The Conference Record of the Eleventh IEEE Photovoltaic Specialists Conference-1 975*, Scottsdale, Ariz , May 6-8, 1975 (Institute of Electrical and Electronics Engineers), pp 468-475

²⁵EWGreenwich and F A Shirland (Westinghouse Research Labs), "Accelerated Life Performance Characteristics of Thin-Film CU₂S Solar Cells-CdS," *Proceedings, Electrochemical Society Solar Energy Symposium*, Washington, D C , May 2-7, 1976

²⁶J F Jordan, Photon Power, Inc , private communication, Apr 5, 1976

²⁷S Wagner, et al , *Appl.Phys.Lett.*, 26, 229, 1975

²⁸JShay, et al , *Appl.Phys.Lett.*, 27, 89,1975

efficiencies greater than 5 percent have been reported with polycrystalline CdSe-based photoelectrochemical cells.^{29 30 31 32 33 34}

CELLS DESIGNED FOR USE IN CONCENTRATED SUNLIGHT

High efficiencies are important for cells used in concentrated sunlight, since increased cell performance means a reduction in the area which must be covered with the magnifying optical equipment, which dominates the system's cost.

Modified silicon cells, designed to perform in concentrated sunlight are not inherently more expensive than ordinary cells, but are always likely to cost more per unit of cell area since production rates will be lower and since more care will be taken in their manufacture. However, since the cells cover only a fraction of the receiving area, much more can be spent on any individual cell. Cells such as the thermophotovoltaic device and the $Ga_xAl_{1-x}As/GaAs$ cells may be considerably more expensive per unit area than the silicon devices, but this cost may not be significant since the devices can be used with concentrations of 500 to 1,000 or more and can be much more efficient. A variety of approaches are being investigated for achieving high-efficiency performance in concentrated sunlight.

Optimizing Conventional Silicon Cells for Use in Concentrated Sunlight

The current from a photovoltaic cell increases almost linearly with increasing sunlight intensity and the voltage increases slightly faster than the logarithm of the in-

tensity. These effects would lead to an increase in overall cell efficiency, except 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 operating in intense sunlight by carefully designing the wires used to draw current from the cells, optimizing the resistivity of the cell material, changing the thickness of the cell junction, and otherwise taking pains in cell manufacture (e.g., better antireflective coatings and surface texturing, higher quality silicon, precisely designed gridlines, etc.). Efficiencies as high as 17.9 have been reported for silicon cells operating at 1000 C in sunlight concentrated 200 times.³⁵

Several ingenious techniques have been suggested for improving performance of silicon devices used in intense sunlight with novel designs.

Interdigitated Back-Contact Cells

An "interdigitated back-contact" cell exposes an unobstructed wafer of intrinsic (i.e., very 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. (The name comes from the shape of the positive and negative electrical contacts on the back side of the cell. See figure X-3.) An efficiency of 15 percent concentration, with ratios up to about 280, has been reported for a preliminary version of this cell; it is believed that straightforward design improvements will result in cells which are at least 20-percent efficient. "

²⁹Mark S Wrighton, MIT, private communication, Mar 26, 1977.

30A. B. Ellis, et al., *J. Amer. Chem. Soc.*, 98, 1635, 6418, 6855(1976)

³¹C. Hodes, et al., *Nature*, 216, 403, 1976,

³²B. Miller and A. Heller, *Nature*, 262, 680, 1976.

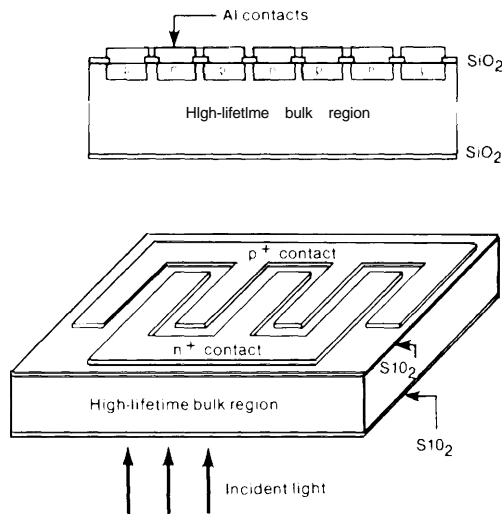
³³D. L. Laser and A. J. Bard, *J. Electrochem. Soc.*, 123, 1027, 1976.

³⁴K. F. Hardee and A. J. Bard, *J. Electrochem. Soc.*, 124, 215, 1977

³⁵L. S. Napoli, et al., RCA, "High Level Concentration of Sunlight on Silicon Solar Cells," *RCA Review*, Vol 38, No 1, March 1977, p 91

³⁶M. D. Lammert and R. J. Schwartz, Purdue University, "The Interdigitated Back Contact Solar Cell: A Silicon Solar Cell for Use in Concentrated Sunlight," *IEEE Transactions on Electron Devices*, ED-24(4), 1977, pp 337-341,

Figure X-3.—An Interdigitated Back Contact Solar Cell and Cross Section



SOURCE
Lammert M D and R J Schwartz "The Interdigitated Back Contact Solar Cell ASi11 con Solar Cell for Use in Concentrated Sunlight" *IEEE Transactions on Electron Devices*, VOI ED-24 (1977) p 337

Gallium-Arsenide Cells

Gallium arsenide has a higher theoretical photovoltaic efficiency than **silicon because** its excitation threshold is better matched to the energy in the Sun's spectrum.

GaAs cells can be used to achieve high efficiencies in intense radiation, particularly if they are covered with a layer of Ga_xAl_{1-x}As which has the effect of reducing surface and contact losses. Efficiencies as high as 24.5 percent have been measured for such devices operating in sunlight concentrated 180 times,³⁸

In addition, both theory and experiment show that the efficiency of GaAs cells is reduced less by high temperature than is the efficiency of silicon cells.

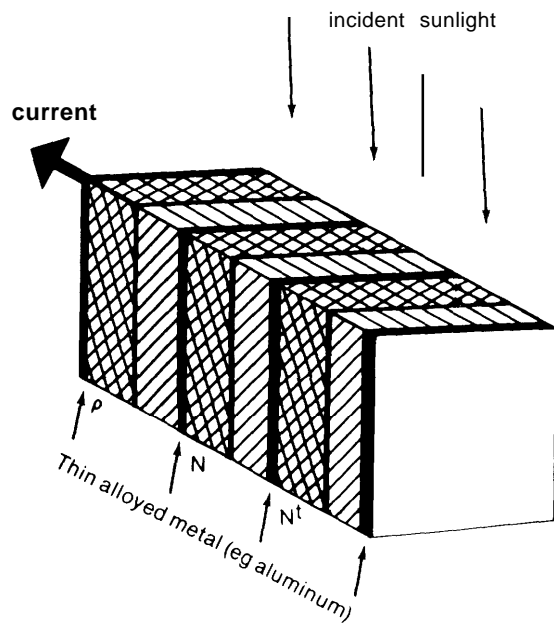
³⁷H Hovel, op cit , p 195

³⁸J Harris, et al , Rockwell International, "High Efficiency Al GaAs/G aAs Concentrator Solar Cells," *The Conference Record of the Thirteenth IEEE Photovoltaic Specialists Conference-1978*, Washington, D C , June 1978

The Vertical Multifunction Cell

The edge-illuminated, vertical, multifunction cell shown in figure X-4 consists of a stack of silicon homojunction devices qualitatively similar to standard cells, illuminated in such a way that the light enters the cells parallel to the junctions. Several recent calculations have indicated that these devices have the potential of achieving efficiencies as high as 30 percent,³⁹ although very little work has been done on designing and testing optimized cells. The maximum measured efficiency to date is 9.6 percent for a device without an antireflective coating.⁴⁰

Figure X-4.—The Vertical Multifunction Cell (edge illuminated)



³⁹H.J Hovel, IBM, "Novel Materials and Devices for Sunlight Concentrating Systems," *IBM Journal of Research and Development*, 22(2), March 1978,

⁴⁰T T Rule, et al , Arizona State University, "The Testing of Specially Designed Silicon Solar Cells Under High Sunlight Illumination," *The Conference Record of the Twelfth IEEE Photovoltaic Specialists Conference-1976*, Baton Rouge, La., November 1976, pp 744-750.

The high potential efficiency results from several features of the device:^{41 42 43}

- Since the vertical multifunction devices are connected in series, they produce higher voltages and lower currents than other concentrator cells with the same power output. The low currents reduce the resistance losses. Series connections also mean, however, that considerable care must be taken to ensure that all of the cell elements are illuminated since an unilluminated unit will act like a large series resistance.
- Like the interdigitated cell discussed earlier, the vertical multifunction devices do not require contacts on the surface (the aluminum connections can cover less than 1 percent of the surface area)⁴⁴ and thus front surface reflections are minimized.
- The multifunction device should be able to make more efficient use of light with relatively long and short wavelengths.
- The multifunction devices should be able to perform better than conventional silicon cells at high temperatures, and its performance at high temperatures improves in high light concentrations; the cells should, for example, be only half as sensitive to temperature at 1,000 x suns as they are in un-concentrated sunlight.⁴⁵

⁴¹B. L. Sater and C. Goradia, "The High Intensity Solar Cell -Key to Low Cost Photovoltaic Power," NASA Technical Memorandum, NASA TM X-71718, 1975.

⁴²C. Goradia and B. L. Sater, "A First Order Theory of the P-N-N Edge-1 Illuminated Silicon Solar Cell at Very High Injection Levels," *IEEE Transactions on Electron Devices*, Vol. ED-24, 4, p. 342, 1977.

⁴³H. J. Hovel, IBM, "The Use of Novel Materials and Devices for Solar Concentrating Systems," *Proceedings DOE Photovoltaic Concentrator Systems Workshop*, Scottsdale, Ariz., May 24-26, 1977.

⁴⁴B. L. Sater, "Current Technology Status of the Edge-illuminated Vertical Multifunction (VMJ) Solar Cell," November 1977 (unpublished).

⁴⁵C. Goradia and Sater, op. cit., p. 350.

The extra manufacturing steps required to fabricate these devices will make them somewhat more expensive than conventional silicon cells, but this difficulty would be offset if the high efficiencies are realized.

Horizontal Multifunction Cells

There have also been proposals for using horizontal multifunction devices using silicon or GaAs. It may be possible to design a cell array capable of producing relatively high voltages on a single chip, thereby reducing the cost of interconnecting devices and reducing series resistance in connections. The inherent efficiencies of these devices are approximately the same as conventional cells, but it may be easier to use the approach to develop practical cells which can more nearly approximate the potential of the materials.⁴⁶

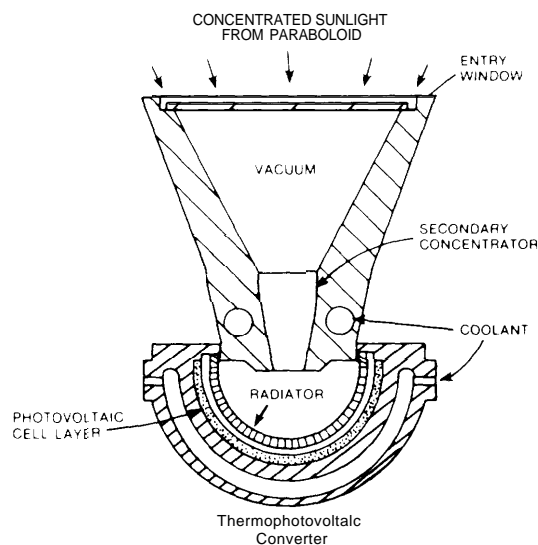
Thermophotovoltaic Cell

The "thermophotovoltaic" cells shown in figure X-5 may be able to achieve efficiencies as high as 30 to 50 percent by making an end-run around the fundamental limits on cell performance discussed earlier. This is accomplished 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 1,800 °C (the effective black body temperature of the Sun is about 5,700 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 through the small aperture where the sunlight enters.) A highly reflective surface behind the photovoltaic cell reflects unabsorbed photons back to the radiating mass and their energy is thus preserved in the system.⁴⁷

⁴⁶H. J. Hovel, IBM, "The Use of Novel Materials and Devices for Solar Concentrating Systems," op. cit., p. 38.

⁴⁷R. M. Swanson and R. N. Bracewell, *Silicon Photovoltaic Cells in Thermophotovoltaic Conversion*, EPRI ER-478, February 1977.

Figure X-5.— Thermophotovoltaic Converter



SOURCE

Swanson, R. M. and R. N. Bracewell (Stanford University): "Silicon Photovoltaic Cells in Thermophotovoltaic Conversion" EPRI ER-478 (1977)

Multicolor Cells

Another approach to achieving high cell efficiencies involves the use of a number of different materials to form cells optimally designed for different colors of light. There are two basic approaches: (1) the use of selective mirrors to separate colors and direct them to different cells, and (2) the use of a vertical stack of photovoltaic cells arranged so that upper layers absorb only high energy (i.e. short wavelength) photons, al-

lowing the remaining photons to reach lower cell levels.⁴⁸ Little experimental work has been done on these devices, but theoretical analysis has predicted that the light-filter devices could achieve efficiencies as high as 46 percent if two separate cells are used and 52 percent if three cells are used. Multi-layer cells using Ge, Si, GaAs, and other materials with two or more layers may also be able to achieve efficiencies above 40 percent. An ingenious scheme for separating colors 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.⁵² A considerable amount of development work will be required to design practical devices, however, and the ultimate cost of fabricating the devices cannot be forecast with any confidence.

⁴⁸H. J. Novel, IBM, "The Use of Novel Materials and Devices for Solar Concentrating Systems," *op cit.*, p. 38

⁴⁹N. S. Alvi, et al., Arizona State University, "The Potential for Increasing the Efficiency of Photovoltaic Systems by Using Multiple Cell Concepts," *Twelfth IEEE-1976*, *op cit.*, pp. 948-956

⁵⁰J. Loferski, Brown University, "Tandem Photovoltaic Solar Cells and Increased Solar Energy Conversion Efficiency," *Twelfth IEEE-1976*, *op cit.*, pp. 957-961

⁵¹A. Goetzberger and W. Breubel, *Appl. Phys.*, **14**, 1977, p. 123.

⁵²The technique was originally suggested for use in connection with scintillation counters in R. L. Garwin, "The Design of Liquid Scintillation Cells," *Rev. Sci. Inst.* **23**, 755 (1952); and R. L. Garwin, "The Collection of Light From Scintillation Counters," *Rev. Sci. Inst.* **31**, 1010 (1960).

CONCENTRATOR SYSTEMS

The contribution of photovoltaic cell costs 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, even though cells designed for use in concentrators may cost more per unit area of cell surface than flat-plate cells. If such systems are used, problems of reducing cell fabrication costs are

replaced with problems of mechanical engineering. In most cases, the energy required to manufacture a concentrator array is many times lower than the energy required to manufacture a flat-plate cell array with a similar area.

The variety of concentrating collectors which can be used with photovoltaic de-

vices is reviewed in chapter XII. Photovoltaic devices can be attached to most types of tracking systems with minimal modifications to the basic collector design. (A two-axis tracking system using Fresnel lenses to focus light on silicon cells is shown in figure X-6.) Attaching a photovoltaic device to a concentrating collector can, however, present some unique design problems:

- One-axis tracking collectors are unable to illuminate the entire receiver surface during most of the day. Thus, only a part of the receiver can actually be covered by cells. In general, it is necessary to connect photovoltaic devices in a receiver in series to achieve acceptable system voltages. Nonilluminated photovoltaic devices have high

Figure X-6.—Experimental Concentrating Photovoltaic Array in Operation.
The Array Employs Fresnel Lenses and Silicon Photovoltaic Cells



SOURCE Sandia Laboratories, Albuquerque, N Mex., 1976.

resistance and the output of a string of cells connected in series would be greatly reduced if one element of the string were shaded.

- It is desirable to maintain a relatively uniform illumination on most cells to maximize cell performance. This is difficult to accomplish with most collector designs. It is possible to design cells capable of performing with acceptable efficiencies in the illumination patterns of specific Collector designs. This can be done, for example, by modifying the pattern of electric contacts on the front surface of the cell, but the market for such specialized cells would necessarily be limited.

It is difficult to compare the attractiveness of concentrating and nonconcentrating photovoltaic devices because of the large number of variables involved; the only completely satisfactory way of making such a comparison is to conduct a complete life-cycle cost analysis of competing systems operating in realistic environments (such as those reported elsewhere in this study). The following formula, however, can be used to obtain a crude estimate of the cost of a concentrating collector which would be competitive with a flat-plate device (assuming that no credit can be given for the thermal energy which can be produced from the concentration systems):

$$C_c = C_{fp} \eta_{fp} r_e r_s (1 - r_c / C_r) + (C_o / k_1) (r_e r_s - r_o) + C_i (r_e r_s - r_i) + C_m r_e r_s \tag{X-1}$$

where the variables are defined as follows:

- C_c = allowed cost of the concentrating collector, excluding the solar cells (\$/m²)
- C_{fp} = cost of flat plate cell array (\$/kW)
- η_{fp} = the efficiency of the flat-plate array
- r_e = ratio of the efficiency of the concentrator photovoltaic system (including losses in the collector optics) to the efficiency of the flat-plate array (including packing factors)

r_s = ratio of solar energy reaching cells in the tracking collector to the sunlight (direct and diffuse) reaching the flat-plate collector

r_c = ratio of the cost of the concentrating cell (\$/kW in one sun) to the cost of a flat-plate cell array

C_i = cost of installing the flat-plate collectors (\$/m²)

r_i = ratio of cost of installing a concentrator to the cost of installing a flat-plate device

C_o = annual cost of maintaining the flat-plate system (cleaning etc.) in \$/m² of collector

r_o = the ratio of the cost of maintaining the concentrating collector to the cost of maintaining a flat-plate system (per m²)

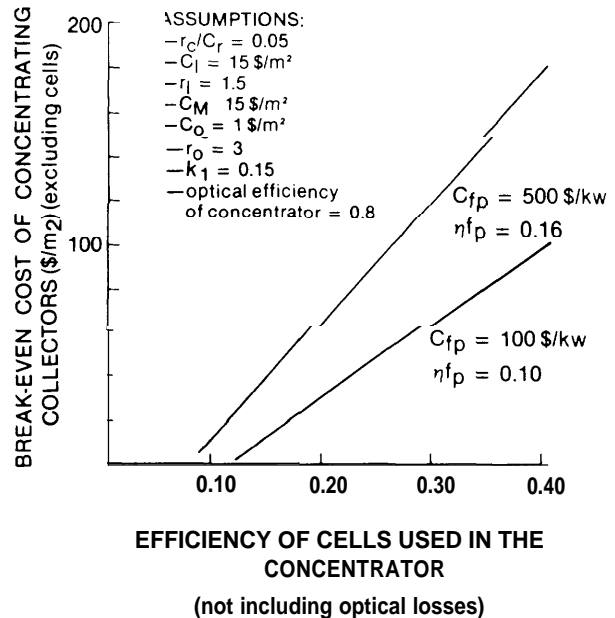
k_1 = the effective cost of capital

C_m = the cost of flat-plate supporting structures (\$/m²)

C_r = concentration ratio of collector

This formula has been used to construct the curves shown in figure x-7.

Figure X-7.— Breakeven Costs for Concentrating Photovoltaic Collectors Compared With Flat. Plate Devices



Assuming that concentrating systems cost so percent more than flat-plate arrays to install and three times as much to operate on an annual basis, concentrator systems would be competitive with \$500/kW—15 percent efficient flat-plate arrays if the concentrating collector costs about \$70/m² and concentrating cells are 20-percent efficient. The concentrator could cost about \$180/m² if concentrating cells are 40-percent efficient. (This example assumes that the optical efficiency of the concentrators is 80 percent and the concentration ratio is at least 10 times the ratio between concentrator cell costs and the cost of flat-plate arrays.) The allowed cost of concentrators will be considerably larger if there is a useful application for the thermal energy available from an active cooling system.

While 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/kW, the cost of supporting and installing the arrays could begin to exceed the cost of the arrays themselves.

General Electric has proposed a design for a photovoltaic shingle which may be able to substitute for a building roofing material. If costs reach \$100 to \$300/kW, it may also be economical 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 south-, east-, or west-facing wall is 40 to 60 percent lower than the output of a collector fixed at an optimum orientation.

PHOTOVOLTAIC COGENERATION

The analysis thus far has considered only the electric 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 devices, and an analysis of the opportunities presented by such devices is much the same as those conducted for conventional systems. In both cases, the net efficiency of systems can only be understood by examining the combined demands for electricity and thermal energy in each proposed situation. There are clearly many useful applications for the thermal energy with temperatures in the 500 to 100°C range which can easily be extracted from most photovoltaic cogeneration devices. About 23 to 28 percent of the primary energy consumed in the United States is used at temperatures below 108 °C.⁵³

With photovoltaic systems, the critical question is whether the electric-generating efficiency which is lost because of operating the cells at higher temperatures is compensated by the value of the thermal energy produced. Cell performance degrades almost linearly with temperature at temperatures of interest 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). This temperature dependence is commonly expressed in the following form:

$$\eta(T) = \eta(28)(1 - \beta[T - 28]) \quad (X-2)$$

where $\eta(T)$ is the efficiency of a cell at temperature T (expressed in °C) and β is the temperature coefficient. The temperature coefficient (β) measured for a number of different cells is illustrated in table X-3. It can be shown in most cases that if a use for low-temperature thermal energy exists, it is preferable to accept these losses of efficiency and use the thermal output from cells directly rather than to maximize cell performance

⁵³Battelle Columbus Laboratories, *Survey of the Applications of Solar Thermal Energy Systems to Industrial Process Heat*.

Table X-3.—Temperature Dependence of Photovoltaic Devices

Material	Cell efficiency at 28° C(%)	Base resistivity (Ω -cm)	Concentrate ion ratio C _r	β = temperature coef - ficient	
Silicon	10.4	0.1	1	0.0035	Sandia cell
Silicon	11.8	0.3	1	0.0035	Sandia cell
Silicon	12.4	0.3	40	0.0032	Sandia cell
Silicon	12.2	2.0	1	0.0040	Commercial cell
Silicon	11.8	10.0	1	0.0046	Commercial cell
GaAs	17.0		1	0.0022	Varian
GaAs	19.2		100	0.0023	Varian
GaAs	18.5		1000	0.0021	Varian
CdS	7.8		1	0.004-0.005	Univ. of Delaware

SOURCES Silicon cell data from Edward Burgess, Sandia Laboratories, private communication.

GaAs data from L. James, Varian private communication

CdS data from John Meakin, Institute of Energy Conversion, University of Delaware (private communication)

and attempt to use a photovoltaic-powered heat pump to produce thermal energy,

GaAs and other high-efficiency cells are less affected by high temperature operation than are silicon devices.⁵⁴ A commercial silicon cell operating with an efficiency of 12 percent at 270 C has an efficiency of only 8 percent if operated at 1000 °C⁵⁵, while a GaAs cell with an efficiency of 18.5 percent at 280 C can operate with 16-percent effi-

⁵⁴H J Hovel, IBM, *Semiconductors and Semimetals*, op cit , p 168

⁵⁵E L Burgess and J G Fossum, Sandia Laboratories, Albuquerque, "Performance of n + -p Silicon Solar Cells in Concentrated Sunlight," *IEEE Transactions on Electron Devices*, E D-24(4), 1977, p. 436

ciency at 1000 C and about 12-percent efficiency at 2000 °C.⁵⁶

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 employed. If photovoltaic cogeneration proves to be attractive, concentrator photovoltaic systems may continue to be economically attractive even if the price goals for flat-plate arrays are achieved.

⁵⁶L. James, Varian Corp , private communication, 1977,

THE CREDIBILITY OF THE COST GOALS

The most satisfactory technique for anticipating the future cost of photovoltaic devices would be to anticipate future manufacturing techniques and develop a precise cost estimate for each processing step; this approach is taken in the next section. Unfortunately, the results of such analyses are inconclusive since many future manufactur-

ing processes capable of dramatic cost reductions are based on techniques which are now only laboratory procedures or which anticipate progress in research. It is possible, however, to make some estimates of potential cost reduction by examining the history of cost reductions achieved in similar types of manufacturing.

A common statistical technique for analyzing the history of cost reductions is called the "learning-curve" technique.⁵⁷ This technique attempts to correlate the price of a product with the cumulative production experience of the industry manufacturing the product. In many cases, a rough correlation appears to exist, although the rate at which prices decrease varies greatly from one industry to another. The rate of "learning" is quantified by determining how much the price decreases when the cumulative production volume doubles: if a doubling of accumulated volume results in a price decrease of 10 percent, the system is said to be on a "90-percent learning-curve;" if a doubling of production volume results in a price decrease of 30 percent, the system is said to be on a "70-percent learning-curve."

The most obvious place to look for a historical analogy for predicting the price reductions possible in photovoltaic devices is the semiconductor industry which produces silicon devices using many of the techniques now used to construct silicon photovoltaic devices. The history of prices in the transistor and silicon diode industries is illustrated in figure X-8. The results are difficult to interpret since the price reductions clearly do not follow a simple linear learning curve, but they do indicate that a learning curve of 70 percent is not impossible. The analogy is far from perfect, of course, since miniaturization techniques which were used effectively to reduce the price of semiconductor electronics cannot be used in the manufacture of photovoltaic devices; the size of photovoltaic devices used in flat-plate arrays cannot be reduced since power produced by a unit area of photovoltaic surface is limited by the intensity of sunlight on the Earth's surface. The learning-curve method is probably valid for making crude estimates of future cell prices since learning curves of 70 to 90 percent have been observed for most products, even when miniaturization is not used in the manufacturing process.

⁵⁷Boston Consulting Group, *Perspectives on Experience*, 1971.

MARKETS

The learning curve cannot be used to estimate the rate at which prices will fall without information about the size of the market at each future price. Unlike most other power sources, the demand for photovoltaic devices exists at a large range of prices, since the equipment can provide power in remote areas where conventional alternatives are extremely expensive. The unique features of the equipment may lead to the discovery of markets for energy where no market now exists. The large 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 cells at 1976 prices was about 380 kW⁵⁸ of which about 280 kW were sold by U.S. manufacturers. U.S. Government purchases during this period were about 108 kW, of which about 50 kW were used in satellites.⁵⁹ 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).⁶⁰ Sales during 1977 were expected to be about twice 1976 levels.

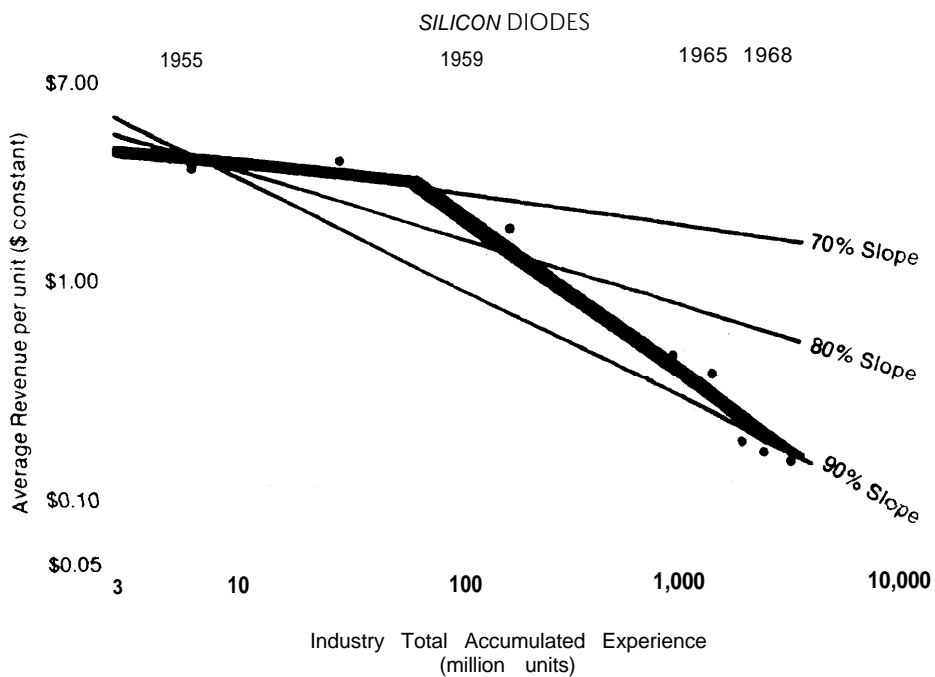
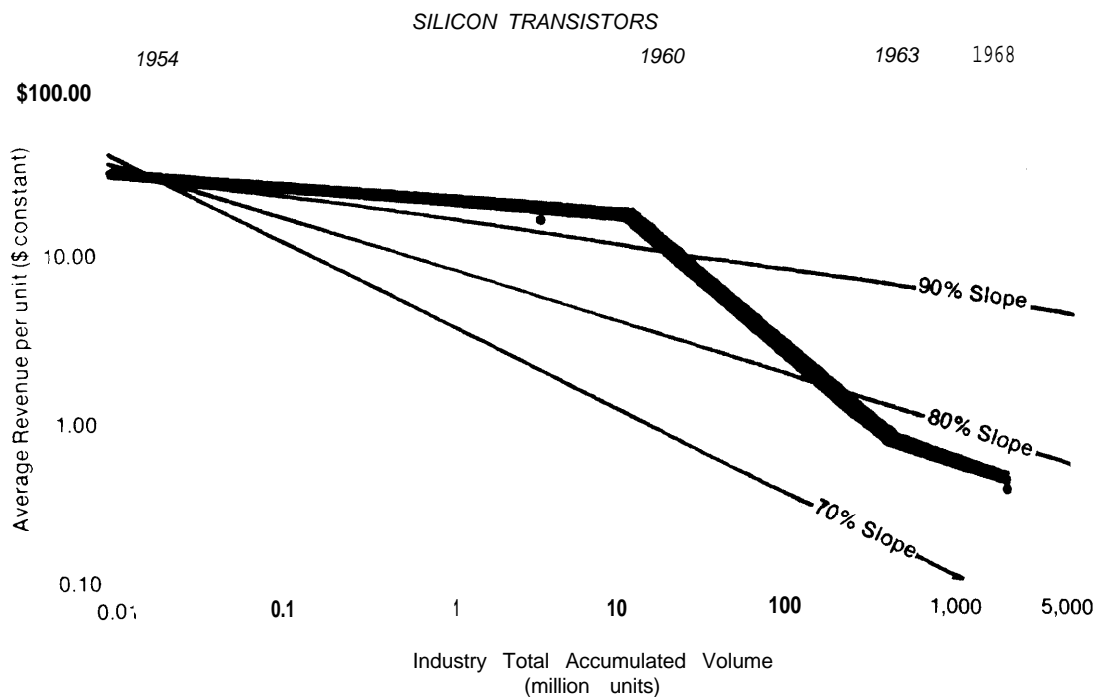
Several market surveys for photovoltaic equipment have been completed during the past several years, and some of these are summarized in table X-4. The considerable differences in the forecasts reflect differing judgments about the future cost of conventional energy and other forms of solar energy, about 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, etc.) and installa-

⁵⁸BDM Corporation, *Characterization of the Present Worldwide Photovoltaics Power Systems Market*, May 1977, p. 1-1.

⁵⁹Intertechnology Corporation, *Photovoltaic power Systems Market Identification and Analysis*, Aug. 23, 1977.

⁶⁰Intertechnology Corporation, *op. cit.*

Figure X-8.— Boston Consulting Groups' Learning Curve



**Table X-4.—Market Forecasts for Photovoltaic Devices at Different Prices
[in megawatts of annual sales]**

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

SOURCES ERDA briefing on the "Photovoltaics Program," Sept 9, 1977.

BDM Corporation, "Characteristics of the Present Worldwide Photovoltaic Power Systems Market," May 1977, p 1-1

Intertechnology Corporation, "Photovoltaic Power Systems Market Identification and Analyses," Aug 23, 1977

BDM Corporation, *DOD Photovoltaic Energy Conversion Systems Market Inventory and Analysis, Summary Volume*, p 17.

P D Maycock and G F Wakefield (Texas Instruments) "Business Analysis of Solar Photovoltaic Energy Conversion," *The Conference Record of the Eleventh IEEE Photovoltaic Specialists Conference*, 1975 Scottsdale, Ariz May 1975, pp 252-255

The Motorola Corporation

tion. 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.

The surveys seem to agree 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/kWh for electricity, and prices in more remote areas are often higher (if power is available at all).⁶¹ 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—two serious problems for developing countries,

Other possible areas where sales of photovoltaic equipment may increase rapidly during the next few years include applications by the U.S. Department of Defense (large, cost-effective purchases appear possible during the next few years)⁶² and the armed forces of other nations; the agricultural sector, for irrigation and other pumping ap-

⁶¹Telegrams received from A.I.D. from posts in numerous developing nations during July and August 1977 in response to a request for information about local utility rates

⁶²BDM Corporation, *DOD Photovoltaic Energy Conversion Systems Market Inventory and Analysis, Summary Volume*, p. 17

placations; and the transportation industry, for highway markers and lighting.^{63 64}

If prices fall below about \$0.50/watt, an explosive growth in sales could occur since at this price photovoltaic equipment might provide electricity which is competitive with residential and commercial electricity rates in many parts of the United States.^{65 66} By the time prices fall to \$0.10 to \$0.30/kW, the 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 the Nation now supplies and consumes electric energy. Moreover, when array prices 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.

Each of the projections of markets can be used to predict the rate at which prices fall given an assumed rate of "learning." Three forecasts and three different learning curves have been used to construct the forecasts shown in figure X-9. It can be seen that with the RCA estimate of markets and a 70-percent learning curve, the technique predicts that prices will reach \$500/kW in 1986. If prices fall according to a 75-percent learning curve, however, the price will not reach \$500/kW until after 1990. Using the less optimistic Texas Instruments (TI) estimates of markets, prices would not fall to \$1,000/kW until nearly 1990, even with the 70-percent learning curve,

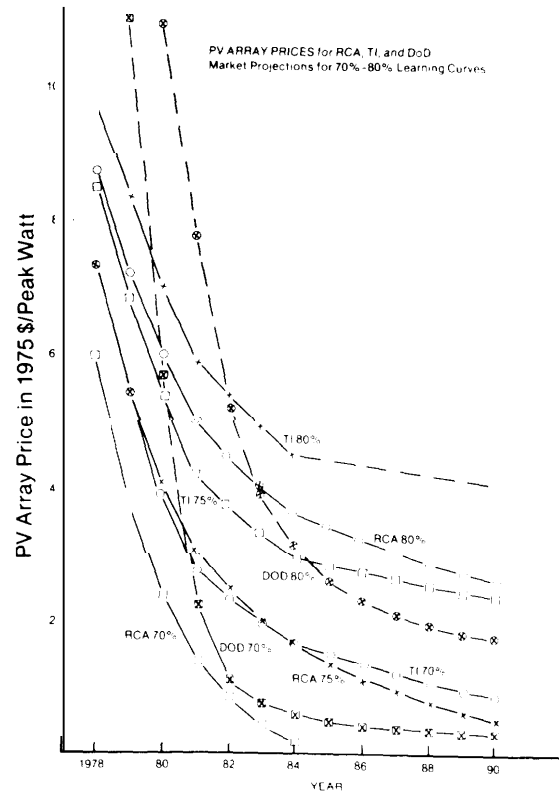
⁶³Intertechnology Corporation, op. cit.

⁶⁴BDM Corporation, *Photovoltaic Market*, op cit.

⁶⁵Westinghouse Corporation, *Final Report: Conceptual Design and Systems Analysis of Photovoltaic Power Systems, Volume I, Executive Summary*, April 1977, p 45

⁶⁶See volume I I of this study

Figure X-9. -Photovoltaic Array Prices for Several Market Projections



NOTE: With the exception of the "DOD sales" curves, it has been assumed that the Federal Government spends \$129 million for photovoltaic systems between 1978 and 1981, of which 40 percent is actually used to purchase cell arrays (the remainder being spent for design, installation, storage, control systems, and other supporting devices). The forecasts assume that cumulative production of cells through 1975 was 500 kW and that average array prices at the end of 1975 were \$15/Watt.

The figure also illustrates the extreme sensitivity of the forecast of potential price reductions to the assumptions made about intermediate markets. If the BDM Corporation forecasts of potential cost-effective military applications are correct and the military purchases devices for all cost-effective applications, prices can fall to \$500/kW by 1986, even if a 75-percent learning curve is assumed.

If the cost of photovoltaic devices is to be reduced through an expansion of the market, the industry will have to grow extremely rapidly for the cost goals to be met. For example, if prices follow a 70-percent learning curve, the cost goals can be met if the pro-

duction rate of cells doubles each year. (The times required to achieve different price reductions, given a learning curve and production doubling time, are summarized in table X-5.) Such expansions are possible but they could make it difficult for small companies now manufacturing cells to expand fast enough to meet demands.

[n spite of its limitations, the learning-curve technique can provide some useful guidance by establishing whether the cost goals anticipated for photovoltaic devices exceed any historic rates (the goals are optimistic, but not impossible by this test), and they can be used to explore the sensitivity of price reductions to different forecasts of potential markets.

AN ANALYSIS OF MANUFACTURING COSTS

Silicon

The vast majority of the photovoltaic cells now being sold are single-crystal silicon cells in flat arrays. (See figure X-1 O.) The bulk of Federal funding to reduce the cost of cells is being directed to silicon technology. The Federal Low-Cost Silicon Solar Array (LSSA) project, managed by the Jet Propulsion Laboratory (JPL) has made a careful analysis of the component costs of each step in the manufacturing process and is

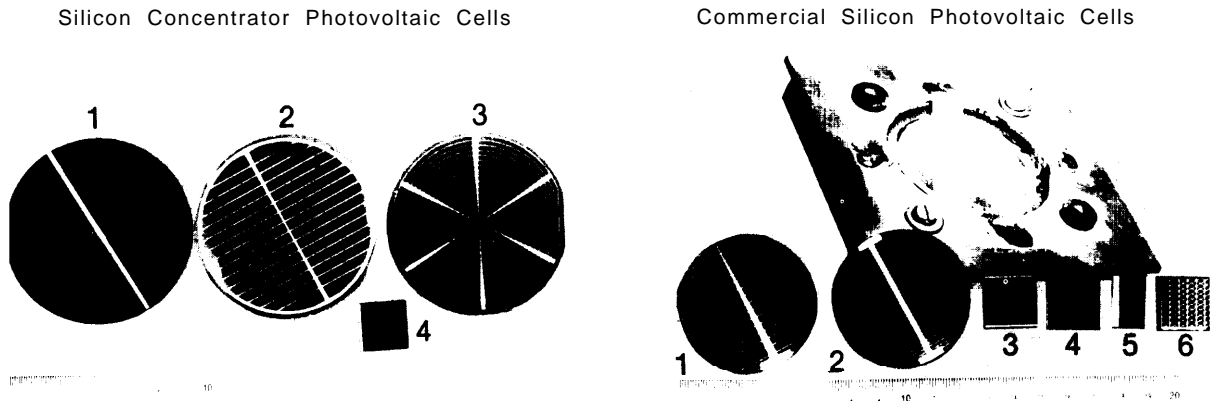
Table X-5.— Years To Achieve Indicated Price Reduction as a Function of Learning Curve and Assumed Growth in Demand

Price reduction (P/P_0)	Learning curve (percent)	Number of times production rates double each year			
		4	2	1	1/2
30	70	3.0	5.5	10.0	18.0
	75	3.6	6.6	12.3	22.6
	80	4.4	8.4	15.7	29.4
50	70	3.4	6.2	11.4	20.9
	75	4.0	7.5	14.1	26.1
	80	5.0	9.5	18.0	34.0
100	70	3.8	7.2	13.4	24.7
	75	4.6	8.7	16.5	30.9
	80	5.8	11.0	21.1	40.2
150	70	4.1	7.8	14.5	27.0
	75	5.0	9.4	17.9	33.7
	80	6.2	11.9	22.9	43.8

Assumptions: Price in 1976 = $P_0 = \$15,000/kWe^a$
 Cumulative sales volume in 1976 = $S_0 = 500 kwe^b$
 Annual sales in 1976 = $B = 250 (kWe)^c$
 $t_0 = 1976$ (base date)

aJW, Yerkes, (ARCO Solar, Inc.) Private Communication
 bJLindmeyer, (Solarex Corp.) Private Communication.
 cClifford, (Solarex Corp.) Private Communication, Oct 1976
 SOURCE: Prepared by OTA

Figure X-10.— Commercial Silicon Photovoltaic Cells



Scale in Centimeters

Photos John Furber, OTA

Manufacturer:

1. Solarex.
2. Arco Solar (Printed contacts)
3. Motorola.
4. Optical Coatings Laboratory, Inc.
(Space Cell Utilized In Sat elites)

Manufacturer:

- 1-4. Spectrolab.
5. Sandia Laboratories,
6. Solarex.

systematically examining techniques for reducing costs in four major areas.

- Production of the pure silicon feed-stock,
- Preparation of a thin sheet of silicon,
- Fabrication of cells, and
- Arrangement of the cells in a weather-proof array.

JPL objectives for cost reductions in each area are shown in table X-6. In reaching these goals, maintaining high cell efficiency will be critically important since many costs in cell manufacture and in the installation of photovoltaic arrays are proportional to overall cell area and not to power.

SILICON PURIFICATION

The purified polycrystalline silicon used as the raw material of commercial cell manufacture now costs about \$65/kg. The Jet Propulsion Laboratory estimated that, if the goal of \$0.50/watt is to be reached, the silicon material cost must be reduced to

about \$10/kg and the amount of silicon wasted in the manufacturing process considerably reduced.⁶⁷ Perhaps even more importantly, current techniques for manufacturing silicon are extremely inefficient in their use of energy; approximately 7,000 kWh of energy is required to manufacture a cell with a peak output of 1kW (assuming that cells are 100 microns thick and 82 percent of the silicon entering the manufacturing process is wasted).⁶⁸ 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 have been experimentally verified, and it should be possible to

⁶⁷H Macomber, JPL, *Proceedings, ERDA Semi-annual Solar Photovoltaic Program Review Meeting, Silicon Technology Programs Branch, San Diego, Calif., January 1977*, p 68.

⁶⁸L P Hunt, Dow Corning Corp., "Total Energy Use in the Production of Silicon Solar Cells From Raw Materials to Finished Product," *Twelfth IEEE-1976*, op. cit., pp 347-352

Table X-6.—The Distribution of Costs in the Manufacture of silicon Photovoltaic Devices Using Contemporary Technology [all costs in \$/peak W]

	Representative data for 1976	Ingot technology			Non ingot technology	
		1978	1980	1982	1984	1986
Polysilicon	2.01	1.16	.76	.28	.14	.06
Crystal growth and cutting	4.18	2.50	1.43	.67	.23	.10
Cell fabrication	5.97	1.87	1.01	.58	.34	.19
Encapsulation materials78	.22	.12	.09	.07	.03
Module assembly and encapsulating	3.99	1.25	.68	.38	.22	.12
Price	16.96					
Goal	20.00	7.00	4.00	2.00	1.00	.50

Does NOT include Inflation— prices in 1975 constant dollars

NOTE The detailed price goal allocations are for silicon ingot technology up through 1982 and for silicon sheet Technology in 1984 and 1986. These allocations for use within the LSSA Project are subject to revision as better knowledge is gained and should not be construed as predicted prices.

It is expected that after 1982, ingot and sheet technology modules will be cost competitive, with the possibility that the \$50/W goal can be achieved by either technology. Technology developments and future production cost parameters will be major factors in determining the most cost effective designs.

SOURCE Jet Propulsion Laboratory Low Cost Silicon Solar Array Project Received by OTA June 1977

develop cell arrays capable of producing all the energy used in their manufacture in 3 to 4 months." 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.

It is possible to produce photovoltaic cells with silicon less pure than the "semiconductor grade" material now used in cell manufacture, but a careful analysis must be made to determine whether the lower silicon costs would compensate for the additional system costs which would be incurred by the reduced cell efficiency which results. Manufacturing very high efficiency cells for use in concentrators may even require silicon which is of higher purity than the material now used to produce most semiconductors.

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 because construction of

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 silicon 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 of 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.

Improved sawing techniques may be able to cut silicon material requirements by two-thirds by producing thinner silicon cells and reducing the material lost as sawdust. 70 lm-

"A. Kran, IBM, *Proceeding, Symposium on the Materials Sciences Aspect of Thin Film Systems for Solar Energy Conversion*, Tucson, Ariz., May 20-22, 1974

⁶⁹Hunt, *ibid.*

proving the techniques used to grow crystals could also reduce losses. Development of a ribbon or thin-film, crystal-growing process could greatly reduce wastage. Development of an amorphous silicon cell with adequate performance would dramatically reduce silicon requirements in cells since these cells would 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.

FORMATION OF SILICON SHEETS

Growing pure silicon crystals and sawing them into thin wafers now represents about 25 percent of the price of arrays. A number of active programs exist for improving the batch processes in which crystal ingots are currently being produced and sawed into wafers⁷² 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. Development of an ingot technique adequate to meet the \$1 to \$2 per watt cost goal appears to be assured, and improved ingot techniques may even be adequate to meet the 1986 cost goal. The problems remaining in this technology 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 production.

⁷¹"Low-Cost Silicon Solar Array Project," *Quarterly Report-2, July-September 1976*, pp 1-4

⁷²Jet Propulsion Laboratory, *Low-Cost Silicon Solar Array Project, Report-2, July-September 1976*, pp 4-57

⁷³McComber, JPL, op cit, p 71

Crystal Growing and Slicing

All of the silicon photovoltaic devices now sold are manufactured from wafers sawn from single-crystal boules (2- to 3-inch diameter cylinders of silicon). These wafers represented about 35 percent of the cost of photovoltaic arrays in 1976 (see table X-6). The crystals are commonly grown by dipping a seed crystal into a silicon melt in a quartz crucible which is a few degrees above silicon's melting point and by slowly withdrawing the growing crystal from the melt. The crucible and the crystal are counter-rotated to grow a straight crystal of uniform, circular cross-section. The crystal is pulled from the crucible until most of the molten silicon has been withdrawn and removed from the melt. The entire apparatus is then allowed to cool so that the crystal can be taken out of the airtight chamber. As the remaining molten silicon solidifies in the crucible, the crucible usually breaks, adding about \$50 to the cost of the boule. This procedure is called the "Czochralski" (Cz) or "Teal-Little" method. The boule is sawed into thin wafers which are sent to the next stage of the cell fabrication process. Several commercial silicon cells manufactured using this technique are shown in figure X-10. A variety of new concepts have been proposed for reducing the cost of the crystal-growing processes, some involve radically new approaches where thin films or ribbons are solidified directly from the molten silicon.

- Improved sawing techniques might reduce the material lost in the sawing process; currently, nearly 50 percent of the crystal grown is lost as silicon sawdust. Techniques are being developed which use multiple saws with thin saw blades, sawing wires, and other advanced processes to decrease the material lost in sawing and increase the number of silicon wafers produced from a single crystal by producing thinner wafers. 74 75

"Texas Instruments, Inc., and Varian have ERDA contracts to improve sawing techniques. See R. G. Forney, et al. JPL, op cit

⁷³LSSA Quarterly Report, op cit, pp 4-117, 4-115

- The molten silicon in the quartz crucible from which the crystal boule is withdrawn can be continuously replenished, leading to longer crystal draws and a lower requirement for crucibles. (This process could also save a number of processing steps.)
- The silicon material lost in sawing could be recycled for further use if it is not contaminated in the cutting process.
- Techniques can be used to increase the diameter of the crystals grown by using the standard Czochralski process. Crystals now in use are typically 3 inches in diameter, but crystals 10 inches in diameter have been grown in laboratories. An experiment is now underway to grow three 12-inch diameter crystals in one continuous heating cycle.⁷⁷ Choice of an optimum diameter will depend on a detailed study of the manufacturing process. (Problems in cutting the crystals increase with crystal diameter.)
- The rate of crystal growth can be increased if columnar grains can be tolerated in cell wafers (research is required to determine the extent to which such grains can be tolerated or their effects minimized).
- Considerable energy and capital equipment could be saved if a process could be developed for growing a crystal in a mold. The Crystal Systems Company is currently examining a concept in which a seed crystal is placed in one end of an insulated mold filled with molten silicon. A temperature gradient is maintained along the mold so that the crystal grows from the end with the seed crystal to fill the mold.⁷⁸ This technique is commonly used to grow metal crystals, but has not yet been successfully

adapted to the growth of semiconductor-grade silicon crystals.

- improvements in cutting circular wafers into the hexagons required for close packing are possible through the use of a laser-slicing technique being developed by Texas Instruments.

Table X-6 indicates that if current techniques are converted to mass production, silicon wafer blanks can be produced for about \$112/m² (\$0.80/watt if the cell is 14-percent efficient) if polycrystalline material were purchased for \$35/kg. This could be reduced to approximately \$78/m² if polycrystalline material were purchased for \$10/kg. A recent analysis conducted for DOE by Texas Instruments estimated that it would be possible to produce "solar-grade" polycrystalline silicon for \$10/kg (or \$214/kW at 14 percent efficiency),⁷⁹ and for approximately \$5/kg if arrays are to be manufactured for \$1 (/)/k W. 80

Single Crystal Growth—Ribbons and Sheets

Research has been underway for at least 15 years to develop a process by which single-crystal silicon can be produced in the form of ribbons or sheets. Thin ribbons would be appropriate for use in solar cells without the crystal-slicing steps required for boules. This would eliminate the costs involved in slicing the crystals and could make more efficient use of silicon. This would not only eliminate expensive operating steps, but could reduce trimming losses when cutting round cells to hexagonal cells. The Department of Energy has been funding Mobil-Tyco, Solar Energy Corp., IBM, Motorola, RCA, the University of South Carolina, and Westinghouse to assess the merits of a variety of processes for growing single-crystal ribbons and sheets.⁸¹

One technique for doing this is the "edge-defined, film-fed growth" process (EFG);

⁷⁶M. Goldes (President of SunWind Ltd), private communication, Aug 16, 1976

⁷⁷R G Forney, et al , JPL, op cit

⁷⁸R G Forney, et al , JPL, op cit.

⁷⁹Ibid.

⁸⁰Ibid

⁸¹E RDA, *Semiannual National Solar Photovoltaic Program Review Meeting*, University of Maine, August 1976

work began on this process about a decade ago. The EFG process utilizes a graphite die on top of a crucible of molten silicon. A narrow pool of molten silicon forms on the top of the die by capillary action. A thin ribbon of silicon is slowly withdrawn from this pool.⁸² Such a ribbon is shown in the growth

⁸²B Chalmers, "The Photovoltaic Generation of Electricity," *Scientific American*, November 1976, p 34

process in figure X-11. Photovoltaic cells made from EFG ribbons have shown efficiencies as high as 10 percent.⁸³ Intensive work is proceeding on the EFG process but several difficulties remain: 1) contain i nation

⁸³K. Ravi, et al., 12th *IEEE Photovoltaic Specialists Conference*, Baton Rouge, La., Nov. 15, 1976

Figure X-1 1.—Silicon Ribbon Being Grown by the "Edge-Defined Film. Fed Growth" Process



(Mobil Tyco Solar Energy Corp)

of the ribbon by impurities from the die results in efficiencies lower than other silicon cells; 2) the graphite die is attacked by the molten silicon; and 3) the process is currently quite slow. Ribbons 2- to 21A-cm wide can now be grown at rates of 2 to 7 cm per minute. The objective is a growth rate of approximately 18 cm. per minute.⁸⁵ A recent analysis by IBM indicated that a large-diameter Czochralski boule can grow silicon crystal areas at a rate equivalent to 20 to 40 simultaneously pulled ribbons.⁸⁵

Other ribbon techniques under investigation include the IBM "Capillary Action Shaping Technique" (CAST) which uses a wetted die, and the RCA "inverted stepanov" technique which uses a nonwetted die. Both techniques share many of the problems of the EFG approach.⁸⁶

Another process for manufacturing ribbons is the web-dendrite crystal growth process. Unlike EFG, this process requires no die, and the die contamination and die erosion problems are, therefore, avoided. Strips of silicon 2 meters long, 0.15mm thick, and 22mm wide have been grown at rates of 2 to 3 cm per minute; the objective is a growth rate of 18 cm per minute.⁸⁷ Difficulties which remain with this process include: 1) the fact that careful temperature control is necessary, which probably precludes the simultaneous growth of several ribbons from one melt; and 2) relatively slow growth rates.

Polycrystalline Sheets

Work is also underway to develop low-cost techniques for producing sheets of polycrystalline silicon with crystal grains large enough in size and oriented properly

to allow the production of cells with acceptable efficiencies. Some processes are yielding individual crystal grains 1 to 10 mm on a side, blurring the distinction between single and polycrystalline devices. Perfection of such processes could lead to more efficient use of the silicon feedstock and replaces the expensive task of growing a perfect crystal with a casting, forming, or depositing process which may be much less expensive. Some of the methods proposed would create a thin layer of polycrystalline material on a solid backing, or substrate, thus eliminating the cost and material waste associated with slicing the silicon material into wafers. Concepts include:

1. Dipping a substrate into molten silicon, covering the substrate with a thin coating of polycrystalline silicon. (Honeywell).
2. Continuously pulling a thin sheet of silicon from the surface of a pool of molten metal where silicon vapor is being deposited. (General Electric).
3. Depositing silicon from a silicon-halide gas directly onto a hot substrate. It may be possible to combine the final stage of silicon purification (distillation) with this deposition process (Rockwell international and Southern Methodist University).
4. Forming heated silicon material under pressure in rollers (University of Pennsylvania).
5. Casting blocks of polycrystalline material and slicing the blocks (Crystal Systems, Salem, Mass.).

CELL FABRICATION

The process of converting silicon wafers into an operating photovoltaic array with 1 kW peak output involves a number of individual steps which now require many hours of hand labor,⁸⁸ adding about \$6 to the price

⁸⁴Ibid

⁸⁵Kran (1 BM), "Single-Silicon Crystal Growth by Czochralski and Ribbon Techniques—A Comparison of Capabilities," *Proceedings, Symposium on the Material Sciences Aspect of Thin Film Systems for Solar Energy Conversion*, Tuscon, Ariz., May 20-22, 1974, pp 422-430

⁸⁶"Low-Cost Silicon Solar Array Project," *Quarterly Report-1*, July-September 1976, p 4-57

⁸⁷Ibid

⁸⁸P. D. Maycock and G. F. Wakefield, Texas Instruments, "Business Analysis of Solar Photovoltaic Energy Conversion," *Eleventh IEEE-7975*, pp 252-255

of a 1 watt cell. Processes include the creation of the photovoltaic junction, the addition of electrical contacts, and the application of anti-reflective coatings.⁸⁹ Studies of mass-production techniques conducted for JPL by Motorola, Texas Instruments, and RCA all indicate that this cost could be reduced to \$0.30 to \$0.90/watt⁹⁰ using known mass-production apparatus, if plants capable of producing about 5 to 50 MW annually were constructed. The costs associated with each step in the fabricating process are shown in table X-7. Projecting further price reductions, however, requires a fair amount of optimism. It can be seen from table X-4, however, that cell prices must fall to \$1 to \$2/watt before there will be markets large enough to support several competing fabricating plants of the size envisioned in the JPL studies. It is likely that manufacturers will show greater desire to invest in fabrication equipment than in the more capital-intensive devices required to

manufacture silicon wafers. This is because significant cost reductions can be accomplished with plants much smaller than 50 MW/year, and it is much less likely that fabricating plants would become obsolete—even if breakthroughs dramatically reduce the cost of manufacturing silicon wafers.

The laborious and expensive processes for making photovoltaic cells are also extremely inefficient in their use of energy. Silicon material, for example, is melted when it is purified, cooled, and shipped to the crystal-growing facility where it must be melted again to grow a crystal, again cooled, heated at least once more during cell fabrication, and then cooled to ambient temperatures for the third time. No attempt is made to recover any of the heat wasted when the cells are cooled. The efficiency of this process could clearly be improved significantly to reduce both the cost of the cell and the time required for the cell to “pay-back” the energy used in its manufacture once it is installed.

⁸⁹ERDA “Photovoltaics Program “
“h! acomber, JPL, op cit , pp 71-72

Table X-7. —The Major Steps in Manufacturing a Silicon Photovoltaic Device

	Surface prep	Junction formation (alternate)	Metalization	Other processes	Module fabrication	Totals
Motorola	0.282	0.080	0.082	0.042	0.385	0871
RCA	0.003	Ion 0.044 (Spin 0.081) & PO Cl ₃ (Print 0.048)	0.101	0.045	0.114	0309 to 0.343
Texas Instruments	0.035	Spin 0.048 (Ion O 092)	Thick Film 0.050	0.093	Hermetic 0.272 Nonhermetic 0.135	0391 to 0.586

Assumptions

- 1) cells would be made using wafers Sliced from ingots
- 2) Based upon an extrapolation of present technology with reasonable development but without technological breakthroughs
- 3) 50 MW/year production of a single design.
- 4) 14 percent cell efficiency

* Does not include cost of silicon material nor wafers

SOURCE JPL Loh Cost Silicon Solar Array Project (received by OTA June 1977)

MODULE ASSEMBLY AND ENCAPSULATION

Finally, the process of connecting cells together into arrays and encapsulating them to protect the cells from the weather must be reduced by a factor of 10 from current costs to about \$0.12/watt.⁹¹ A variety of techniques have been proposed and the cost reduction seems feasible, but the exact technique which will be used is not yet clear.

Thin Films

The nonsilicon thin-film technologies which show the greatest potential for reaching the cost goals early in the 1980's are all based on the CdS/Cu₂S heterojunction cell. Much more work has been done on the problem of reducing the cost of manufacturing CdS/Cu₂S than on any other thin film.

Cadmium sulfide cells are produced commercially in the United States by Solar Energy Systems (SES) of Newark, Del. These cells are produced in batch processes⁹² and hermetically sealed in glass. Their efficiency is 3.2 percent with an array efficiency of 2.5 percent.⁹³ SES is attempting to keep their array prices competitive with the market price of silicon arrays. An early prototype cell is shown in figure X-12.

No technical barriers to scaling up the current manufacturing procedures are foreseen, but a significant amount of "process development" will be required to bring prices below \$1,000/kW.⁹⁴ Researchers at Westinghouse estimate that a factory based on this process capable of manufacturing cells for \$1 to \$2/watt could be producing commercial products within 2 years of a decision to initiate the project.⁹⁵

⁹¹See table X-6

⁹²F. A. Shirland, Westinghouse Research Labs, private communication, Mar. 26, 1976

⁹³S. DiZio (President, SES) private communication, Apr. 7, 1976.

⁹⁴Ibid.

⁹⁵F. A. Shirland, Westinghouse Research Labs, private communication, Mar. 26, 1976.

Figure X.12.—Thin-Film Cadmium Sulfide-Copper Sulfide Solar Cells

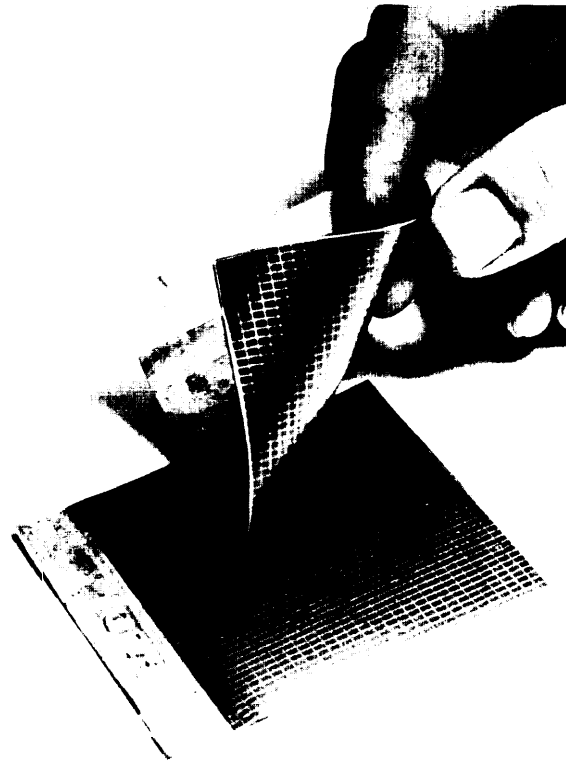


PHOTO: Courtesy of the University of Delaware

Photon Power, Inc., of El Paso, Tex., is developing a chemical spray process which forms cadmium sulfide solar cell panels directly on hot float-glass as it comes out of the glass factory.

Photon Power has completed a pilot plant in El Paso for testing the technique. 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/watt by 1980.⁹⁶ Low costs are possible because all of the processes in cell manufacturing (cell growth, junction formation, ap-

⁹⁶G. Rodrick, (President, Photon Power, Inc.), private communication, March 1978

plying contacts, and encapsulation) involve spraying a series of chemical layers onto hot glass moving through the plant on a continuous conveyor. Laboratory devices produced with a similar process have yielded 5.6-percent efficiencies, and cells with 8- to 10-percent efficiencies appear possible. " Even higher efficiencies may result if the promising results of experiments mixing zinc with cadmium can be integrated into the process.

Photon Power 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. A preliminary calculation indicated that a plant costing about \$140 million would be able to produce 2 GW/year for \$0.05 to \$0.15/watt.⁹⁸ The major technical challenge in increasing output will be finding a way to increase the speed of the spray application process from the 2 cm per minute in the pilot plant by about an order of magnitude to match the rate at which glass is produced from a flat-glass facility.⁹⁹ It will also be necessary to

⁹⁸G A Samara (Sandia Laboratories, Albuquerque), *Proceedings, ERDA Semiannual Photovoltaic Advanced Materials Program Review Meeting*, Washington, D C , Mar 22-23, 1977

⁹⁹J F Jordan, Photon Power, Inc , *International Conference on Solar Electricity*, Toulouse, France, April 1976

⁹⁹J F Jordan, Photon Power, Inc , private communication, April 1976

determine how much of the cadmium not initially captured on the glass can be recycled (this is important since cadmium is expensive and toxic) and to determine how well the hydrogen chloride, sulphur, and sulfurous acids can be recycled.

The French National petroleum company, Compagnie Francaise des Petroles, owns controlling interest in Photon Power. Libby-Owens-Ford and D. H. Baldwin Co., own minority interests.

Patcentre International of Hartfordshire, England is working on a spray process very similar to Photon Power's. They report 5.5-percent efficiency for their laboratory devices, and hope to market a commercial product in 1980.¹⁰⁰

A number of other cells, usually based on heterojunctions between an element in group III and group V of the periodic table, are being investigated as candidate thin film cells, but few are beyond the stage of basic laboratory research. The present performance of some of these experimental devices is shown in table X-2.

¹⁰⁰G Kaplan, IEEE Spectrum, "Power/Energy Progress Report," *IEEE Spectrum*, Vol 15, No 1, January 1978, p 51

MATERIALS AVAILABILITY AND TOXICITY

Enthusiasm about cells based on materials other than silicon must be tempered to some extent by uncertainties about the health hazards which they may present and about the limits imposed on their production by U.S. and world supplies of component materials. Both cadmium and arsenic, used in GaAs cells, are toxic and while it may be possible to reduce the hazards they present to manageable proportions and while both materials are already used extensively in commercial products and manufac-

turing, it clearly will be necessary to examine these hazards with some care before recommending an energy system which would significantly increase the use of these materials near populated areas. Domestic supplies of both cadmium and gallium 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 and, in the case of cadmium, known world reserves limit the ultimate potential of CdS/Cu₂S

devices to about the level of current U.S. energy consumption.

SILICON

Silicon is nontoxic and in plentiful supply (about one atom in five in the Earth's crust is a silicon atom), although current production rates of purified silicon are not adequate to support a large solar industry. The manufacture of silicon devices with present techniques involves the use of a number of hazardous chemicals (PH₃, BCl₃, H₂S₂, HCl, HCN).¹⁰¹ Existing State and Federal laws should be sufficient to ensure that releases of these materials into the air and water are kept to acceptable levels, although vigilance will be needed to ensure compliance with these regulations. Meeting the standards may add to the cost of the devices.

CADMIUM

Cadmium is a cumulative heavy-metal poison with a half-life in the human body of 10 to 25 years. Cadmium poisoning is believed to lead to accelerated aging, increased risk of cancer, heart disease, lung damage, birth defects, and other problems.¹⁰² Chronic exposure to airborne cadmium can lead to emphysema and other respiratory problems.¹⁰³ Cadmium, however, is used in many commercial and industrial products; it is used for corrosion protection on bolts and screws, in paints, plastics, rubber tires, motor oil, fungicides, and some types of fertilizers.¹⁰⁴ Increased use of cadmium resulting from large-scale manufacture of CdS/Cu₂S cells could result in in-

creased release of cadmium from mining, refining, and manufacturing of the cell, and it would increase the amount of cadmium present in products located near populated areas, thereby increasing the risk of exposure in the event of fires, accidents, or the demolition of buildings.

More stringent standards may be needed both in manufacturing processes involving the material and in permitting usage of the material in commercial products. At present, cadmium is not subject to any environmental controls, but under both the Toxic Substance Control Act (P. L. 94-469) and the Resource Conservation and Recovery Act (P. L. 94-580), EPA has jurisdiction over its regulation which, if instituted, could include both solar and other household uses.

It is apparently possible to significantly reduce the cadmium released in the manufacturing process, and it appears that with proper encapsulation CdS cells can be used in residential areas with minimal hazard.¹⁰⁵ Exposure to the material would only occur during fires, accidental breakage, or building demolition. The acceptability of such exposure can be judged better when meaningful standards have been developed.

U.S. production of cadmium in 1970 could support the annual manufacture of cell arrays with a peak output of 5,000 to 20,000 MWe (assuming cells are 10-percent efficient). World production is about five times greater than U.S. production.¹⁰⁶ The higher figure applies to the spray process for manufacturing cells, which results in cells about 6 microns thick. Significant increases in cadmium production may be achievable, however, if demand increases. Identified U.S. reserves of cadmium are sufficient to produce cells with an annual output equal to the current U.S. consumption of electricity. Known world reserves are about five times greater than U.S. reserves.¹⁰⁷

¹⁰¹J.G. Holmes, et al, "Environmental and Safety implications of Solar Technologies," *Proceedings, 1977 Annual Meeting American Section of the International Solar Energy Society*, Orlando, Fla., June 1977, p. 28-7

¹⁰²N A Esmen, et al., University of Delaware, *Environmental Aspects of Cadmium Sulfide Usage in Solar Energy Conversion— Part P— Toxicological and Environmental Health Considerations — A Bibliography*, NSF/RANN, SE/C I 34872 /T R73/5, June 1, 1973, Section II

¹⁰³Holmes, op. cit., p. 287.

¹⁰⁴Esmen, op. cit., section II & IV

¹⁰⁵Esmen, op. cit.

¹⁰⁶H.J. Hovel, IBM, *Semiconductors and Semimetals*, op. cit., p. 219.

¹⁰⁷R A Heindl, *Mineral Facts and Problems*, U.S. Bureau of Mines, U S. G.P.O., 1970, p 515.

GALLIUM ARSENIDE

Undissociated GaAs is harmful but apparently not highly toxic. A lethal dose for an average adult is about one-third kg (0.7 lb).¹⁰⁸ To ingest this much GaAs, a person would have to eat the amount of GaAs in about 20m² (200 square feet) of flat-plate arrays or the amount of GaAs in a field of concentrating arrays covering about 3 acres, clearly a Herculean task. The coatings and protective encapsulation placed on cells should be able to reduce any hazards associated with normal operation of GaAs devices to acceptable levels.

The major danger arises when the material disassociates as a result of a fire or some other accident, since many arsenic compounds are highly toxic and recognized carcinogens,^{109 110} The As₂O₃ which would be released in a fire could contaminate land and water near the fire site. Since the cells would most probably be used in connection with high concentrations of sunlight, care must be taken to ensure that the materials do not vaporize and escape if a breakdown in the cell cooling system occurs. The amounts of arsenic used in a concentrating collector, however, would be extremely

¹⁰⁸Based on LD₅₀ of 4,700 mg/kg body weight cited in the *Registry of Toxic Effects of Chemical Substances*, 1975 Edition, U S Department of HEW, NIOSH

¹⁰⁹N I Sax, *Dangerous Properties of Industrial Materials*, Fourth Edition, Van Nostrand Reinhold Co., 1975, pp 420-421

¹¹⁰George L Waldbott, *Health Effects of Environmental Pollutants*, C V. Mosby Co., 1973, pp. 202-203

small. A device with a concentration ratio of 1,000 would, for example, use only about 0.16 gm per m² of collector area. This concentration is 250 to 1,500 times smaller than the concentration of As₂O₃ recommended by the U.S. Department of Agriculture for weed control.¹¹¹

Gallium supplies should not place a significant constraint on the use of GaAs devices. U.S. consumption of gallium in 1973 was 8.5 metric tons per year, most of which is imported. If this amount of GaAs were used to produce 50-micron-thick cells used in tracking collectors producing concentration ratios of 1,000, the arrays would have a peak output of about 10 GWe at an efficiency of 20 percent. These arrays would have an average output of about 1 percent of the average output of all electric-generating facilities in the U.S. in 1977.¹¹³ Domestic production of gallium could be increased substantially if an attempt is made to extract the gallium associated with coal, aluminum, and zinc ores. A recent study indicated that the United States could produce about 600 metric tons/year of gallium from these sources.¹¹⁴ So the gallium resource is ample. World resources of gallium are about 1.1 x 10⁵ metric tons.¹¹⁵

¹¹¹USDA *Herbicide Manual*, 1965

¹¹²Y C M Yeh, JPL, private communication, Apr. 25, 1975

¹¹³H. J. Hovel, IBM, *Semiconductors and Semimetals*, op. cit., p 219

¹¹⁴R. N. Anderson, "Available Supply of Gallium and Arsenic, NASA-Langley, Contract Order No L42953A, 1976

¹¹⁵H. J. Hovel, IBM *Semiconductors and Semimetals*, Op cit, p 220

PERFORMANCE OF CELLS IN REAL ENVIRONMENTS

Since the output of cells varies as a function of temperature, it is necessary to compute cell temperatures in order to obtain an accurate estimate of the output of cells installed in various types of collectors. The temperature of the cells depends on the effective heat-transfer coefficient of the system used to provide cooling. In simple flat-plate systems, the heat loss from the

front (and possibly also the back) of the arrays provides adequate cooling. In concentrating devices, it is usually necessary to provide more sophisticated cooling systems. These systems can be passive [i. e., large, finned radiating surfaces attached to the cell), or active cooling can be provided by pumping liquids across the back of the cell.

PASSIVE COOLING

The heat-transfer capabilities of a variety of passive heat exchangers have been measured, although much more work must be done to obtain adequate data in this area. The results, shown in table X-8, are expressed in terms of an "effective heat-transfer coefficient" k_e , where

$$k_e = [\text{rate of heat removal (kW/m}^2 \text{ of heat exchanger)}] / (T - T_a) \quad (x-3)$$

In this, k_e varies with wind speed and thus depends not only on the type of heat exchanger attached to the cells, but also on the air circulation possible in each installation.

Table X-8.— Effective Convective Heat-Transfer Coefficients [k_e] for a Variety of Cooling Systems

Device	Wind velocity	k_e (kWjm'OC)
Air circulating passively through metal pan in back of cells	0	0.015
Same as above	'average'	0.025
Flat plate with finned metal heat-reject ion surfaces	"average"	0.30
Active water cooling with 'simple flow'	—	1-3
Active water cooling with "impingement cooling"	—	3-10

SOURCE Table prepared by OTA from data supplied by F T Bartels, (Spectrolab, Inc.) Mar 1976.

In order to obtain a relation between cell temperature T and insolation level I , an energy balance is written

$$\alpha I = k_e (T - T_a) + \eta I \quad (x-4)$$

where α is the absorptivity of the encapsulated cell and T_a is the ambient air temperature. The value of I is given by the following relations for flat-plates or concentrating systems:

$$I = I_D \cos \theta_i \tau(\theta_i) + I_d \tau_d \text{ (flat plates)} \quad (x-5)$$

$$I = I_D C_r \eta_o \text{ (concentrating systems)}$$

where:

I_o = direct normal solar intensity (kW/m²)

θ_i = angle between the Sun and the normal to the cell

$\tau(\theta_i)$ = transmissivity of cell covers for direct radiation (at angle θ_i)

I_d = intensity of diffuse solar radiation (kW/m²)

τ_d = transmissivity of cell covers for diffuse radiation ($\tau(\theta_i)$ integrated over all incident angles)

C_r = geometric concentration ratio of concentrator optics

η_o = optical efficiency of the concentrator

Equations (X-2, X-3, and X-4) can be combined to yield an expression for cell efficiency in terms of insolation level:

$$\eta = \eta(28^\circ) \frac{[1 - \beta(T_a - 28) - \beta \alpha I / k_e]}{[1 - \eta(28^\circ) \beta I / k_e]} \quad (X-6)$$

ACTIVE COOLING

If water is pumped through a heat exchanger attached to the cells, the value of k_e can be made as high as 3 to 10 kW/m²°C. With such high rates of heat removal, cell temperatures can be maintained at 150°F (65 °C), even at concentration ratios near 1,000. The removed thermal energy available in the cooling fluid (Q_A) is given by

$$Q_A = \frac{I[\alpha - \eta(28^\circ)(1 - \beta[T_F - 28])] - U_L(T_F - T_a)}{1 + [U_L - I\eta(28^\circ)\beta] / k_e} \quad (X-7)$$

where I is defined as before. U_L is the heat loss coefficient which differs with each collector design. This equation assumes the entire receiver area is covered with cells. T_f is the average temperature of the cooling fluid (a more sophisticated equation considering cell coverage ratios less than unity and the difference in inlet fluid temperature is developed in chapter VIII.

The cell temperature (T) is given by

$$T = T_f + Q_A / k_e \quad (X-8)$$

and the cell efficiency (η) is given by

$$\eta = \eta(28^\circ) (1 - \beta[T_f + Q_A / k_e - 28]) \quad (X-9)$$

PHOTOCHEMICAL ENERGY CONVERSION

Photochemical energy conversion has many of the advantages of photovoltaic energy conversion and, in addition, the advantage that the chemicals may be stored for later use. However, the technology is not as well developed as photovoltaics, and much research remains to be done. The nascent state of photochemical energy conversion is compounded by the fact that public awareness and Government funding are both low, and thus research has been for the most part confined to a few universities,

In 1972, Fujishima and Honda announced the discovery of a process by which light energy incident on an electrode suspended in water could be used directly to convert the water into hydrogen and oxygen without any noticeable degradation of the electrode.¹¹⁶ The original Japanese work has generated a considerable amount of interest and a number of other materials have been examined.^{117 118}

A system being studied by research teams of the Allied Chemical Corporation and Massachusetts Institute of Technology is il-

¹¹⁶A Fujishima and K. Honda, "Electrochemical Photolysis of Water at a Semiconductor Electrode," *Nature* 238, July 1972, pp 37-38

¹¹⁷K. L. Hardee and A. J. Bard, *J. Electrochem. Soc.*, 124, 215 (1977)

¹¹⁸M. Wrighton and J. M. Bolts, "Characterization of Band Positions Photoelectrodes for the Photoelectrolysis of Water," paper delivered to the American Chemical Society, San Francisco, Calif., September 1976, and *J. Phys. Chem.*, 80, 2641, 1976.

¹¹⁹Hydrogen Production From Solar Energy, *SITREP Energy R&D*, Report No. 154, Navy Energy and Natural Resources R&D Office, Feb 18, 1977.

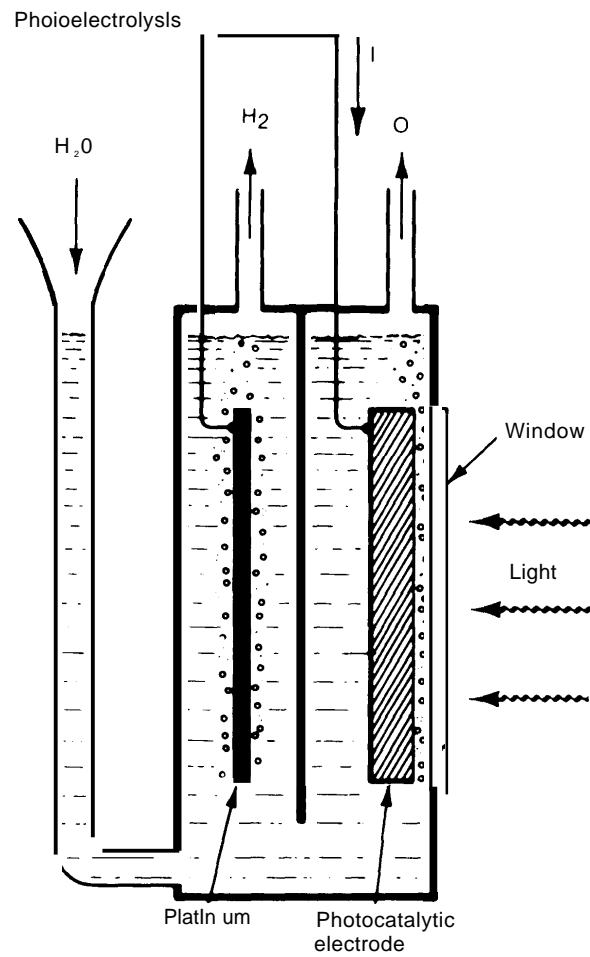
lustrated in figure X-13. In this system, hydrogen is produced at the platinum cathode and oxygen is generated at an anode made from a semiconductor material such as TiO₂ or CaAs. Some work has also been done on systems in which both electrodes are semiconductors. Other techniques for generating hydrogen have also been demonstrated. Researchers at the California Institute of Technology have demonstrated that hydrogen is released when light strikes a complex Rhodium compound.¹²⁰ Research at the University of North Carolina at Chapel Hill has led to the development of a ruthenium compound which can split water into hydrogen and oxygen when applied in a monolayer to a glass surface and exposed to sunlight.¹²¹ All of these processes now exhibit very low efficiencies, and long-term stability has not been demonstrated. Almost no work has been done to determine the potential cost of such systems.

The photosynthetic process used by plants to convert sunlight into storable fuel sources is clearly a photochemical system with great potential. Work is underway to better understand the basic chemistry of the process and, of course, there is increasing interest in the use of plant materials as a fuel source. The use of biological materials as an energy source is beyond the scope of the current study.

¹²⁰M. Simon, "UNC Professor Patents Solar Energy Process," *Chapel Hill Weekly*, June 1976.

¹²¹Gray Discovers Rhodium Compound at Caltech," *The California Tech*, Oct. 7, 1977, pp. 1, 4.

Figure X-13. — Photochemical Energy Conversion



SOURCE:
Goodenough, J. B. (Professor, Oxford University, England) "The Options for Using the Sun," *Technology Review* (MIT), 79(1), October/November 1976, pp 62-71