Turning our attention to the dc side of the circuit in Fig. 6.6, whenever T_1 and T_4 are on, $v = v_o$. Whenever T_2 and T_3 are on, $v = -v_o$. The average value of v is

$$V \equiv \frac{1}{\pi} \int_{-\alpha}^{\pi-\alpha} V_o \sin \omega t \, d(\omega t)$$

$$= \frac{2V_o}{\pi} \cos \alpha \tag{6.4.1}$$

This is also the average voltage at the solar cell array since there is no average (dc) voltage across an ideal inductor, whose dc impedance is zero. V_o and α, through Eq. (6.4.1), determine the array operating voltage, V. V and the I-V curve of the array determine the array current I. The inverter then presents a (controllable) constant voltage load to the array, much like a battery.

The power-conversion efficiencies of inverters range between 90 and 98 percent, depending on the size of the inverter. Adding a third thyristor string would allow the inverter to connect the array to a three-phase power grid. Equation (6.4.1) still holds, but the i_o waveform becomes an ac pulse train of 120° pulses. From Fig. 6.6, the inverter generates ac power at a power angle of simply α. It has been suggested (Landsman, 1981) that by reducing the inductance and thus allowing the inductor current to vary with time, both the power factor and the current harmonics can be improved. In that case, a large capacitor should be connected in parallel with the solar cell array so that the array current and voltage remain fixed at the maximum-power point essentially free of ripples.

6.5 COSTS OF POWER CONDITIONERS

Both choppers for electric car control (similar to the maximum-power-point trackers) and controlled rectifiers (similar to the synchronous inverters) cost less than $1 per watt in the kilowatt range. Larger units cost less per watt. It should be possible to incorporate maximum-power-point tracking in an inverter at nominal added cost. For maximum-power-point tracking, the array operating voltage must be electronically controllable (see Sec. 6.3). In the case of a synchronous inverter, this can be achieved by controlling α as indicated in Eq. (6.4.1). A control circuit is needed to vary α until the array voltage and current are set at the maximum-power point, i.e., when $dI/dV = -I/V$.

Figure 6.7 shows the photovoltaic power conditioner/inverter costs versus unit power rating as estimated by several manufacturers (Jones, 1978). The actual costs of power-conditioning and control systems of six 16- to 135-$\mathrm{kW_{pk}}$ systems completed in 1981 ranged between $0.46 and $2.70 per

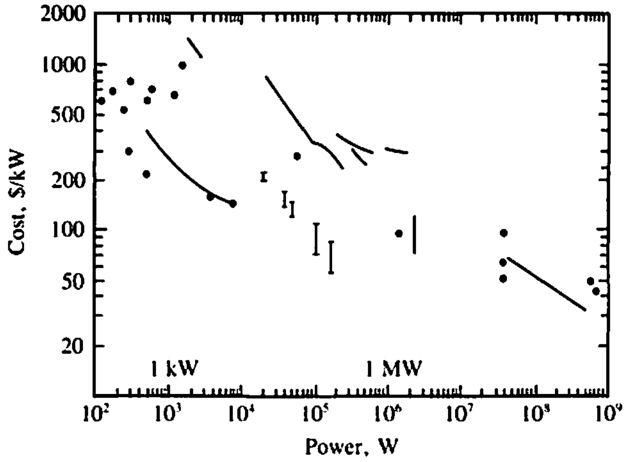


Figure 6.7 Solar cell power conditioner/inverter cost versus unit power rating. Each symbol represents estimates made by a different manufacturer in 1975 dollars. (*Jones, 1978*).

W_{pk}, representing 2.2 and 9 percent of the total system costs, respectively (Burgess, 1981). The costs did not correlate with the power ratings of the systems, although the lowest cost was achieved in the largest system. The cost of power-conditioning equipment is expected to drop, simply because of increased volume of production, and to stabilize around 5 percent of the total system cost in the future.

6.6 ISSUES OF ENERGY STORAGE

Only the storage of *electrical* energy is considered here. Some photovoltaic systems also generate thermal energy, but the storage of solar thermal energy is well covered by other books.

Energy storage is not necessary in some systems, such as those for agricultural water pumping. In general, there is a need for energy storage in a photovoltaic system that is not connected to a utility grid. For these small and medium-sized systems, the lead-acid battery is currently the only practical means of storage. In the future, some advanced battery may be the choice. Less conventional storage elements such as flywheels are also being investigated.

Because of the high cost of batteries, energy storage is sometimes avoided even when the system is separated from the utility power grid. For example, when a photovoltaic system supplements a diesel generator it may be advantageous to select a lower power rating for the photovoltaic system so that even on the sunniest days there is hardly any photovoltaic energy to be stored. This way, no energy storage is needed.

When the solar cell system is connected to a utility grid, it becomes less clear whether to employ energy storage. Energy storage is no longer needed to ensure the uninterrupted supply of electricity. Furthermore, any excess electricity produced by the photovoltaic system can be fed into the utility grid for a credit. Although the buyback credit should be lower than the selling rate charged by the utility, it can be surprisingly high (see Sec. 8.1). Even assuming a very conservative buyback rate of 40 percent of the selling rate, on-site energy storage appears to be uneconomical and unwarranted (Jones, 1980). In fact, an on-site storage system has more value in storing utility-generated energy to avoid the peak-period price under a typical time-of-day rate system than in storing photovoltaic-generated energy to avoid the difference between the buyback and selling rates. Other legal and institutional aspects of utility buyback are discussed in Chap. 8.

Energy storage on the customer/photovoltaic-power-producer's side of the watt-hour meter is not attractive. What about storage on the utility side of the meter? What if the photovoltaic power is generated at utility-run central stations? There, the question becomes essentially divorced from the fact that photovoltaic power is intermittent and fluctuating. Unless photovoltaic power accounts for, say, more than 10 percent of the total generating capacity on a grid—an unlikely situation for some time to come—the fluctuation in photovoltaic output is small compared with the hour-to-hour and day-to-day fluctuations of the electricity demand. The need for energy storage to ensure uninterrupted service is nonexistent or at most questionable. On the other hand, with or without photovoltaic generation by customers or by the utility at central solar cell stations, the use of energy storage to level the load and avoid the high power production costs during peak demand periods (see Fig. 8.4) is beneficial and is being practiced today. A utilities-sponsored study (De Meo, 1978) has also reached the probably obvious conclusion that any energy-storage facilities owned by the utility should be available to the general system rather than dedicated solely to use by photovoltaic generation plants. The presence of large photovoltaic plants could provide added incentive for employing energy storage, however.

Energy-storage technologies suitable for the utilities are conventional pumped hydro, underground pumped hydro, compressed-air storage, and batteries. Pumped hydro storage is the most economical and the only one in large-scale use today. Battery storage is the most attractive new technology. It has the advantage of being modular, a factor that promises a relatively short lead time from order to installation. Other advantages are the capability for adding sections as they are needed, and a wider choice of sites, such as substations. In addition, batteries can respond to momentary fluctuations in load demand and thus improve system regulation and stability. The inverter attached to the battery storage can also generate reactive power, as shown in Fig. 6.6, for power factor correction.

6.7 ENERGY-STORAGE TECHNOLOGIES

For small and intermediate systems, the only practical choice for energy storage today is the lead-acid battery. For the utilities, the most economical storage is pumped hydro storage. Both the small and intermediate systems and the utilities can benefit from advanced batteries. To store half a day's output of a 1-kW_{pk} photovoltaic system requires about 4 kWh of storage. If the storage element is discharged to a depth of 80 percent (in order to lengthen the lifetime of a battery), then 5 kWh of storage should be installed.

Lead-Acid Batteries

When charging current passes through a lead-acid battery, energy is stored by converting the lead sulfate ($PbSO_4$) on the battery electrodes into a mixture of pure lead (Pb), lead dioxide (PbO_2), and sulfuric acid (H_2SO_4). The reaction is reversed when the battery is discharged.

Among the many types of lead-acid batteries available, the type used in forklift trucks and electric cars is most suitable for photovoltaic energy storage. These batteries can last 1500 deep discharge–charge cycles at a reasonable premium in price.

Recent experience with four medium-sized lead-acid battery storage subsystems of photovoltaic systems indicates that the energy efficiency for one discharge–charge cycle is about 80 percent and the subsystem costs range between $82 and $110 per kWh (Brench, 1981). The subsystem costs include installation, shipping, gas detectors, and ventilation equipment. The battery costs are 60 to 70 percent of the total subsystem costs. It has been estimated that automated high-volume production could reduce the cost of suitable lead-acid batteries to $20/kWh in 1975 dollars.

Advanced Batteries

Lead in the lead-acid battery accounts for both the large weight and the high cost of the battery. Advanced batteries avoid the use of expensive materials, as shown in Table 6.1, which lists some of the most intensely pursued developmental batteries.

The sodium-sulfur battery is also known as the *beta* battery because it employs beta-alumina as a solid electrolyte. Molten sodium and sulfur combine to become sodium polysulfide during discharge. The reaction is reversed

Table 6.1 Some advanced batteries

Advanced battery	Active materials cost, \$/kWh	Cell energy density, Wh/kg	Demonstrated battery size, kWh
Lead-acid	8.5	25	large
Sodium-sulfur	0.5	150	100
Zinc-chlorine	0.85	100	50
Zinc-bromine	1.7	90	80
Iron redox	1.0	85	20

during charge. This is the only battery in Table 6.1 requiring operation at a high temperature (300 to 350°C). It is also the battery receiving the most research effort. Organizations known to be developing the beta battery include Ford, GE, Dow Chemical, Brown-Boveri, British Rail, Yuasa (Japan), and Compagnie Générale d'Électricité.

The designs and operations of the zinc-chlorine battery and the zinc-bromine battery are similar. During charge zinc is deposited on the negative electrode and bromide ions are oxidized at the positive electrode to become bromine which dissolves in the aqueous electrolyte. A porous separator between the electrodes retards the transport of bromine from the positive to the negative electrode.

The iron redox battery is being developed at GEL Corporation in the United States. During charge iron is deposited on the negative electrode. The SO_4^{-2} ions drift across a membrane to the positive electrode where they combine with the $FeSO_4$ electrolyte to form $Fe_2(SO_4)_3$. The membrane retards the flow of the Fe^{+3} ion.

Other Storage Technologies

Pumped hydro storage is in use for utility load leveling on a grand scale. However, all utility energy storage is of only peripheral relevance to photovoltaic generation, as discussed in Sec. 6.6. To "charge" pumped hydro storage, water is pumped from one lake to another lake located at a higher elevation. When water is discharged into the lower lake through the turbine generator, electricity is generated.

In 1977, there were 57 billion watts and 271 billion kWh of installed pumped hydro storage capacity in the United States. Pumped hydro storage can be developed for about \$30/kWh; the United States has already exploited its most attractive sites.

Storage of compressed air in underground caverns for use in Brayton cycle engines and in other ways has been investigated. The only large operating compressed air storage is in Huntorf, Germany. This 290-MW load-leveling system has been in operation since 1978. A 220-MW system in Pike County, Illinois, is scheduled to be completed in 1986 (Lihach, 1982).

A flywheel can store 10 times more energy per unit weight of the system than a lead-acid battery at an estimated cost of $75/kWh. The low weight of the flywheel makes it particularly attractive as an energy source in cars and buses. A prototype photovoltaic flywheel storage system has been developed (Jarvinen, 1981). The flywheel is a 15-inch diameter, 400-pound steel rotor that turns at 7500 rpm to store 1 kWh of energy.

6.8 SUMMARY

For a stand-alone photovoltaic system, the only generally practical technology for energy storage is the lead-acid battery. Because batteries are expensive it is advantageous to use the minimum acceptable amount of storage. The cost-effectiveness of the maximum-power-point tracker is marginal for small systems containing storage batteries.

When a photovoltaic system can be connected to a utility power grid, it is generally more economical to opt for the connection in lieu of battery storage even if the ratio of the energy buyback rate to the selling rate is very low. The dc-to-ac inverter is similar to a controlled rectifier and should be able to perform maximum-power-point tracking as well. The cost of the power-conditioning equipment is and will be around 5 percent of the system cost.

It is uneconomical for the utilities to install storage facilities dedicated to use by centralized or distributed photovoltaic generation plants. The principal reason for storage is load leveling.

REFERENCES

Brench, B. L. (1981), Record, 15th IEEE Photovoltaic Spec. Conf., 642.
De Meo, E. A., and Bos, P. B. (1978), *EPRI ER-589-SR*, Electric Power Research Institute.
Dewan, S. B., and Stranghen, A. (1975), *Power Semiconductor Circuits*, John Wiley & Sons.
Jarvinen, P. O., Brench, B. L., and Rasmusen, N. E. (1981), Record, 15th IEEE Photovoltaic Spec. Conf., 636.
Jones, G. J. (1980), Record, 14th IEEE Photovoltaic Spec. Conf., 1025.
Jones, G. J., and Schueler, D. G. (1978), Record, 13th IEEE Photovoltaic Spec. Conf., 1160.
Landsman, E. E. (1978), Record, 13th IEEE Photovoltaic Spec. Conf., 996.
——— (1981), Record, 15th IEEE Photovoltaic Spec. Conf., 627.
Lihach, N. (1982), *EPRI Journal*, Oct., 16.
Westinghouse (1979), Semiconductor Division, *Introduction to Power Electronics*.

PROBLEMS

6.1 *Need for storage and inverter* Discuss the needs and considerations for energy storage and dc-to-ac inversion of an agricultural water pumping system, a system serving a remote village with and without a parallel diesel generator, and a rooftop system connected to the utility grid.

6.2 *Step-down dc chopper* Explain the operation of the circuit shown in Fig. 6.4 and show that $V = V_B T_{\text{off}}/T_{\text{on}}$.

6.3 *Maximum-power point* Graphically verify and convince yourself that Eq. (6.2.4) is the correct test for maximum-power point. Graphically follow the control strategy discussed below Eq. (6.2.4) and show that the operating point converges to the maximum-power point.

6.4 *Three-phase inverter* Draw a three-phase (three ac lines) version of the inverter shown in Fig. 6.6. Find the new waveforms.

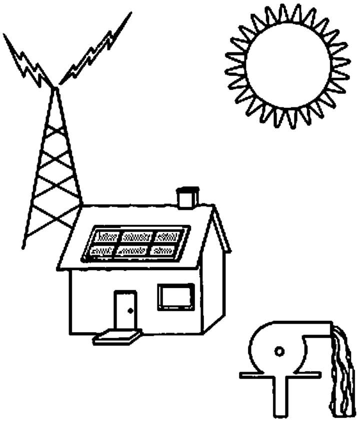
6.5 *Energy storage for utility plants* Suppose that the cost of power production is the same at all production levels so that there is no incentive for load leveling whatsoever. Discuss whether the utility should then install storage for dedicated use by the photovoltaic generation plants.

CHAPTER

SEVEN

CHARACTERISTICS OF OPERATING CELLS AND SYSTEMS

CHAPTER OUTLINE



We have previously described how solar cells work and are manufactured, and explained techniques used for sunlight concentration, energy storage, and power conditioning. Here we bring these elements together and discuss characteristics of photovoltaic cells that are now commercially available. Present and future applictions of solar cells are considered in detail to show the design decisions made and to introduce the early data on cell life and system reliability.

7.1 CHARACTERISTICS OF COMMERCIALLY AVAILABLE CELLS

The majority of the terrestrial solar cells now available commercially are flat-plate array cells made of single-crystal silicon having minimum stated efficiencies ranging from 12 to 16 percent. Some of these and other commercial cells appear in Figs. 7.1–7.4. Efficiencies of complete modules of these cells are typically only about 10 percent, owing to reflective losses and to inactive areas between cells and where structural members are located. At least two dozen firms supply cells and modules (see list of suppliers, Appendix 8), and the total worldwide sales for 1982 should be about 10 MW_{pk}. Polycrystalline silicon cell modules having around 8.5 percent efficiency are now available from a few suppliers. Several firms sell cadmium sulfide cells. Prices for encapsulated cell modules run typically twice those of the unmounted cells.

The first commercial gallium arsenide concentrator cells are reportedly available; they are based on a design yielding a demonstrated array efficiency of 18 percent. Approximately 14 percent efficient single-crystal silicon concentrator arrays can be obtained commercially. A recent estimate for a large-scale silicon concentrator array installed, including two-dimensional tracking and foundations (Fig. 7.5), is \$12/W_{pk} (1980 dollars) for a 470 kW_{pk} system, with an expected price decline to \$2/W_{pk} after 15 MW of such units have been produced and sold. Some firms sell entire PV power systems for specialized applications, such as remote radio transmitter-receivers or navigational aids. Others provide engineering design service to tailor systems for particular applications.

Specification sheets supplied by manufacturers vary widely in content but all typically contain an *I-V* plot for cells, often taken under different illumination conditions and at different temperatures and often identifying the maximum power point. Open-circuit voltage, short-circuit current, efficiency, and mechanical characteristics such as size, weight, and mounting information are also specified. An example is shown in Fig. 7.6.

Listed prices for Si cells up to 12.5 cm in diameter in quantities of thousands range from \$9/W_{pk} upward. Individual cells may cost two or three

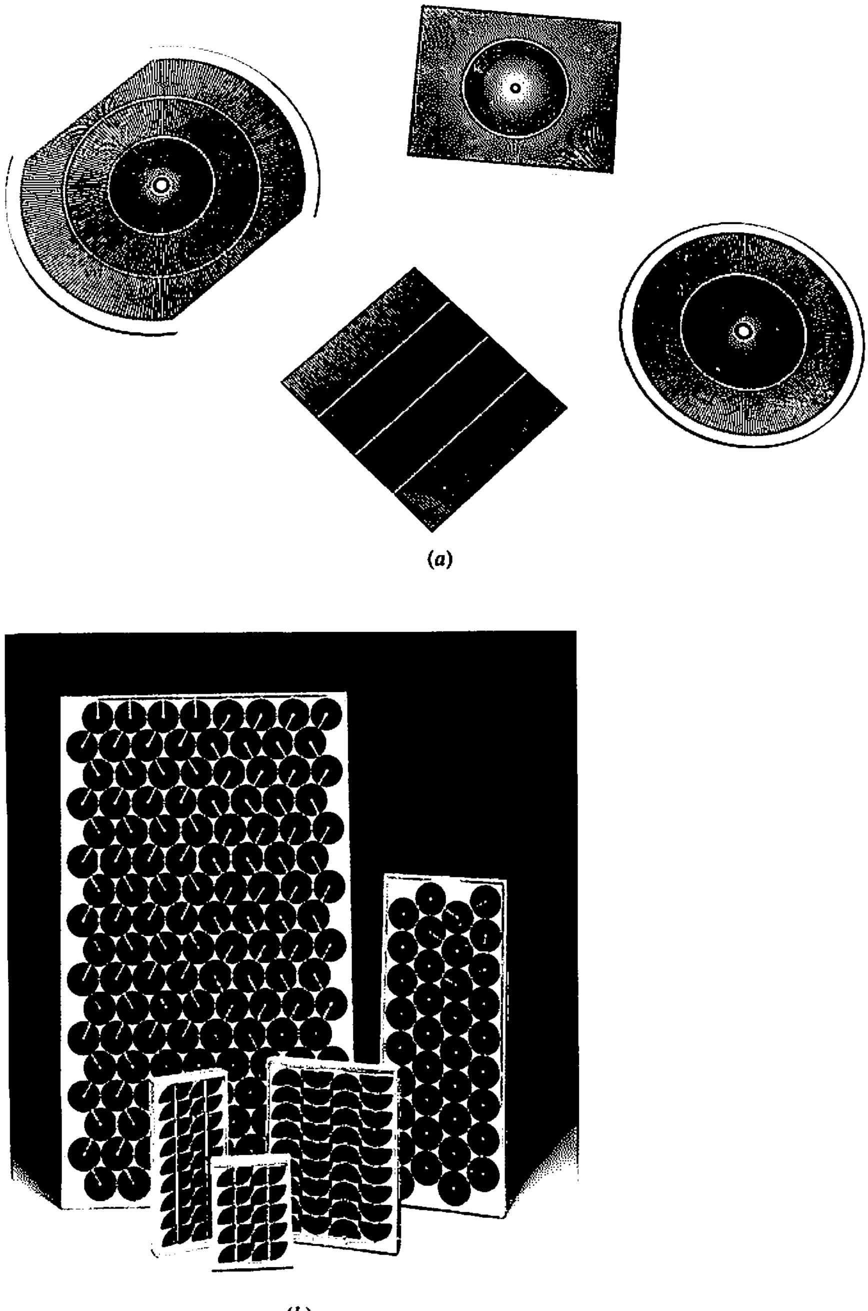


Figure 7.1 Single-crystal silicon solar cells (*a*) for one-sun and concentrator use, and one-sun solar cell modules (*b*). (*Courtesy Applied Solar Energy Corporation, with permission.*)

Figure 7.2 Solar modules containing polycrystalline silicon cells for powering communications equipment. (*Courtesy AEG-Telefunken, with permission.*)

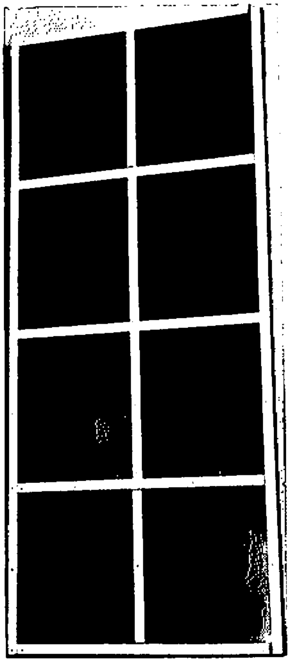


Figure 7.3 Panel of eight 24-in^2 CdS/Cu$_x$S cells formed on sheets of float glass coated with conducting tin oxide. The continuous CdS layer has been divided by laser scribing into parallel individual cells approximately $\frac{3}{8}$-in wide. (*Courtesy Photon Power, Inc.*)

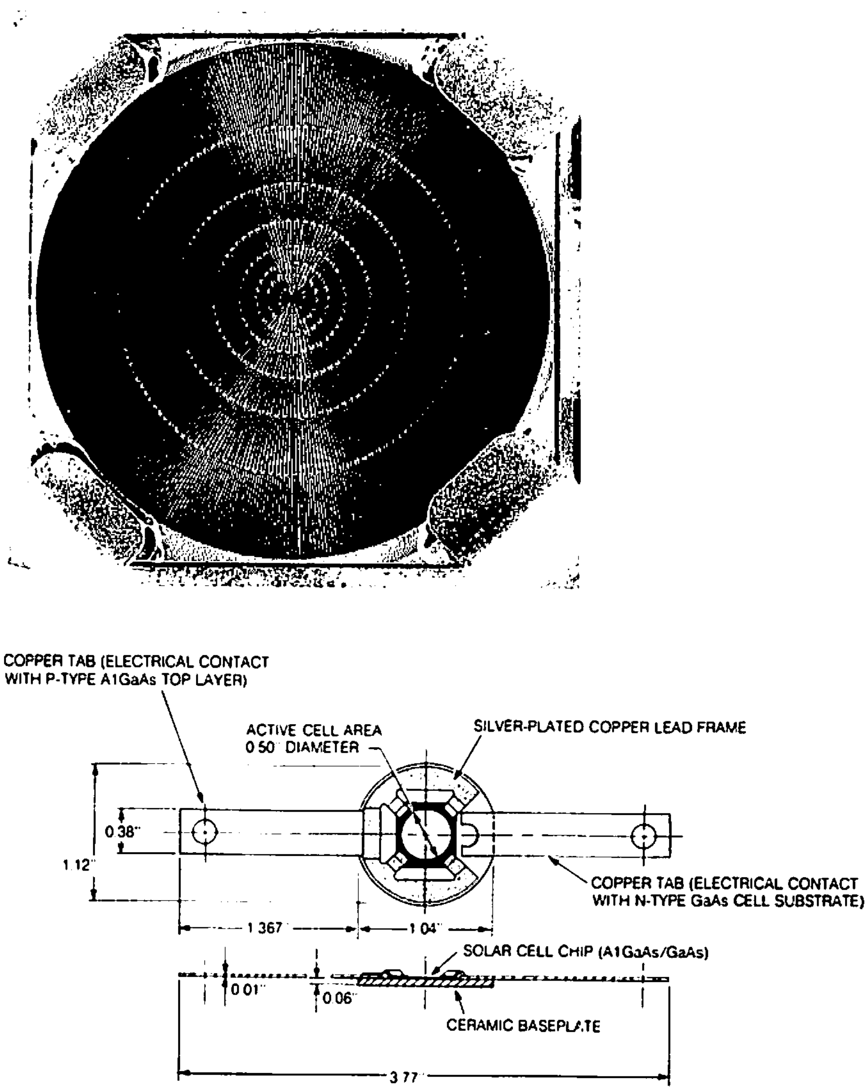


Figure 7.4 Close-up of gallium arsenide concentrator cell and sketch of cell mounting structure that permits heat transfer from cell through ceramic baseplate to passive cooling member. (*From Varian Associates, with permission.*)

times that amount, as with most electronic parts. These prices are appreciably higher than both the current DOE goals and the prices reported for large block purchases by the U. S. government. This disparity likely results from several factors: the somewhat lower costs possible when large markets for cells are assured, the lowered marketing costs associated with bulk sales, and a will-

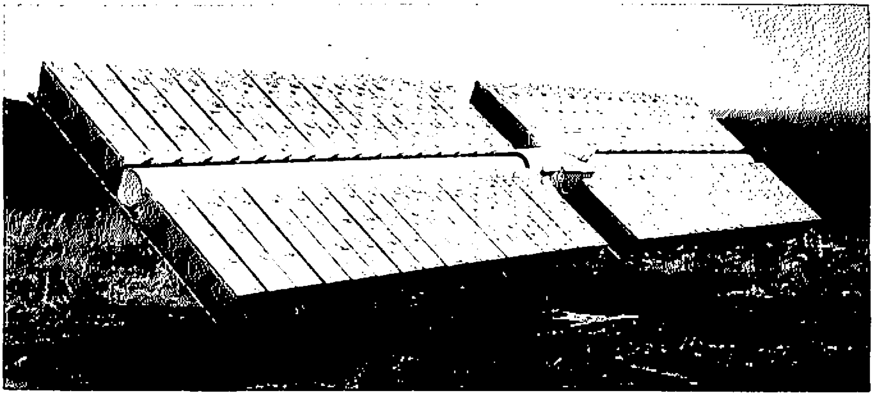


Figure 7.5 Two-axis tracking concentrator solar cell array. Design intended for use in Soleras and Dallas-Ft. Worth Airport projects. *(Photo by Arco Solar.)*

ingness of some suppliers to buy into the market to establish an early position in the photovoltaic industry.

Demonstrated efficiencies of selected research cells are tabulated in Appendix 5.

7.2 TYPES OF APPLICATIONS

Because of their high cost, terrestrial solar cells have been used to date primarily in governmentally funded test and demonstration projects, or where some unique feature of the PV approach has been important. Examples of the latter are:

- The *portability* of light weight solar cell modules for powering hand-carried communication equipment.
- The *ability to operate far from an electric utility*, necessary in PV systems for cathodic protection of pipelines and bridges or for supplying isolated villages with electricity.
- The *convenience and reduced maintenance* of PV systems exploited in PV-powered marine navigational aids, which formerly required frequent visits for maintenance and delivery of fuel.

In many of these applications, solar cells are already economically competitive with other power sources. In remote areas, power from a solar cell system having battery storage may be more reliable than power transmitted a long distance from an electric utility. If technological innovations and economies of scale in manufacturing bring down the costs, PV-produced power will become increasingly competitive with power from conventional

Electrical Characteristics

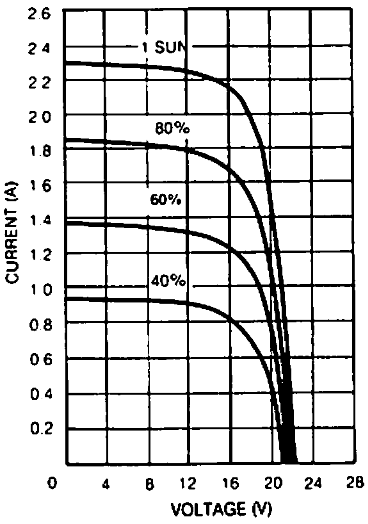
	SX-100	SX-110	SX-120
Peak power (Pp)	32	36	40
Voltage at peak power (Vpp)	17	17.25	17.5
Current at peak power (Ipp)	1.9	2.1	2.3
Short-circuit current (Isc)	2.2	2.35	2.5
Open-circuit voltage (Voc)	22	22.25	22.5

NOTES:

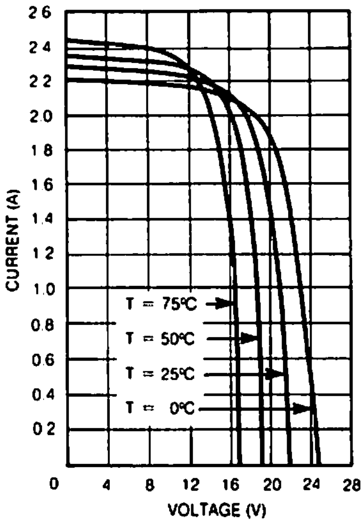
1. Panels are measured under full sun illumination (1kW/m^2) at 25°C ± 3°C cell temperature. Minimum performance is 2 watts less than peak. The ruling specification is peak watts. For a more detailed explanation, see our *Electrical Performance Measurements* bulletin.

2. Electrical characteristics vary with temperature.

Voltage (Voc)	increases by decreases by	2.4mV/°C/cell	below above	25°C
Current (Isc)	increases by decreases by	25uA/°C/cm^2	above below	25°C
Power (peak)	increases by decreases by	0.4%/°C	below above	25°C



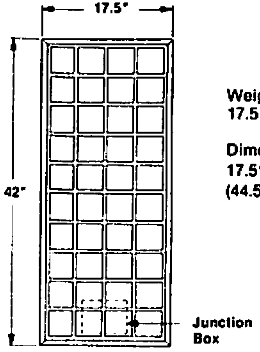
SX-110
Performance at Various Light Intensities, T = 25°C



SX-110
Performance at Various Temperatures at AM1 (1kW/m^2)

NOTE: These curves are representative of the performance of typical panels at the terminals, without any additional equipment such as diodes, cabling, etc. These curves are intended for reference only. Curves for the SX-100 and SX-120 panels are available from Solarex Marketing.

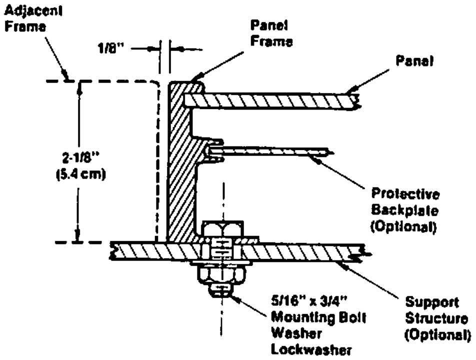
Mechanical Specifications



Weight:
17.5 lbs (7.9 kg)

Dimensions:
17.5" x 42" x 2.1"
(44.5cm) x (106.7cm) x (5.4cm)

Cross Section of Panel



Reliability and Environmental Specifications

These panels are subjected to intensive quality control during manufacture and rigorous testing before shipment. They are designed to meet or exceed the following tests with no performance degradation:

- Repetitive cycling between −40°C and 100°C.
- Prolonged exposure to 90-95% humidity at 70°C.
- Wind loading of over 160 m.p.h.

All SX Series panels are covered by the standard Solarex 5 year limited warranty.

Options and Accessories

Backplates — Anodized aluminum backplate protects the panel in harsh environments. Backplates are available either mounted inside the panel frame at the factory or as components to be mounted onto the panels during field assembly.

Diodes — In-line blocking diode prevents reverse current flow from the panel to the battery during darkness. Bypass diode is available for high voltage systems to provide alternate current path protection.

For multiple panel arrays and large power regulation, contact Solarex Marketing.

Specifications are subject to change without notice. 6024-1 5/82

Figure 7.6 Sample specification sheet for commercial PV panel containing 40 series-connected 10 cm × 10 cm semicrystalline silicon solar cells. (*Courtesy Solarex Corporation.*)

sources. We will then see the application of solar cells to more common uses, such as residential lighting, refrigeration, and air-conditioning.

Many present types of applications are listed in Table 7.1. As the comments there show, these uses are characterized by quite different combinations of factors—such as whether energy storage is required, whether connection to an electric utility grid is necessary or desirable, and whether one must convert the dc power from the cells to ac power. The diversity of end-uses suggests that different types of PV systems and solar cells will continue to be in demand:

- High-efficiency solar cells will be used where the area for cell deployment is limited or the cost of land is high.
- Cells having only a few percent efficiency may be used in consumer devices such as electronic calculators and watches if their cost is low enough.
- On-site energy storage is not necessary if there is a connection to an electric utility grid that can absorb excess PV power and supply back-up power when PV systems are not functioning. The impacts of such arrangements on utility management and on power costs are substantial.
- Some applications do not require energy storage because the energy demand arises when PV systems are functioning. One example is the residential air-conditioning load, and another is the well-insulated refrigerator whose cooling system can be operated quite intermittently. In some cases, the pumping of irrigation water is necessary only during sunny periods when the PV systems are operating.

Table 7.1 Examples of terrestrial applications of solar cells

Typical power levels for some applications are given in braces

Application	Comments
I. Large land installations	
Building power systems	Provide power to single-family homes, apartment, public, or commercial buildings. Often installed on rooftops. [1 to 100s of kW)
Central power station	Feeds ac power to utility grid for transmission and distribution. [MW to multi-MW]
Forest Service lookout	Supplies lights, communications, refrigeration; energy storage desirable.
Military installations	For remote site; solar and wind power complementarity useful to provide more continuous supply. Grid connection, ac or dc output possibly useful. Storage likely necessary.
Village power system	Water pumping, refrigeration, lighting, communications. [0.1 to 100s of kW]

I. Large land installations (*continued*)	
Water pumping systems	Mobile systems with no storage, to multi-kW fixed systems that may be grid-connected or independent, operate on ac or dc. [power to multi-kW]
Water purification	[multi-kW]
II. Communications equipment	
Emergency or remote telephone	Energy storage desirable or necessary.
Emergency or portable radio	Storage desirable or necessary. [power to 50 W useful]
Microwave telephone repeater station	Storage necessary; dc output usable.
Military radar installation	Storage necessary. [multi-kW]
Radio broadcast station	Storage or grid connection as back-up necessary; dc output usable. DOE demonstration project as described in text. [multi-kW]
Railroad telephone system	For communications between caboose and engineer on train.
Television receiver in village	[50 W usable]
III. Remotely sited equipment of all kinds	
Alarms	Intrusion, smoke, and fire alarms. Energy storage necessary. [watts]
Cathodic protection system	To prevent corrosion of pipelines, bridges, and structures. Energy storage desirable; usually no grid connection.
Desalinization system	Electricity used for pumping; may be tolerant to fluctuating supply of energy.
Electric cattle fence	Dc output usable; energy storage necessary; usually no grid connection.
Highway dust storm and other warning signs	Energy storage necessary. [watts]
Navigation aids for boats, ships, aircraft	Energy storage necessary. [10s of watts]
Offshore or remotely sited land-based equipment	Lighting, refrigeration, communications equipment; storage desirable.
Scientific instrumentation for for field use	Remote recording or telemetry; storage desirable.
IV. Miscellaneous	
Airplane	Ultra-light "Gossamer Penguin" in 1980 flew powered directly by solar cells without battery storage.
Electronic calculator	Powered by room lights. Energy storage not necessary. Low efficiency cells may be used.
Electronic watch	Solar cells used to recharge battery.

City dwellers in industrialized countries are accustomed to thinking of their electricity supply only when it fails (or when the bill arrives in the mail), as the source has been perfectly elastic, stretching to fill any demand placed upon it. With solar cell systems the situation is different, and each proposed application has required the design of a PV supply tailored for that use. As the market for PV-powered devices grows, standardized cell modules and power-supply packages may be expected, possibly built into the equipment by the original manufacturer. A number of suppliers of solar cells now also sell the balance-of-system (BOS) components such as batteries and power-conditioning equipment, and complete PV systems. In the next section we look at many different applications that have been made and studied to date.

7.3 OPERATIONAL PHOTOVOLTAIC SYSTEMS AND DEVICES

Actual photovoltaic power supplies have ranged in power rating from the multi-kilowatt down to the milliwatt level. Tests have been made of both general-purpose systems supplying power for many different uses and of systems that provide electricity for a single purpose such as the pumping of irrigation water. Here we shall consider the operational experiences reported to date generally on the larger systems, and then examine in more detail a few selected PV supplies at all power levels. A tabulation of many stand-alone, residential, and intermediate load center PV systems is given in Appendix 9.

Large PV Power Systems

Experience with the major DOE-supported PV power systems, listed in Table 7.2, has been summarized by Macomber et al. (1980), who found that reliability has been generally good, particularly with respect to the solar cells and modules themselves. Systems of the single-application type operating at 120 volts or below have been extremely reliable, since failure rates of components have been very low. As an example, in the Mead, Nebraska, agricultural facility (Romaine, 1979), during 27 months of test only 48 of the 2240 modules in the array (2 percent) failed to deliver power, and unscheduled outages of the entire system were quite rare. In the three DOE applications at 240 V dc, reliability has varied from good to poor, but the higher operating voltage may not be the reason. For example, overall system efficiency of the 97,000-cell Mt. Laguna, California, installation has been consistently around 85 percent but some silicon cell cracking (due to overheating and hail damage) and encapsulation delamination has been observed to reduce array output and raise concern over the lifetime of the array, suggesting also the need for

Table 7.2 Some of the higher-power-level DOE-sponsored PV power systems

Peak power	Location	Comments
350 kW	Saudi Arabia	Soleras village project. Complete power supply for villages utilizing tracking concentrator arrays. Operational.
240 kW	Blytheville, Arkansas	Mississippi County Community College (MCCC). System on newly constructed campus employing 40× parabolic concentrating trough, tracked east-west about north-south axis, with 440-V ac inverter-produced output. Excess power to be sold back to utility and with 130°F coolant stream from array to heat campus buildings. Operational.
200 kW	Senatobia, Mississippi	Northwest Mississippi Junior College. Supply for retrofitted campus buildings. Operational.
100 kW	Natural Bridges National Monument, Utah	System providing power at visitor center in remote scenic area for staff residences, maintenance shops, and water sanitation system. Operational June, 1980.
60 kW	Mt. Laguna, California	System providing on average 10% of power used in Air Force radar installation, with approximately 10% diesel-powered generator backup. Operational August, 1979.
25 kW	Mead, Nebraska	Agricultural PV power system for pumping irrigation water, running fans in grain drying bins, and powering nitrogen fertilizer plant (electric arc discharge in air process). Operational 1977.
15 kW	Bryan, Ohio	DC-only system supplying a daytime commercial radio broadcast station (WBNO) that also has connection to utility grid. Operational August, 1979.
7.3 kW	Concord, Massachusetts	System Test Facility (STF) to provide power, initially at 8-kW level, for typical residential load profile. Operational 1979.
3.5 kW	Schuchuli, Arizona	DC village power supply system for pumping water, lighting, refrigeration, and washing and sewing machines. Operational December, 1978.
1.8 kW	Tangaye, Upper Volta	Village power supply for potable water and grain milling. Operational March, 1979.

accelerated life testing of PV system components. No breakdowns or instabilities have occurred in that system, however.

In a surprising number of these tests, the load devices failed—for example, some refrigerators, weather instruments, and a grain grinder—and in a number of cases trouble was caused by balance-of-system components such as voltage regulators and controls, and batteries. It has been found that highest system efficiencies occurred in cases where the load was relatively constant and well matched to the supply, and where inverters to convert the dc array output to ac for use were not required, as in the daytime commercial radio broadcast station in Bryan, Ohio, where dc itself is used. In cases where people could operate the loads according to their own desires, as in village power systems, sometimes the actual electric loads departed enough from the predicted loads to cause the PV system to be unable to continue normal operation, suggesting the need for more flexible control devices. In systems where the load fluctuates with time, as in the residential systems test facility listed in Table 7.2 (Sacco, 1979), the inverter was too lightly loaded at times and so operated inefficiently, reducing the fraction of the array power that was actually delivered to the load. Inefficiencies resulting from components other than the PV modules have not been negligible and, in the case of systems involving both battery storage and inverters, this fact can result in the need for about a 50 percent larger PV array than one might suppose necessary.

For several reasons it would be unfair to draw sweeping economic conclusions from the costs of these experimental systems, which have ranged from the $20/W level upward. These systems have contained monitoring and data-collection devices that would not be used in later production systems, and they have been made mostly of one-of-a-kind components whose costs would drop in large volume production. Further, because of the lack of broad experience with PV systems, the engineering and construction have been done conservatively and quite carefully, and therefore at premium cost. Perhaps the clearest lessons learned from these tests have related to the balance-of-system components: it is necessary to give considerable attention to increasing the efficiencies of those components and reducing their costs. Standardized system and subsystem design should help in the cost reduction. Improving the efficiency of the solar cells themselves will, of course, permit reduced array sizes and consequently reduced related costs.

Other observations include finding unexpected damage due to lightning even though supposedly adequate protection had been provided by overhead grounded masts to establish cones of protection for the arrays beneath them. Using higher-rated fuses and connecting metal-oxide varistors (surge suppressors) between conductors and ground appears to solve the problem of lightning-caused outages. On the nontechnical side, it was observed during the installation of the 1.8-kW village power system in Tangaye, Upper Volta, that the villagers were eager to have the system and to help in its installation and operation. It is encouraging to note that in the grid-connected Mississippi County Community College project, the buy-back rate proposed by the utility for the purchase of excess PV power is, at least for the first few years of operation, the full industrial purchase rate of roughly $0.02/kWh. If such a policy continues and is followed generally, it will have a positive effect on the economics of grid-connected PV systems.

Electric utilities are showing growing interest in PV systems for primary power production. For example, a 1-$\mathrm{MW_{pk}}$ PV facility designed, built, owned, and operated by ARCO Solar will sell power to the Southern California Edison Company. The system employs 108 two-axis tracker units, each of which contains 256 flat-plate silicon solar cell modules. The facility is to be operational by the end of 1982, only eight months after announcement of the start of construction.

Next we consider several different PV systems in somewhat more detail, to provide a more concrete view of this new technology.

Village Power-Supply Systems

Several modest-sized village systems are presently in use (Ratajczak and Bifano, 1979). A 3.5-$\mathrm{kW_{pk}}$ system is operating in a Native American (Indian) village in the Southwestern United States. In the 2700-inhabitant village of Tangaye, Upper Volta, a 1.8-$\mathrm{kW_{pk}}$ PV system generates power to pump water and grind grain. And a part of the flat-plate PV array for a 5.5-$\mathrm{kW_{pk}}$ system in an Indonesian village is shown in Fig. 7.7.

A 350-$\mathrm{kW_{pk}}$ system has been built as part of SERI's Project Soleras to demonstrate the feasibility of large PV power systems for isolated villages. In this joint United States–Saudi Arabian venture, the ultimate goal is to design and install 1-MW power systems. The first 350-$\mathrm{kW_{pk}}$ Soleras system utilizes the two-axis tracked 40× silicon cell concentrator arrays shown in Fig. 7.5, which follow the sun under computer and sensor control. A single 2.7 × 12 meter array as shown is expected to provide 2.2 $\mathrm{kW_{pk}}$ (19.8 A at 114 V) under 0.8 $\mathrm{kW/m^2}$ insolation at 40°C with less than 1 m/s windspeed. In case of a sandstorm or hailstorm, the array will protect its acrylic lenses by turning over to its stowed position with the aluminum heat radiating and convecting structures facing the sky. The entire assembly is environmentally sealed, and sand slides off the lens surfaces upon stowing each day. Measured array efficiency is 10 percent (sunlight to dc power). A second-generation model of this concentrator had 14 percent efficiency when tested at Albuquerque, N. M.

The first of these village systems is described in some detail here to show differences in design philosophies of a stand-alone photovoltaic and a grid-connected electrical system. For example, dc operation was chosen to avoid dc/ac inverter losses, and the PV array and storage batteries were located next

Figure 7.7 Solar cell power supply located in Indonesia. (*Courtesy AEG-Telefunken, with permission.*)

to the water well and its pump, which is the heaviest load in the system. Priorities on types of appliances, hours of use, and the schedule for possible load shedding were decided by the villagers, and some system components were redesigned to increase their efficiency.

Photovoltaic Power System at Schuchuli, Arizona

A 3.5-kW_{pk} photovoltaic power system has been operational since December 1978 in the 15-family, 95-person village of Schuchuli ("Gunsight"), Arizona, on the Papago Indian Reservation (Bifano et al., 1978; Ratajczak et al., 1979). The 120-volt dc system powers the following devices, in the order of priority determined by the villagers:

1. *Village water pump.* A 120-V dc, 2-hp, permanent-magnet jack pump delivering approximately 4.2 m^3/h (1100 gal/h) and connected to a 42-m^3 (11,000-gal) storage tank replaces a diesel-powered pump. Consumption for villagers and livestock varies from 8.7 m^3/day (2300 gal/day) in winter to 19 m^3 (5000 gal/day) in summer, plus about 3.6 m^3/day (960 gal/day) for the single community clothes washer. Pumping time is 3.1 h/day in winter and 5.4 h/day in summer. A control system limits pumping to mid-day hours except in emergency situations.
2. *Lights.* Forty-four 20-watt 120-V dc fluorescent lights were installed with specifically designed 120-V dc/23-kHz inverter ballasts that permit the lamps to produce the same light output as with 120-V ac/60-Hz ballasts. Lights are in houses (two each, one in the kitchen and one in another room), feast house (six), domestic services building (two), church (two), and in the electrical equipment building (four). Previously kerosene lanterns were used.
3. *Refrigerators.* Fifteen personal, 0.11-m^3 (1-ft^3) lockable refrigerators are located together and powered in groups of three by single compressors having $\frac{1}{8}$-hp 120-V dc permanent-magnet motors. Custom-designed, these refrigerators are particularly well insulated with polyurethane foam and their evaporator cold walls contain a gel that is frozen by the refrigerant circulating in the system.
4. *Clothes washer.* One wringer type, having a $\frac{1}{4}$-hp permanent-magnet, 120-V dc motor, is operated from a clock timer up to 12 h/day, 7 days/week.
5. *Sewing machine.* One is available for community use, having a $\frac{1}{8}$-hp 120-V dc universal motor and small light.

The solar cell array consists of twenty-four 1.2 m × 2.4 m flat-plate silicon solar cell panels, arranged in three rows of eight panels each in a 21 m × 30 m fenced and locked area. Tilt angle is adjusted manually four times a year to 3.5° (summer), 26° (spring and fall), and 48° (winter). Panel frame and support structures are designed to withstand 45 m/s (100 mi/h) winds. The 8064 cells are approximately 8.9 cm across and about 15.5 percent efficient. Voltage regulation is achieved by 24 relays that switch strings of PV cells, protected by blocking diodes, to the main bus to keep the voltage constant. System over-voltage and under-voltage conditions are also sensed and cause either the PV array or the loads to be disconnected, and an alarm indicator to light.

Battery storage is provided by fifty-one 2380-A · hr capacity series-connected cells, in parallel with four pilot cells for load management (three having 310-A · h capacities and one having 1055-A · h capacity). Capacities are measured at 77°F and a 500-h discharge rate. The batteries have lead-calcium plates capable of deep-discharge cycle operation. As battery capacity decreases, loads are sequentially shed: At 50 percent depth-of-discharge, the washing and sewing machines are disconnected; at 60 percent, the lights; at 70 percent, the water pump; finally, at 80 percent, the refrigerators. Upon recharging, loads are reacquired in order. The NASA Lewis Research Center computer program for solar cell system sizing, used to design this village system, indicates that with a 20 percent degradation of cell output due to potential darkening of the silicone encapsulant and to dirt accumulation, and a ±20 percent variation from average values of insolation, the maximum depth of discharge of the batteries should be about 60 percent.

Operation of the system is being monitored by automatic recording equipment, and the effects upon the villagers' lives of introducing the PV system are being studied. Cost projections, assuming a moderate growth of market demand for such systems, indicate they can provide power at \$1.76/kWh in 1978 dollars on an annualized basis (20-year life, 8 percent discount factor, 5 percent per year escalation of electricity costs over normal inflation). This rate is midway between the \$1.55/kWh for 6255 kWh/yr estimated for electricity from the Papago tribe's utility authority and the \$1.91/kWh from the nearest private power company. No adverse environmental effects of the system have been identified.

PV-Powered Agricultural Facility at Mead, Nebraska

The 25-kW_{pk} experimental facility at Mead, Nebraska (Hopkinson, 1980), is designed to operate a 20-hp motor 12 h/day to pump 5.7 m^3/min (1500 gal/min) of irrigation water for a 0.32-km^2 (80-acre) field of corn. After the harvest, the array powers two 5-hp fans that force air through two 210-m^3 (6000-bushel) grain-drying bins in which the corn crop is stored. Operation of a 3-kW electric arc discharge-in-air nitrogen fertilizer generator is also scheduled. The facility is composed of two large arrays of solar panels (described below), lead-acid storage batteries having a 90-kWh total capacity, an inverter for changing dc array output to three-phase ac, a dummy electric load for power management and array testing, and control circuitry. The system is tied to the three-phase, 240-V ac utility grid that delivers power or distributes excess power generated by the PV system to other utility customers.

The array consists of two parallel, 113-m-long rows of solar panels located one above the other on a sloping berm forming the edge of the cornfield. At the base of the berm is a 2500-m^3 (2-acre-ft) reservoir into which a pump driven by power from the utility at night deposits well water which is pumped during the day by power from the array and from storage. Supports for the frames holding the PV panels are reinforced concrete piers 76 cm in diameter extending 2.9 m into the soil. The modules are made up of single-crystal silicon cells purchased from two different manufacturers. In each array the cells are connected in series-parallel arrangements to provide outputs at around 150 V dc. In one of the two slightly different arrays, each group of 44 cells is connected in series to form a module having a nominal 16.5-V output. Modules are paralleled in groups of four, making what are termed *quads*, each having a protective diode in parallel across it to carry the current in case a cell becomes open-circuited. Nine of these quads connected in series form a so-called substring having a 150-V output. Finally, three of these substrings are paralleled so their currents add, giving an output of at least 5.9 A at 150 V, or 885 W minimum. Series-protective diodes in the positive legs of the three substrings are used to guard against excessive currents.

Figure 7.8 shows a block diagram of the system. The array, at upper left, feeds the dc bus that can also be connected via relays to the storage battery, an inverter, a 20-hp dc motor coupled to the irrigation water pump, and a bank of resistors serving as a power dump used primarily for test and measurement purposes. The battery charger can be driven from the ac grid when it is necessary to use utility power to charge batteries. The batteries are not intended to carry the system through periods of cloudy weather, but rather to

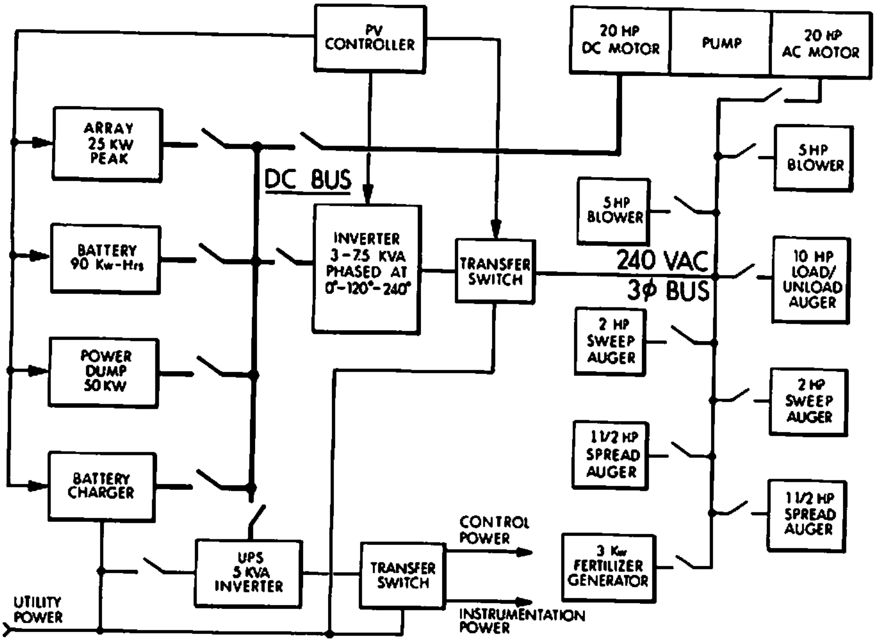


Figure 7.8 Block diagram of Mead, Nebraska, PV-powered agricultural complex. *(Reprinted with permission from Project Rept. COO-4094-10, "The Mead, Nebraska, 25-kW Photovoltaic Power System," W. R. Romaine, Lincoln Lab., M.I.T., January 5, 1979, p. 23, DDC AD-COO-4094-10.)*

square up the curve of output versus time of day: the battery is charged in the middle of the day when the PV array provides excess power, and the battery returns energy during morning and afternoon hours when the insolation is less. Excess PV power can also be fed back into the utility grid after it is converted to three-phase 240-V ac power by the inverter. An uninterruptible power supply (UPS) was included to ensure a stable supply for the control and instrumentation circuitry after it was found that the utility power at this site was subject to frequent brief interruptions.

The electric loads include either an ac or dc motor for the irrigation pump. It was found that the efficiency of the dc motor equalled that of the ac motor, 87 percent, and so the 10 percent power loss in the inverter could be avoided. The 3-kW nitrogen fertilizer generator employs an electric arc in air which produces oxides of nitrogen that are trapped in water containing limestone. The result is water containing calcium nitrate, a desirable form of fertilizer.

Microirrigation Systems

At the other end of the scale of pumping capacities is the portable microirrigation system shown in use in Fig. 7.9. This prototype unit consists of a 240-W flat-panel PV array mounted on a wheelbarrow frame and connected to a submersible pump for raising water from shallow wells.

The units were designed after study showed (Smith, 1977) that there was need for them in the broad, alluvial valleys and deltas of great rivers such as the Nile and the Ganges, where millions of farmers live on very small plots of prime crop land with plentiful water that must, however, be raised to the levels of the fields. The power required for this purpose is surprisingly small: for a one-hectare plot (2.5 acres) planted in a nonrice cereal grain, to lift surface water 1.5 m requires just 320 Wh/day, or about 70 W_{pk}, if one assumes a 50 percent pumping efficiency (Smith and Allison, 1978). Having additional irrigation water would increase yield or permit a second crop, and the added value to the farmer would be greater than the cost of these microirrigation sets even at the 1978 prices prevailing for silicon solar cells made conventionally but in large quantities. A unit price of $1200 is projected when these units are manufactured in quantities of more than 10,000.

The use of storage batteries was avoided because of the 50 lb or so they would add to the weight, the intolerance of lead-acid batteries to deep discharge or the higher cost of discharge-tolerant batteries, the need for the occasional addition of relatively pure water, and the 75 percent turnaround efficiency typically found. The unit shown combined a small vertical turbine pump with a $\frac{1}{3}$-hp permanent-magnet dc motor whose efficiency is 85 percent. A dc motor was chosen because of the relatively low efficiency of fractional-horsepower ac motors, and secondarily because then there is no need for an inverter. A solid-state controller adjusts the load impedance seen by the array to maximize power output as the pump is used at different depths or as the

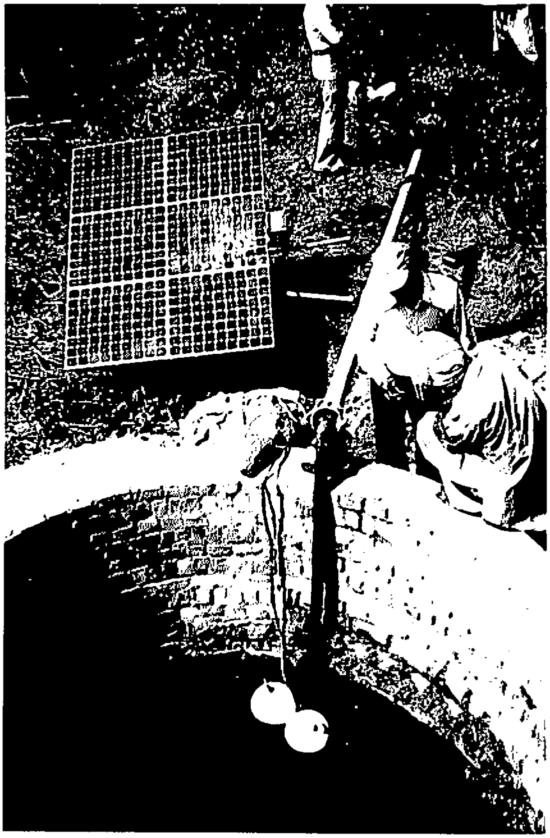


Figure 7.9 Microirrigation system raising water from a shallow well to irrigate a field. The submersible pump is beneath the spherical floats. *(Courtesy Solar International.)*

insolation changes. Under AM1 conditions, the model shown will lift 0.17 m^3/min (45 gal/min) about 2.4 m, and 0.10 m^3/min (27 gal/min) can be lifted 4.9 m.

These systems could be manufactured in Third World countries. Purchase of the units by the small farmers for whom they were designed would presumably require an initial subsidy of some kind. It has been suggested that a progressive pricing scheme might be instituted, since the farmer who purchased a second unit would be able to pay a higher price more reflective of the true cost of the unit, because of the additional output then being obtained from the farm.

Remote Applications Without Grid Connection

Largest of the growing number of these remote applications is the 100-kW_{pk} system dedicated in June 1980 in Natural Bridges National Monument in southeastern Utah, where the system powers six staff residences, maintenance facilities, a visitors' center, and a water-sanitation system at the 31-km^2 (7600-acre) park, which is the site of three of the world's largest natural sandstone bridges (Jarvinen, 1978). In a 5700-m^2 cleared area, the array field is composed of 48 subfields producing just over 2 kW each. Total module area is 1700 m^2, with 990 m^2 of silicon cell area. Actual conversion efficiency based on gross module area is from 5 to 7 percent. With its battery storage, the back-up of a 40-kW diesel powered generator is expected to be required only 5 to 10 percent of the time, during extended periods of inclement weather.

Other remote applications in use or planned include the following, which are of particular interest.

In a reverse-osmosis water-desalinization system, a 250-W PV array would supply pumps to bring in water to be treated and to maintain the pressure on the water being forced through a semipermeable membrane that blocks passage of the salt. The plant will produce 180 liters of water per hour from 360 liters of well water having a maximum salt content of 1 percent (Telefunken, 1980).

Communications systems employing from ten to several hundred watts of PV-supplied power are in use by park personnel, law enforcement agencies, and commercial firms. A fairly typical installation in the mountains of California is shown in Fig. 7.10. In Lasel, West Germany, an area that formerly

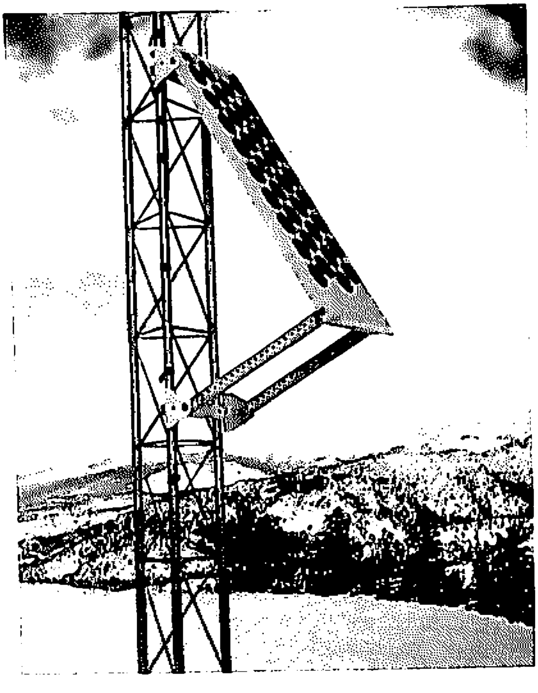


Figure 7.10 Solar cell panel on Martis Peak, California, used to power remote forest lookout communication system.

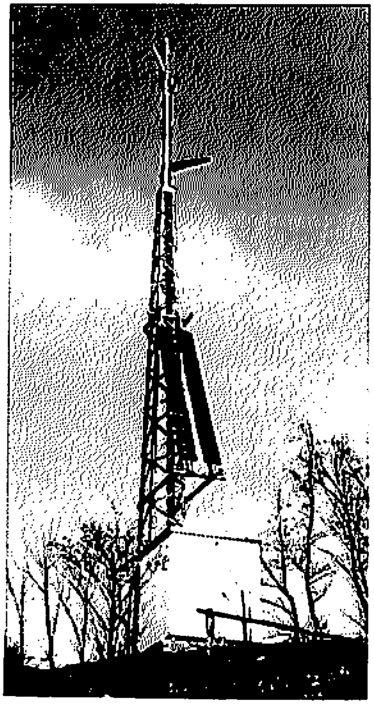


Figure 7.11 Solar-cell-powered TV repeater. *(Courtesy AEG-Telefunken, with permission.)*

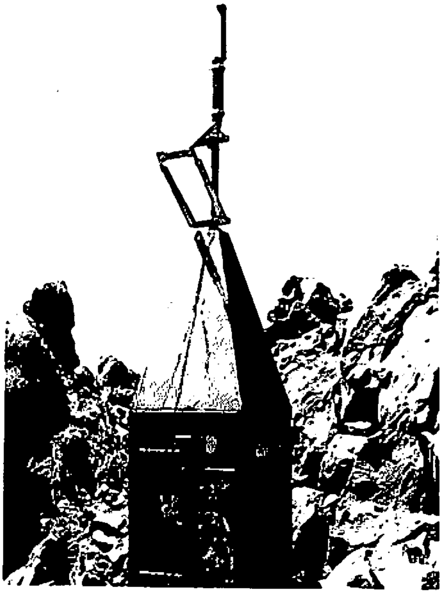


Figure 7.12 National Park Service radio communications repeater atop 3186-m-high (10,453-ft) volcanic Lassen Peak in California. Before installation of the solar panel, a helicopter had to deliver charged storage batteries to the site every two months.

had poor television reception because of line-of-sight obstructions is now receiving broadcasts relayed by a PV-powered fill-in transmitter that receives the faint signal from the main transmitter, amplifies it, and rebroadcasts it locally (Fig. 7.11). Radiated power is 2 W and the PV supply is rated at 240 W. To reduce battery requirements, a supplementary wind-driven generator is also included in this system (Telefunken, 1980).

Photovoltaic supplies of from 35 to 150 W are used to power remotely located television receivers for communication and education. Radio and radio-telephone repeater stations in many places around the world are being fitted with PV power supplies, typically at the hundreds-of-watts level. Figure 7.12 shows one such repeater station.

Photovoltaic supplies can, of course, be used in conjunction with solar thermal collector systems to pump the heated water from the collectors to the point of use. Several installations have been made of "total energy systems" like that sketched in Fig. 7.13. This is a simple 5× solar cell concentrator system in an enclosure having a transparent front cover. Air forced through the enclosure is heated and both the electrical output from the cells and the

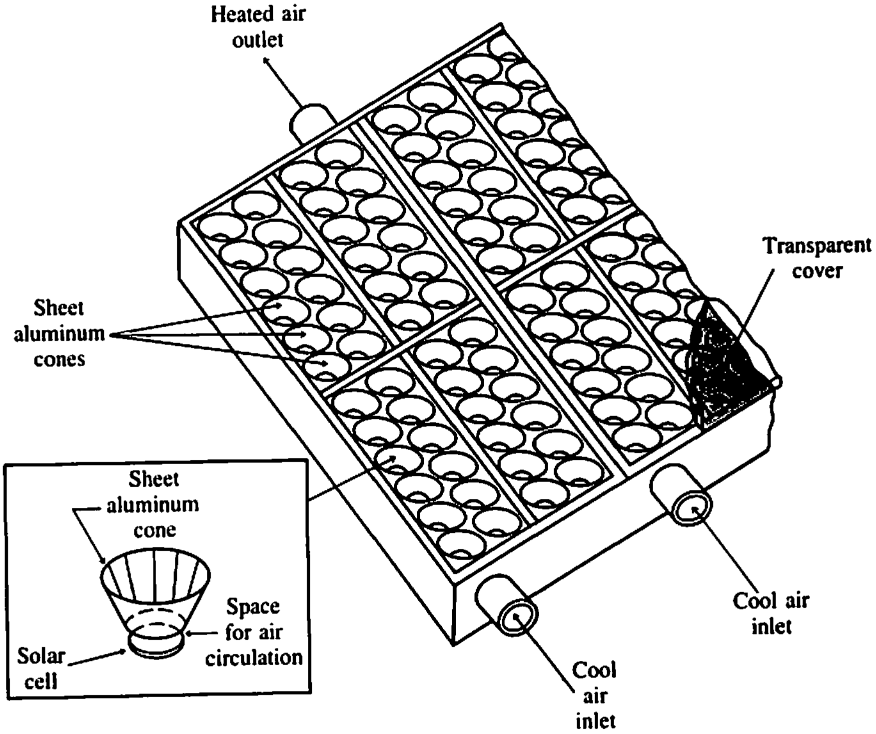


Figure 7.13 Total energy system employing solar cells with some concentration produced by the sheet aluminum cones. Air circulated through the covered boxes can be used to heat a dwelling or commercial building. A single concentrating cone and solar cell are enlarged for clarity. (Drawing is simplified sketch of commercial unit made by Solectro-Thermo, Inc.)

thermal energy of the heated air are available for use. Maximum power outputs for the 1.2 × 1.2 m^2 (4 × 4 ft^2) modules are 58 W electrical and 720 W thermal. The heated air is used for space heating in some applications and to preheat water in other installations.

The module just described is dimensioned to permit easy integration into buildings which, in the United States, often employ structural members measuring 4 ft × 8 ft. Another solar cell module that can be installed quite simply is the General Electric photovoltaic shingle, consisting of sealed hexagonal units that can be fastened onto a roof to seal it and produce power.

A final example of a simple application that is not so remote is the 8-W PV supply for a traffic counter located beside some city streets in Glendale, Arizona. Though grid power is available nearby, it is not used since battery storage is included in the system and the substantial cost of making a weatherproof connection to the electricity grid wires is avoided.

Portable Applications

To distinguish "portable" from "movable" someone has said that when a piece of equipment is portable a person can carry it *and* something else at the same time. By this definition, some significant movable PV devices include PV-powered navigation buoys and solar cell power supplies for pleasure boats, both being rated in the 50- to 100-W range. The really portable applications are ones where the use of PV panels provides the user with great mobility by eliminating the need for carrying bulky batteries. A clear example of this use is the field radio system shown in Fig. 7.14, powered by four lightweight panels capable of producing about 40 W_{pk}.

Solar cell–powered watches and even a sun-recharged flashlight are no longer rarities. The PV-powered pocket calculator of Fig. 7.15 can be operated either in sunlight or under artificial indoor lighting, and it needs no batteries because of its intentionally intermittent use. Failure of the only moving part of these devices—the on-off switch—is avoided: no switch is used as there are no batteries to run down. The power consumed by integrated circuits in a calculator and by a liquid-crystal display is so low that less than a milliwatt is adequate, permitting the use of cells having relatively low efficiency. An example is amorphous silicon cells, discussed in Chap. 10, which can be deposited directly on a transparent cover for this application.

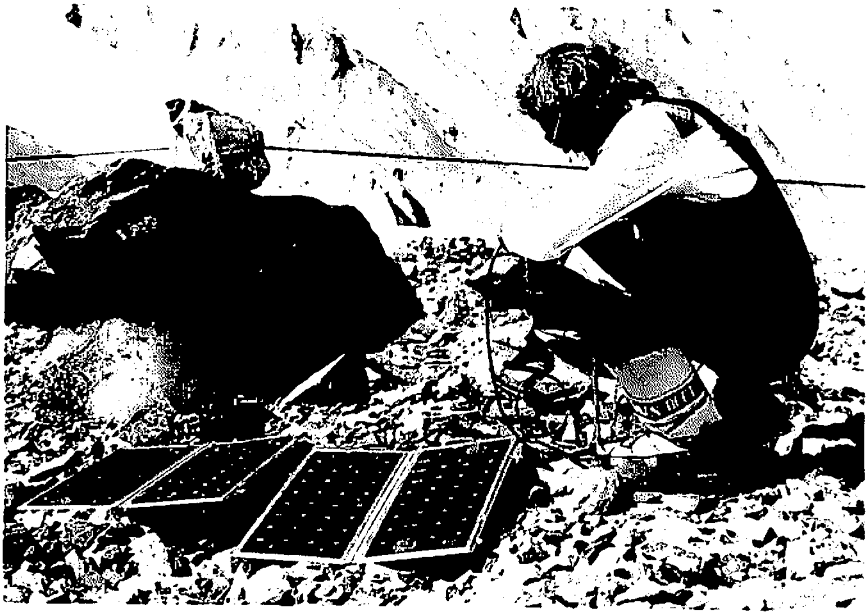


Figure 7.14 Portable solar panel powering communications radio transceiver at remote field location. *(Courtesy AEG-Telefunken, with permission.)*

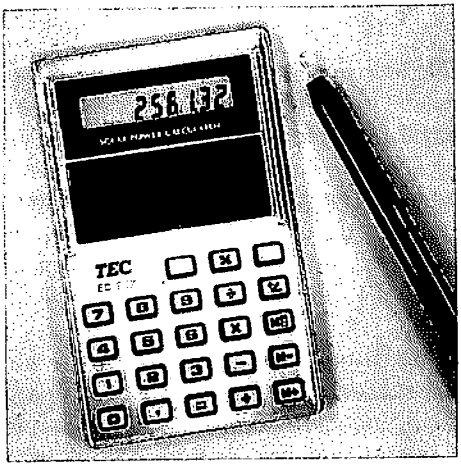


Figure 7.15 Calculator powered in ambient light by amorphous silicon solar cell visible below the liquid-crystal display.

7.4 SUMMARY

Portability, reliability, and operation far from conventional power sources are considerations that have led to many present terrestrial uses of solar cell systems. In large government-supported demonstration projects, the cells have generally performed well, though some problems have been encountered in equipment used with the cells. Most systems used to date have been designed for their specific applications, but increasing use of standardized modules is expected, for economic reasons.

REFERENCES

Bifano, B. J., et al. (1979), Social and Economic Impact of Solar Electricity at Schuchuli Village: A Status Report, DOE/NASA/20485-79/3 (NASA TM-79/94), June.

Bifano, B. J., Ratajczak, A. F., and Nice, A. W. (1978), Design and Fabrication of a Photovoltaic Power System for the Papago Indian Village of Schuchuli, Arizona, DOE/NASA/1022-78/39 (NASA TM-78948), June.

Hopkinson, R. F. (1980), Performance of a PV powered 20-hp dc/ac irrigation system and a 3 kW nitrogen generator, Record, 14th IEEE Photovoltaic Spec. Conf., 115–120.

Jarvinen, P. O. (1978), Natural Bridges National Monument, Utah—Solar Photovoltaic Power System Design, 2nd National Conf. on Technology for Energy Conservation, Albuquerque, N.M., 24–27, January.

Macomber, H. L., et al. (1980), Photovoltaic applications—Past and Future, Record, 14th IEEE Photovoltaic Spec. Conf., 1004–1017.

Ratajczak, A. F., and Bifano, W. J. (1979), Descriptions of Photovoltaic Village Power Systems in the United States and Africa, DOE/NASA/2-485-79/1, April.

Romaine, W. R. (1979), The Mead, Nebraska, 25 kW Photovoltaic Power System, MIT Lincoln Laboratory, Lexington, Mass., C00-4094-10, 5 January.

Sacco, S. B. (1979), Description of the MIT/Lincoln Laboratory Photovoltaic Systems Test Facility, MIT Lincoln Laboratory, Lexington, Mass., C00-4094-41, 30 June.

Smith, D. V. (1977), Photovoltaic Power in Less Developed Countries, MIT Lincoln Laboratory, Lexington, Mass., C00-4094-1, 24 March.

Smith, D. V., and Allison, S. V. (1978), Micro Irrigation with Photovoltaics, MIT Energy Laboratory, Cambridge, Mass., MIT-EL-78-006, April.

Telefunken (1980), Data from technical bulletins supplied by the Telefunken Company.

PROBLEMS

7.1 *Personal electricity use* Table 8.2 in the next chapter lists typical power ratings for electric household appliances. Considering those that you use personally, estimate your electrical energy usage. Compare this with what you actually use, as given on your utility bills, and consider reasons for any difference. Compare these figures with the per capita electric energy usage in the United States (obtain this from Fig. 1.3, assuming the U.S. population is 220 million) and explain the sources of the large discrepancy.

7.2 *PV system ownership and maintenance* Suppose a PV system at your dwelling or business can supply all the electrical energy you use there. Would you want to own and maintain the PV system, or pay more for your electricity to have another party take care of ownership and maintenance matters? If the latter, what percentage increase in the cost of electricity would you be willing to pay for this convenience? Independent of the ownership and maintenance issue, would you want to maintain a connection to the electric utility in order to obtain backup power?

7.3 *Concentrator or flat plate* Discuss the tradeoffs between concentrator and flat-plate PV systems in a variety of applications and locations differing in clarity of sunlight, availability of maintenance personnel, value of a thermal output in addition to electrical output, etc., assuming the concentrator system is 50 percent more efficient than the flat-plate system.

7.4 *Power versus energy* A *Newsweek* (news magazine) article states that ". . . a 50 square feet solar cell panel on the roof can not even generate enough electricity to power a toaster." Is this true? Is it misleading? What is your response to this?

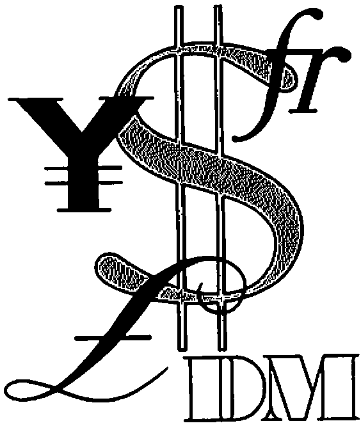
7.5 *Business/applications opportunities* If someone wants to establish a small business in the general field of solar cells, what would you suggest and why? Discuss the opportunities in manufacturing, sales, installation, services, or overlooked or rapidly growing applications.

CHAPTER

EIGHT

ECONOMICS OF PHOTOVOLTAIC POWER

CHAPTER OUTLINE



The frequent question, "When will solar cells be practical?" is really many questions, and to frame an answer one must consider the viewpoint of the person asking it. The resident of an industrialized country wants to know when the cost of putting solar cells on the roof overhead will be equal to the amount saved because of reduced payments to the energy utility. The businessperson wants to know when photovoltaics might become a profitable enterprise, and the student wonders whether it will soon be a good field in which to work professionally. The utility executive and the energy planner want to know when PV-produced electricity will account for a significant fraction of the large amounts of power and energy they deal with. And, on the low end of the scale of energy magnitudes, the concern in villages may simply be to know when a 100-W unit may actually be installed to pump water for cattle and humans.

From the strictly technological perspective, solar cells are already practical, and they are continually being improved. But the question being asked is really one of *economic* practicality, and the simplest answer to the question is, "When the price of the electricity from the PV system becomes lower than that for electricity from the alternative sources available for this application." For powering spacecraft, solar cells were economical long ago, even at capital acquisition costs around \$50,000/kW$_{pk}$, because they weighed much less than the alternative systems that stored energy in batteries or in chemical fuels. And in some remote applications, terrestrial cells are already practical. Examples in Sec. 7.3 are the Schuchuli village and remote forest communication systems where a grid connection is far too expensive and a diesel generator involves high costs for fuel purchase and delivery, and for maintenance.

8.1 SOME GENERAL RULES

One cannot state when the price of PV-produced electricity will have fallen enough to permit truly widespread application, but a few general principles are clear:

1. *As costs of PV-produced electricity are gradually reduced, economic practicality in a particular geographical region occurs first where the cost of electricity from other sources is highest.* The value of the electricity in a grid is highest at the load, after transmission and distribution from the power-generating station, and so in industrialized countries, economic feasibility will occur first at dispersed load sites such as dwellings and light commercial establishments.
2. *Economic feasibility of PV power is highly dependent upon the future prices of electricity from conventional sources.* These prices reflect, as

noted earlier, fuel prices and the rate of inflation. Computer simulations of economic trends typically make high and low assumptions about the expected rise of the price of electricity from the grid and the rate of inflation. These simulations then yield different dates for practicality, depending on the high and low values assumed.

3. *The time at which economic practicality of PV systems will occur is very dependent upon the characteristics of the individual consumer using the PV system.* The location of the user is important because of the geographical variation of insolation and because the price of power from the grid varies greatly. For example, residential electricity in the Northeastern United States costs two or three times what it does in the Southeast. Does the individual user consider and compare with that of the alternative grid power the *life-cycle cost*—total costs for the 20- or 30-year life of the system—or are only the *first-year costs* considered and compared? Is there a governmental tax credit available as an incentive for installation of solar equipment (amounting, for example, in 1980 to 40 percent in U.S. federal income tax, and 55 percent of costs per function in the State of California, subject to certain limitations and conditions)? If so, the amount of that credit will affect the perceived cost and attractiveness of the solar option. The income-tax bracket of the purchaser is also relevant because interest paid on money borrowed to buy and install the PV system may be deductible from income when figuring the tax to be paid.

   Other individual choices having economic implications both upon the consumer and upon the electric utility to which the consumer is connected are the degree to which intermittency of the electricity supply will be tolerated and hence the amount of grid back-up that will be sought, the power buyback policy of the utility, whether time-of-day pricing is used by the utility, and whether the utility or the customer will want to own and maintain the PV system. Finally, if the consumer will be able to use the thermal output from the PV system this will obviously tend to favor economic feasibility.

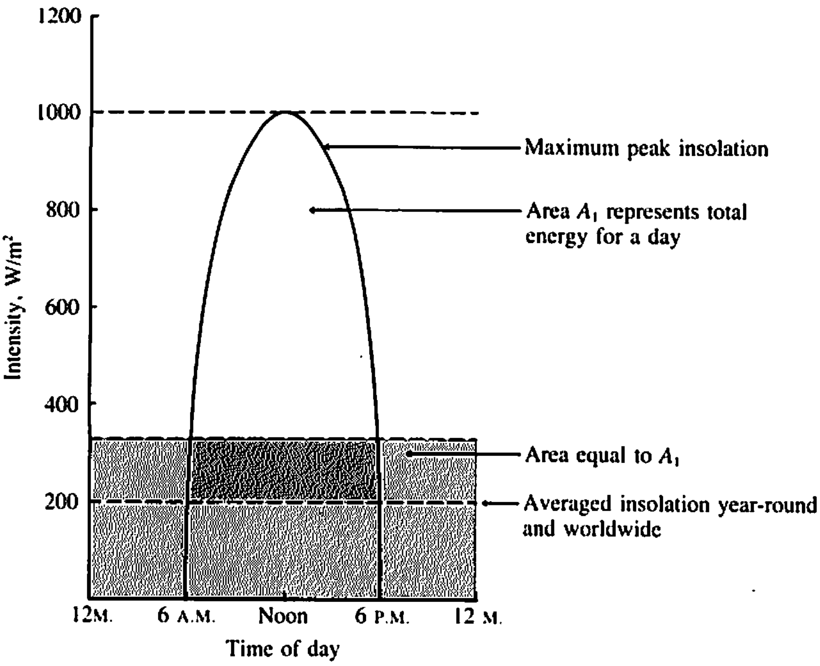
4. *Very different economic and technological criteria apply in the industrialized and the nonindustrialized countries.* In some parts of the planet it may be desirable economically and socially to engage otherwise unemployed persons to adjust PV panels periodically through the day rather than relying on complicated, possibly unreliable electro-mechanical tracking systems. It may be worthwhile in some countries for people to set up portable PV systems in fallow fields temporarily to generate electricity for local use, storage, or for feeding into a utility grid.

In the remainder of this chapter we will draw from analyses of PV-system prospects at specific locations in the United States, carried out both by governmental agencies and by private firms, to illustrate expectations about

TEN RULES OF THUMB

Here are some *approximate* quantities or relations useful for estimating the characteristics of photovoltaic systems.

1. The maximum peak terrestrial sunlight intensity is 1000 W/m^2, and the average sunlight intensity year-round and worldwide is approximately one-fifth of the peak intensity, or about 200 W/m^2. See Chap. 2 and the illustration below.



2. The area of 10 percent efficient solar cells under maximum terrestrial insolation required for a peak output of 1000 MW$_{pk}$, equivalent to the output of a typical nuclear or large coal-fired power plant, is 10^7 m^2, an area 1.9 mi on a side, or about 0.0001 percent of the total area of the United States.
3. The roof area of a typical single-family house in the United States is around 110 m^2, roughly 1200 ft^2.
4. The average annual electrical-energy consumption for a four-person household in a two-story single residence having a 1700-ft^2 living area is around 7150 kWh, corresponding to an average power utilization of about 815 W throughout the year (OTA, 1978, p. 699).
5. The efficiencies of commercial solar cells in 1980 ranged from about 10 to 15 percent. Typical costs of solar cells purchased in fairly large quantities

were around \$10/W$_{pk}$ in early 1980. Costs are predicted to fall to about \$0.70 (1980 U.S. dollars) by 1985.

6. The cost of a single-crystal silicon solar cells made by conventional techniques is composed of three nearly equal parts: one-third is the cost of the silicon, one-third is the cost of fabricating the individual cells, and one-third is the cost of interconnecting cells and assembling arrays or modules.
7. The nationwide average cost of electricity in the United States in mid-1981 was 5.4¢/kWh. Prices for households, commercial users, and industrial users varied from values around 1¢/kWh in Seattle (1.2, 1.2, and 0.8¢, respectively) up to almost 14¢/kWh in New York (14.7, 14.0, and 11.5¢, respectively).
8. Balance-of-system costs are predicted to increase the cost of solar electric output by a factor of approximately 2.3 times that of the solar cell modules themselves.
9. Solar cells are expected to function for at least 20 years after installation.
10. Large-volume manufacture of electronic or mechanical parts typically results in prices dropping to about a third of the price for individually marketed units.

when solar cells will become economically practical. The key findings are that dispersed application sites will become practical first, and that feasibility will come in the mid-1980's *provided* the cost of solar cells continues to fall toward the levels taken as the DOE goals (Table 1.1), *and provided* the balance-of-system (BOS) costs can be reduced significantly in the next few years.

8.2 COST ANALYSES FOR PHOTOVOLTAIC POWER

It is useful to deal with the costs in three different ranges of power level:

- Residential user, 1- to 10-kW$_{pk}$ level
- Intermediate user, commercial and light industrial enterprises, 100 kW$_{pk}$ to several MW$_{pk}$
- Central power station, 100 MW$_{pk}$ to several thousand MW$_{pk}$

This division is useful because each of these users has quite different financial characteristics and constraints, as well as different electricity-demand schedules, knowledge and perception of the value of time to pay back an investment, and so on.

The dependence of the level and cost of PV power upon the characteristics of the application and the user are for the most part intuitively clear. The cost falls as the cost per watt of the solar cell modules drops, and the cost increases with increasing recurring costs of operating and maintaining the system. If the array efficiency decreases because of aging or is otherwise reduced by underutilization during some months when the load is light, this will increase the effective cost of the power produced and consumed. The greater the insolation, the lower will be the cost per watt produced, since a given array will have a greater output for the same acquisition price. Finally, the cost of assembling the funds to purchase the array will increase the apparent cost of the PV system itself.

These dependencies are expressed in Eq. (8.1.1) for the levelized cost of PV-produced power.

$$E = 10^5 \frac{(C)(F)}{(U)(S)} + OM \tag{8.1.1}$$

In this equation E, the cost in cents per kWh, is *levelized*, meaning it is the ratio of the total costs incurred throughout the life of the system, divided by the number of peak kilowatthours of energy the system produces in its useful life (see Fig. 8.1). C is the installed cost of the system (array and associated equipment) in $\$/\mathrm{W_{pk}}$. S is the ratio of the energy in kWh generated annually to the power rating of the system in $\mathrm{kW_{pk}}$; under ideal conditions S equals the number of hours in a year, 8760, divided by about 5 to account for the ratio of daily average to peak insolation. The utilization factor U, accounting for factors that tend to reduce system output or its value, is discussed below. OM is the operation and maintenance cost, in cents per kilowatthour; it includes charges for cleaning panels, making repairs, and the like. This cost is assumed to be the same during each year the system operates. The factor 10^5 corrects for the mixed units used in the equation. Finally, F is the fixed-charge rate that represents the cost of financing the system. F equals the sum of the annual capital-related charges divided by the initial installed cost of the equipment.

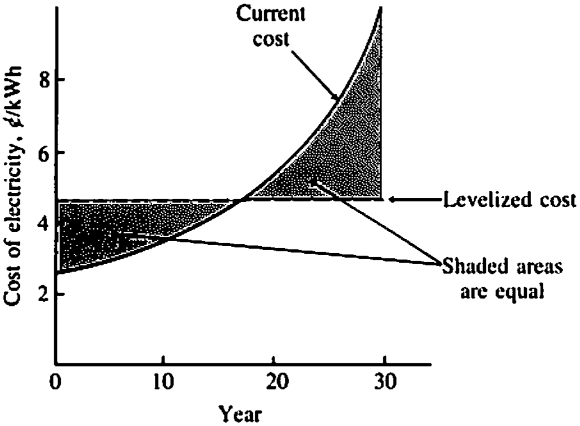


Figure 8.1 Levelized and actual cost of energy. The two shaded areas are equal.

Let us consider the utilization coefficient U and the fixed-charge rate in somewhat more detail. The utilization coefficient U accounts for factors that tend to reduce output of the system, including reduction of optical efficiency due to accumulation of dirt and to degradation of the surfaces through which the light must pass (possibly 8 percent averaged over the life of the system), power-conditioning losses (likely no more than 10 percent), and losses arising in storing and then retrieving energy (if 40 percent of the energy is stored in batteries and only 75 percent of that can be retrieved, then U is reduced by 10 percent). In addition, U is affected by changes in system efficiency due to operating at temperatures higher than the design value (efficiency and U are reduced), or lower than the design value (U increased). Finally, sale of energy back to the utility at too low a price can be thought of as a form of underutilization, reducing U and increasing the effective cost of the output from the PV system. It has been estimated that these factors combined will lead to utilization coefficient values (U) around 0.7, and thus increase the cost of PV power by about 40 percent.

The fixed-charge rate F varies widely for the three different classes of user. For the residential consumer having a rooftop PV system that is treated as an integral part of the residence when the residence is purchased, F involves the amount of the down payment, interest, taxes, and insurance on the PV system, with correction for the tax bracket of the owner and hence possible reduction of interest through tax deductions. Of course, any tax credits allowed for installation of a PV system subtract directly from the cost term C. Typical fixed-charge rates F assumed in calculations of the economic feasibility of PV systems (OTA, 1978) have ranged from about 0.09 to 0.16.

For the intermediate-level application, there is a wide diversity of fixed-charge rates F, the values being generally low for schools and residential condominium or townhouse clusters and high for most commercial enterprises such as shopping centers. For these users there are large differences in the match between insolation and electricity demand. For utilities the fixed-charge rate is also high, including factors such as higher costs of borrowing, substantial business taxes, and payments to stockholders if the utility is publicly owned.

Balance-of-System Costs

Balance-of-system costs can be put in three categories:

1. *"Hard" BOS costs* are incurred only once for the purchase of equipment or for construction and installation. They include costs of power-conditioning and energy-storage equipment, land, foundations and support structures, lightning protection, transportation, and installation.
2. *"Soft" BOS costs* produce no visible equipment or structures and are

amenable to reduction through organizational, rather than technological, changes. These costs cover marketing and distribution, warranty of system, project management and architect and engineer fees, and interest during construction.

3. *Recurring BOS costs* result from operation expenses, maintenance, and replacement of elements that fail.

The DOE system price goal for 1986, when solar cells are assumed to cost no more than \$0.70/W_{pk}, is \$1.60/W_{pk}, requiring the total BOS costs to be only \$0.90/W_{pk}. Present BOS costs are more than ten times this amount, and so a number of cost-reducing measures must be explored.

One can hope for technological improvements to reduce hard BOS costs, an example being the development of improved batteries or redox energy-storage systems that are less expensive than the lead-acid batteries now used. In certain applications, some of the hard BOS costs can be avoided altogether. For example, if the dc output of arrays can be used directly, the cost of inverters is avoided, saving at least \$1/W_{pk} at present prices. In some applications, as noted earlier, energy storage may not be necessary, saving at present prices at least \$0.12/W_{pk}. Costs for land, foundations, and support structures may be relatively insignificant in those applications where PV cells can be mounted on existing structures, such as the rooftops of existing buildings. Further, installation costs can be minimized if standardized modules are designed for installation by relatively unskilled laborers.

Standardization of modules would also help reduce part of the soft BOS costs in custom installations where project management and architect and engineer fees may be substantial. If there is a boom in PV use, marketing and distribution costs might be minimized if the systems were distributed through existing large merchandising outlets, such as those that sell television, radio, and audio systems. Public willingness to invest in PV systems may also increase significantly if a warranty on the entire system is offered either by distributors or by vertically integrated companies that provide all components of the PV systems rather than just the cells themselves. Several such companies already exist and are listed in Appendix 8.

Cost Comparisons

The results of the DOE analysis (Clorfeine, 1980) for residential, intermediate, and central power station installations in three United States cities appear in Table 8.1. Anticipated costs of PV-produced electricity are compared with those expected for conventionally produced electricity (assumed to increase at a rate 3 percent higher than the inflation rate). Note that if the cell and system price goals are met, both in sunny Phoenix, where electricity from conventional sources is relatively inexpensive, and in far less sunny

Table 8.1 Tentative PV system price goals (1980 dollars)

User (date)	Location	Predicted conventional energy price, ¢/kW	System price goal, $/kWh	PV power price if goal is met ¢/kW
Residential (1986)	Phoenix	5.7	1.60	5.2
	Miami	5.5	1.60	6.9
	Boston	9.4	1.60	8.7
Selected intermediate (1986)	Phoenix	6.4	1.60	5.5
	Miami	7.0	1.60	7.3
	Boston	8.0	1.60	9.2
Central power station (1990)	Phoenix	All differ depending on whether baseload, intermediate, or peaking supply	1.10–1.30	4.2–4.8
	Miami		1.10–1.30	5.5–6.4
	Boston		1.10–1.30	7.0–8.1

Boston, where costs of transport drive up the prices of conventional power, the levelized prices of PV electricity in 1986 would be about 90 percent of those of the conventional sources of electricity for the residential consumer. Table 8.1 also shows that, at least for the Phoenix area, PV electricity will become less expensive than conventional power for the intermediate level consumer under the many conditions assumed. The central-power-station costs tabulated must be compared with actual utility costs to determine how much later they may become competitive.

Several other studies have produced similar conclusions but with interesting differences of detail. In analyzing an energy-efficient house located in Phoenix, Hammond (1979) has shown the importance played by the source of back-up power. This house had an assumed annual energy consumption of 7110 kWh/yr and fully 45 percent of that was consumed by evaporative coolers (rather than refrigeration systems) for air conditioning. The shares that these appliances required are of interest in themselves (Table 8.2). Clearly the economic feasibility of PV power depends on what conveniences the consumer regards as essential, since cooling for comfort and drying of clothes in an electric dryer consume more than half the electrical power in this house.

The simulated outputs through the year for two different-sized modules are plotted with the assumed demand in Fig. 8.2. The larger array meets nearly the entire peak load and it produces at other times far more power than is needed. The smaller module produces somewhat more power than is required during June, July, and August. The deficit is assumed to be supplied

Table 8.2 Power ratings and typical estimated annual energy consumption of electric household appliances

Appliance	Typical power rating, W	Typical annual energy consumption, kWh
Electric range with oven	12,000	700
Clothes dryer	4,500	1,000
Dishwasher	1,500	400
Microwave oven	1,450	190
Toaster	1,200	40
Air conditioner	1,100	1,400
Clothes iron	1,000	100
Coffee maker	1,000	110
Automatic clothes washer	700	100
Color television	500	500
Black-and-white television	350	350
Refrigerator/freezer with	–	1,800
automatic defrost (16 ft^3)	–	1,230*
Refrigerator/freezer with manual defrost (12.5 ft^3)	–	1,500
Vacuum cleaner	300	50
Radio	100	90
Incandescent light bulbs	60–150 each	1,500
Fluorescent light bulbs	15–40 each	400
Electric clock	2	18

* Average value for 1979–80 energy-efficient refrigerator/freezer

by a backup source that would provide in those three months 18, 34, and 24 percent of the load, respectively. If the utility could have supplied the backup power in 1979 when the analysis was made, at then-current prices the cost could have been for the 30-yr life \$0.26/kWh. If purchased in 1989 when solar cell modules are assumed to have dropped to no more than \$0.70/W_{pk} in 1980 dollars, the cost would be only about 40 percent of that of conventional sources. This analysis assumes that BOS costs drop as indicated by the DOE system goals, and that the utility can act as the source of backup power. If the back up source must be a diesel-driven generator at the load site, then the PV system will not be less expensive than conventional sources.

The interested reader will find in the OTA (1978) publication a detailed discussion of the issue of economic feasibility, and even a Fortran computer program developed for making cost projections. The entire energy needs (electricity, water heating, and space heating and cooling) are analyzed for the following types of energy consumers with assumed locations of Albuquerque, Boston, Ft. Worth, and Omaha:

- Single-family residence
- A 10-story, 196-unit high-rise apartment building

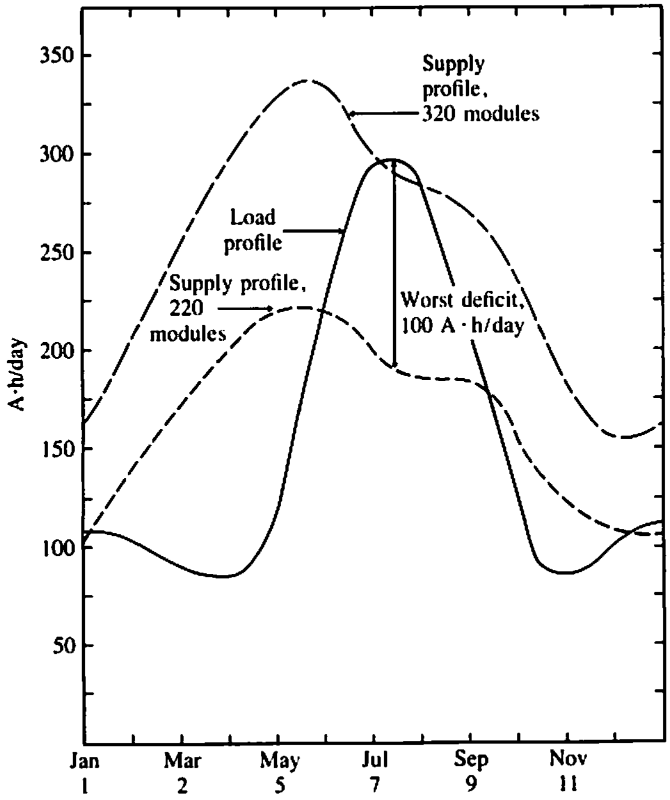


Figure 8.2 Simulated output for two differently sized PV arrays in Phoenix, Arizona, and assumed demand for a single residence. (*After Hammond, 1979.*)

- A 300,000-ft^2 shopping mall
- An entire residential community
- Various industrial installations needing electricity and process heat

The OTA study results generally show that PV systems can be competitive with conventional sources in residential and intermediate uses if the DOE price goals are met. Figure 8.3, on pp. 166–167, is one of several hundred case studies run by OTA, included here to show the level of detail necessary to yield predicted costs. The chief conclusions of the study for this house in Boston fitted with flat PV panels appear in part C of Fig. 8.3. They are that, if no financial incentives are offered for the installation of solar equipment, the levelized cost of PV electricity will be less than that for conventional sources even if a conservative estimate is made about the rate of escalation of electricity prices (the conservative assumption is that those prices rise at the rate of general inflation, which was assumed in this study to be only 5 percent). With steeper cost increases or with incentives such as a 20 percent solar investment tax credit, the savings to the user of the PV system are even greater.

Financial Incentives and Buy-back Policy

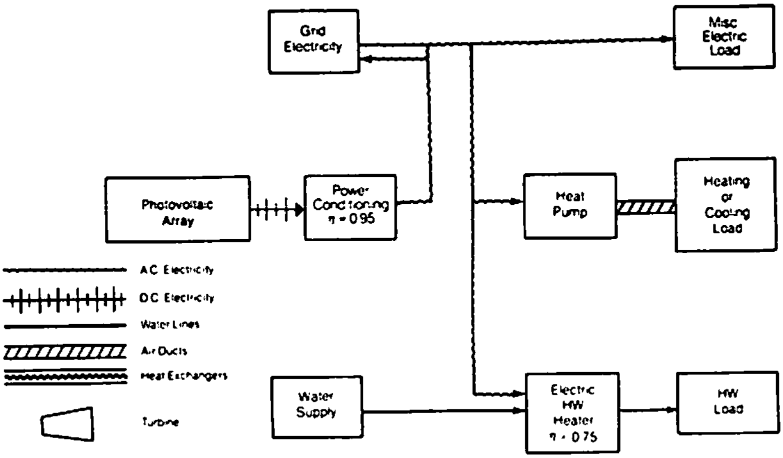
A variety of incentives may be available to encourage individuals to install PV systems. These include state and federal tax credits, low-interest loans, exclusion of PV equipment from the tax base on which property tax is figured, exemption from sales tax, and so on. As examples, in 1980 U.S. federal tax laws permitted an energy tax credit of 15 percent of costs up to a maximum credit of $300 for certain energy conservation items and 40 percent of costs, up to a maximum credit of $4000, for purchase of solar, geothermal, and wind renewable energy-source items. The State of California in 1980 offered a tax credit for individuals of up to $3000 per function (e.g., a PV system providing both electricity and hot water serves two functions, so a $6000 maximum credit applied), but only for taxpayers having an income below $30,000 for couples or $15,000 for single individuals. An electric utility company offered loans for the purchase of solar equipment at an interest rate about one-third the prevailing commercial rate.

The effects of these incentives can be appreciated by considering the changes they make in the life-cycle costs of a PV system (Carmichael et al., 1980). To simplify the example, we assume no buy-back of excess power by the local utility (this issue is considered next) and do not consider the cost of backup power bought from the utility. The yearly cost of the PV system is then

$$\begin{aligned}\text{Yearly cost} = {} & \text{(mortgage payment)} + \text{(increase in property tax)} \\ & + \text{(increase in insurance premium)} \\ & + \text{(operating and maintenance cost)} \\ & - \text{(income tax savings for deducting interest} \\ & \quad \text{and taxes paid on the system)}\end{aligned}$$

The life-cycle costs of the system are the sum of the initial costs—down payment and sales tax—and the yearly costs, corrected for inflation and discounted to reflect the time value of money, for each year of system life. Table 8.3 (p. 168) shows the conditions assumed for a model residential PV system, and Table 8.4 shows the effects of various financial incentives on the life-cycle costs.

The data in Table 8.4 show that the major incentives are produced by exclusion of the PV system from the property tax base, credit on income tax, and the larger interest subsidies. The reader can get a better feeling for the contributions to the cost by verifying some of these figures; of particular



A. ITEMIZED COST OF COMPONENTS

Component	Size	Unit cost	First cost (incl. O&P)	Annual O&M	Life (yrs)
1. Electric heat pump	1.47 tons	800 $/ton	$1,180	$50	10
2. Ductwork	—	—	425	0	30
3. Electric hot water	40 gal.	$225 ea.	225	0	15
4. Air-cooled silicon PV (500 $/kW) ($\eta$ = 0.12)	59 m^2	88 $/$m^2$	*2,600	0	30
——Silicon array @ 60 $/$m^2$			*2,600	0	15
——Shipping @ 2 $/$m^2$					
——Installation @ 8 $/$m^2$					
——25% overhead and profit					
5. Power conditioning	7 kW	114	800	8	30
6. Lightning protection	—	—	300	0	30
7. Extra insulation, storm doors and windows	—	—	981	0	30
TOTAL			$9,111	$58	

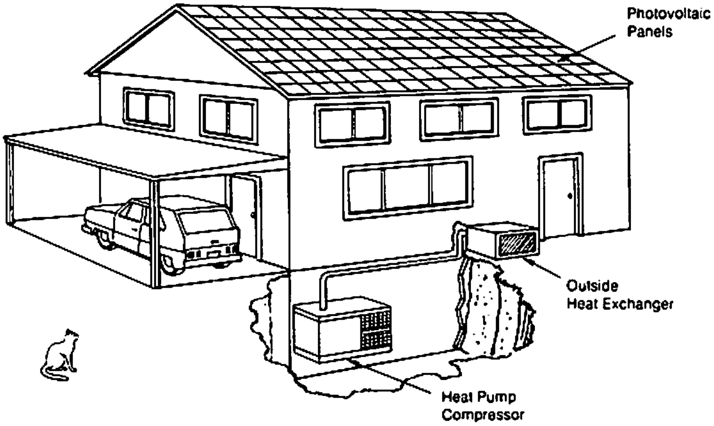
* ½ installed collector cost assumed replaced in 15 yrs., with total replacement in 30 yrs.

ANNUAL ENERGY FLOWS

(Conventional reference system is IF-2)

	Energy consumed by ref. system	Backup consumed w/ solar/conservation	Energy saved (% of total)
Net Electricity (bought-sold) (MWh/unit)	27.1	17.1	36.8
Fuel consumed onsite (MMBtu/unit)	0.	0.	0.
Total energy requirement (bbl crude equiv.)[a]	66.	42.	36.8
Electricity sold to grid annually (MWh, entire building)			3.8
Annual peak electricity demand (kW, entire building)			14.5

Figure 8.3 Sample output from analysis of a hypothetical residential PV system in Boston assuming \$0.50/W_{pk} silicon cells (*OTA, 1978*). In part C of this sample note that even without financial incentives the cost of conventional electricity is higher than that of PV-produced electricity in 1986 and beyond.



B. LEVELIZED MONTHLY COSTS PER UNIT TO CONSUMER (Dollars)[b,c]

(Conventional reference system is IF-2)

	Escalation of conventional energy costs					
	Constant real energy prices		Energy price escalation I		Energy price escalation II	
1. 1976 Startup						
a. Costs using solar (conservation) system:						
Total with no incentives	248.	(292.)	285.	(328.)	433.	(476.)
Total with 20% ITC	238.	(283.)	274.	(319.)	423.	(468.)
Total with full incentives	225.	(254.)	261.	(291.)	409.	(439.)
b. Costs using conventional reference system	*226.*		*274.*		*467.*	
2. 1985 Startup[d]						
a. Costs using solar (conservation) system:						
(capital related costs)	99.	(142.)	99.	(142.)	99.	(142.)
(operation & maintenance costs)	9.	(9.)	9.	(9.)	9.	(9.)
(fuel bill)	0.	(0.)	0.	(0.)	0.	(0.)
(electric bill)	141.	(141.)	197.	(197.)	428.	(428.)
Total with no incentives	248.	(292.)	305.	(348.)	536.	(579.)
Total with 20% ITC	238.	(283.)	295.	(340.)	525.	(570.)
Total with full incentives	225.	(254.)	281.	(311.)	512.	(541.)
b. Costs using conventional reference system	*226.*		*300.*		*602.*	

C. EFFECTIVE COST OF ENERGY TO CONSUMER

(Conventional reference system is IF-2)

	Type of incentives given					
Levelized cost of solar energy or 'conservation' energy[f]	No incentives		20% ITC		Full incentives	
$/MMBtu primary fuel	6.67	(11.10)	5.64	(10.22)	4.27	(7.28)
¢/kWh electricity	7.85	(13.07)	6.63	(12.03)	5.03	(8.57)

	Escalation of conventional energy costs		
Levelized price paid for conventional energy[b,e]	Constant real energy prices	Energy price escalation I	Energy price escalation II
$/MMBtu primary fuel	*6.91*	*8.70*	*15.99*
¢/kWh electricity	*8.14*	*10.24*	*18.82*

Figure 8.3 *(continued)*

Table 8.3 Characteristics of assumed residential PV system owned by home owner

System life	20 yr
Installed cost of system	$10,000
Inflation rate	8%
Interest rate	10%
Discount rate	10%
Operation and maintenance expense (% of installed cost)	1.5%
Insurance	0.3%
Property tax rate	2%
Sales tax	3%
Personal income tax bracket	25%
Down payment	10%
Tax benefit assumed, year after purchase	1 yr

Source: Carmichael et al., 1981.

Table 8.4 Effect of financial incentives on life-cycle cost of residential PV system

System has characteristics listed in Table 8.4 (Carmichael et al., 1981)

Case considered	Life-cycle cost, $	Reduction in life-cycle cost, $
Base case (parameters from Table 8.4)	13,758	—
Exemption from sales tax		
Sales tax rate 3%	13,458	300
Sales tax rate 5%	13,258	500
Interest subsidy		
Interest rate 9½	13,539	219
Interest rate 5%	11,729	2,029
Interest rate 0%	10,125	3,633
Reduction in down payment		
5% down payment	13,672	86
No down payment	13,587	171
Exclusion from property tax base		
25% federal income tax bracket	11,454	2,304
Credit on federal income tax		
40% credit	10,112	3,636
55% credit	8,758	5,000

interest is the importance of the running expenses other than interest—property tax, operation and maintenance expense, and insurance. Incidentally, at this writing it appears that the tax credits for solar installations in the United States are likely to be abolished for fiscal reasons.

Turning to power buy-back policy, a portion (Section 210) of the U.S. Public Utilities Regulatory Policies Act of 1978 (PURPA) establishes important rules governing the flow of power between an electric utility and small power producers (Federal Register, 1980).

Prior to its enactment, a cogenerator or small producer of power wishing to sell excess power to the utility and buy power when it was needed might face three obstacles: (1) The utility was not obliged to purchase the power at an appropriate rate, (2) the utility might charge discriminatorily high rates for backup power supplied to the small producer, and (3) the small producer might be considered an electric utility and thus be subjected to quite burdensome regulations.

PURPA solves the third problem by defining suitable exemptions. The most significant provisions are these:

- ". . . electric utilities must purchase electric energy and capacity made available by qualifying cogenerators and small power producers at a rate reflecting the cost that the purchasing utility can avoid as a result . . . rather then generating an equivalent amount of energy itself."
- The electric utilities must furnish data concerning present and future costs of energy and capacity on their systems, so the small power producer can estimate the avoided costs.
- The utilities must furnish electric energy to qualifying facilities on a nondiscriminatory basis, and at a rate that is just and reasonable.

The first rule means that the *incremental* cost for a utility to generate an additional kilowatt-hour of energy at a specific time of day will be the price paid to the small producer who supplies the utility with a kilowatt-hour at that time. For power supplied at times of peak system loading, then, the price paid to the small producer may exceed the average price of energy charged by the utility, because at such times utilities use diesel generators to meet peak demands, at a cost higher than that incurred in operating more efficient baseload generators (see Fig. 8.4). Thus the conventional wisdom about buy-back policy—that power will be bought back at a "wholesale" rate significantly below the "retail" rate the utility charges its customers—is wrong. Table 8.5 shows the schedule of purchase prices for one utility during a period in 1980 when the average residential ("retail") rate was $0.04770/kWh. As the data in the table show, as much as a 20 percent premium will be paid for power supplied during peak system loading.

The effect of buy-back policy on the cost of PV power can be illustrated by an example. Suppose that in order to meet most of the annual needs a PV

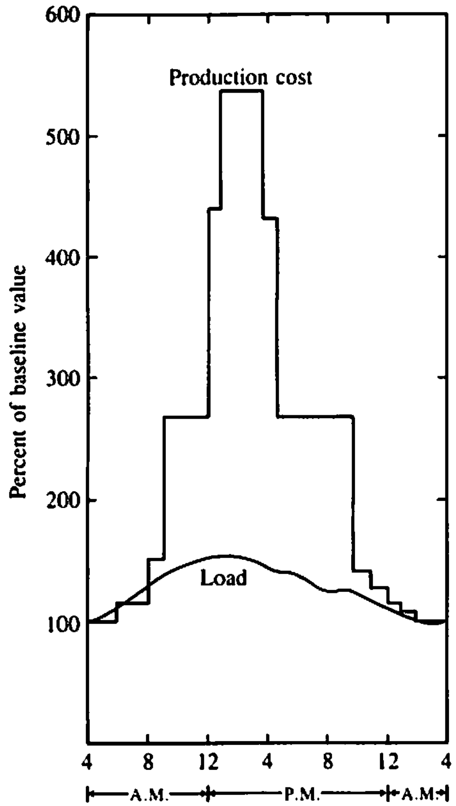


Figure 8.4 Summer daily demand pattern of typical utility. As the load increases above the minimum baseload value to its maximum, about 60 percent higher, the utility obtains power from more expensive generators and production cost increases by more than 400 percent. (*After EPRI Journal, Oct. 1981.*)

Table 8.5 Prices for buy-back of power from cogenerators and small power producers

May 1 through July 31, 1980 (Pacific Gas and Electric Company)

1. Standard weighted average price: 4.994 ¢/kWh
2. Optional time-of-delivery prices (producer pays for additional time-of-day metering equipment required):

On-peak (12:30–6.30 P.M. weekdays)	5.675
Partial-peak (8:30 A.M.–12:30 P.M. and 6:30 P.M.–10:30 P.M. weekdays, and 8:30 A.M.–10:30 P.M. Saturdays)	5.459
Off-peak (10:30 P.M.–8:30 A.M., weekdays and Saturdays; all of Sunday)	4.700