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UNDERSTANDING SOLAR CELLS

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By VITA Volunteers Dennis Elwell and Richard Komp

INTRODUCTION

Solar cells, also called photovoltaic (PV) cells, are a compact source of small amounts of electricity. They are rugged, dependable devices for converting sunlight directly into electrical energy. They have no moving parts and a long working life. System maintenance costs are lower and reliability is much higher than for other power sources. They can be used on any scale, from powering a digital watch to running a multi-megawatt generator for a public utility. Because they are usually arranged in modular panels, it is possible to start with a small system and expand it as necessary without making the early panels obsolete. But because only small amounts of energy are converted by each cell, large-scale electrical requirements require large and costly arrays of PV cells. Thus, the main applications of PV cells have been to supply relatively low demands. Planners who may be considering long-term economics should also consider that selecting PV power helps to achieve a pollution-free environment.

About 1 kilowatt (kW) of radiant energy falls on a square meter (sq m) of the earth's tropics at midday. If a solar panel has an efficiency of 10%, then each square meter of cell array will generate a peak of 100 W of electrical power. A typical 10-W panel, capable of keeping an automotive battery charged, measures 31 cm by 35 cm including the frame.

The idea of capturing solar energy in this way is not new. The copper oxide solar cell was discovered by Antoine Becquerel in 1839 and the amorphous-selenium cell came into use for photographic light meters in the 1890s. In the 1930s, selenium cells were used for power on a small scale in remote locations in the United States. Serious development of photovoltaic technology began, however, when silicon cells were developed and used in the U.S. space program. The first silicon solar cells were used in the U.S. satellite Vanguard I in 1958. Their cost was US$600 for each watt of generating capacity. It has now (1989) dropped to less than $6/W for larger systems.

Solar cells are devices that absorb and convert radiant energy from the sun directly into electrical energy. They are made of materials called semiconductors, which are crystalline solids with an electrical conductivity between those of metals and insulators.

A thin wafer or sheet of the semiconductor is treated ("doped") with chemicals to produce a negative charge (free electrons) on one side and a positive charge (free protons) on the other. (Virtually all commercial solar cells are made so that the front or top surface is negative.) The point at which the positive and negative sides meet is an electronic barrier known as a p-n junction.

The cells convert sunlight into electricity in three major processes:

1. The semiconductor material absorbs the sunlight.

2. Free positive and negative charges are generated and separated into the different regions of the cell. The separation creates a voltage in the cell.

3. The separated charges are transferred as electric current through electrical terminals to the intended application.

The processes work this way: The energy of the incoming sunlight causes electrons to cross the barrier and remain trapped on the front, or negative, side. When contacts are made to the front and back sides of the solar cell, a current flows through wires and devices connecting these contacts. The current is proportional to the intensity of the sunlight that falls on the cell. The back, or positive, electrical contact can be a continuous layer of metal, but the front contact is made in the form of thin fingers, to allow as much sunlight as possible to reach the back layers. The cell is usually covered by an anti-reflection coating and a protective cover to allow cleaning. A more detailed explanation of how photovoltaic cells work is given in references 8 and 9. The structure of a solar cell is shown in Figure 1.

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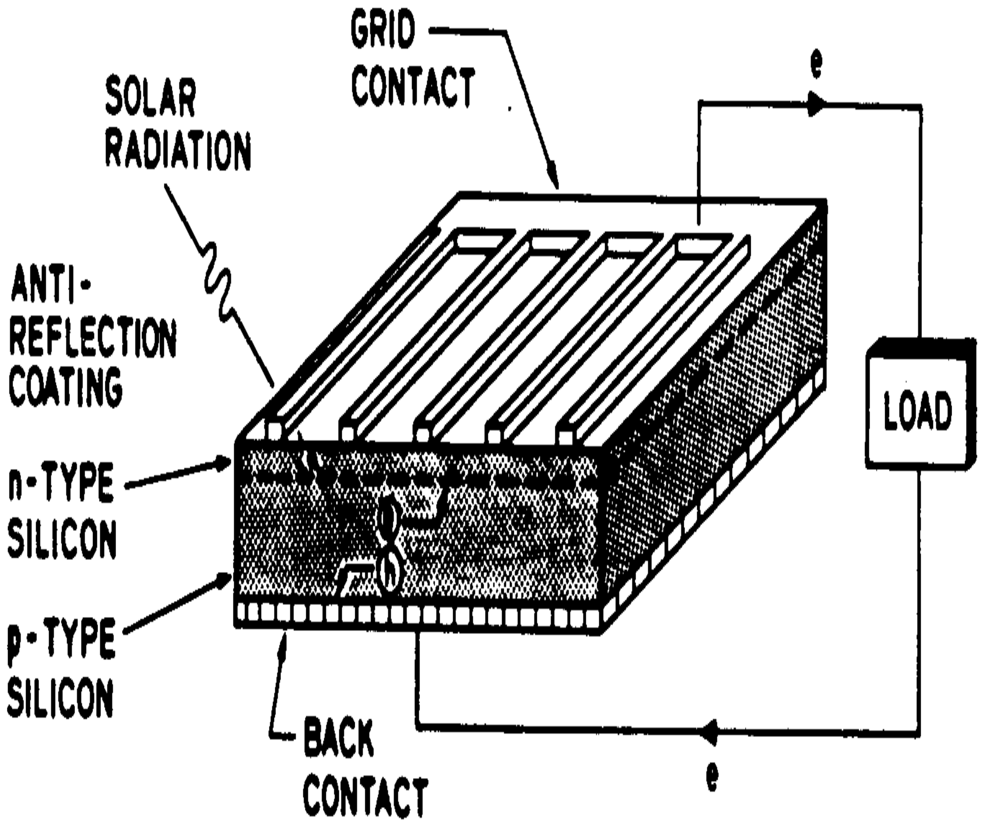

Figure 1. The structure of a solar cell.

Until recently most solar cells were made from single crystal silicon wafers. Crystals, usually 10 cm in diameter, are pulled from ultra-pure molten silicon, then sliced and polished. This process is both costly and wasteful of this expensive, ultra-pure material. The p-n junction is made by diffusing phosphorus (which produces n-type material) into the front surface of a wafer that has been "doped" with boron to make it p-type. Newer techniques use technical-grade silicon cast into blocks, sawed into wafers, and fabricated into cells using the same processes as used in single crystal material. This process is far less expensive and uses considerably less energy to produce the finished cell; about half of the today's large modules are made in this manner. Another approach, still in the pilot plant stage, involves pulling a silicon thin ribbon that does not need cutting into slices. Many other new ideas are being explored with the general aim of producing an efficient, long-lived solar cell at lower cost.

Photovoltaic cells are also manufactured from thin films of amorphous silicon, a glassy material with no regular crystal structure. While this material has proved eminently suitable for small, low-power uses, like solar pocket calculators, amorphous silicon cells cannot yet be used for power generation panels because they become less efficient after a period of exposure to sunlight. In addition, their long-term stability is doubtful. Solar cells should have a useful life of at least 10 years.

Solar cells have also been produced using combinations of different compounds to form the p-n junction. These are called heterojunction solar cells. Copper sulfide/cadmium sulfide cells are inexpensive but their output also tends to degrade too rapidly. Such alternative materials as copper indium selenide offer the promise that a so-called thin-film heterojunction solar cell can be developed. Very efficient but very expensive solar cells can be made from gallium arsenide. They may be marketed as

the active components of devices that focus the solar radiation to reduce the size and number of cells needed.

The output characteristics of a typical photovoltaic cell are plotted in Figure 2. The highest voltage that can be produced by

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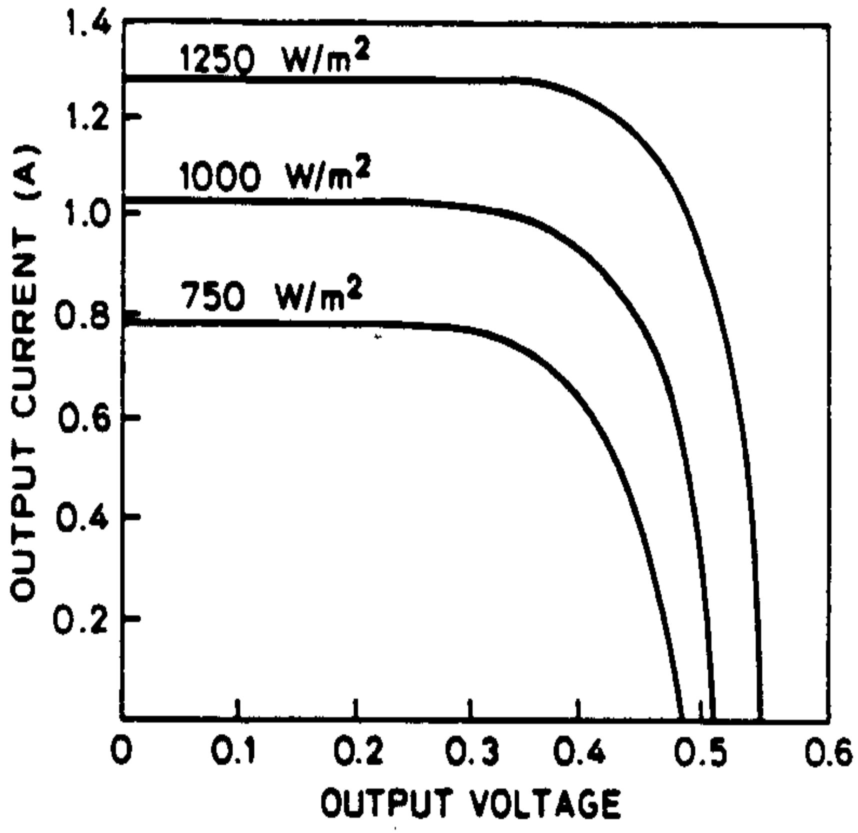

Figure 2. Output of a photovoltaic cell.

a cell is called the open-circuit voltage; this is about 0.55 volts (V) for silicon. As more current is drawn from the cell by the load, the voltage falls. The maximum current that can be drawn from a solar cell, the short-circuit current, is about 300 amperes per square meter in strong sun. For maximum power, a silicon cell should be operated at about 0.45 V (in full sun) and 90% of the short-circuit current. As the intensity of solar radiation falls, the open-circuit voltage falls slowly, but the current falls roughly in proportion to the intensity. Over a daily cycle, the maximum power output is attained when the sun is at its highest and, of course, falls to zero between dusk and dawn. Solar output is reduced on cloudy days, but diffuse sunlight can still produce a useful fraction of full output. Interestingly, a solar cell or module can be shorted or left open circuited indefinitely without being damaged.

The efficiency of a solar cell is defined as the ratio of the electrical power output to the solar power input. The typical efficiency of a PV module is about 10%. This means that when 750 W of sunlight is falling on a square meter of solar array (typical sunlight intensity in most nondesert areas), the solar array would produce 75 W/sq m Solar-cell efficiency tends to fall as the cell temperature rises. This effect can be serious in hot climates where the cell may operate at 50 [degrees] C or even higher. Mounting the cell on an energy-absorbing support (heat sink) will tend to keep the temperature down.

Commercial solar arrays or modules are about 35 by 150 cm and are made with laminated tempered glass fronts and extruded aluminum sides. They can stand temperatures of up to 70 [degrees] C but the plastic laminating material between the cells and the glass cover will yellow with time if exposed to higher temperatures. For higher temperature use, silicon embedding compounds can be used.

SOLAR-CELL SYSTEMS

Since photovoltaic cells give their highest output when pointed directly at the sun, electrical performance can be optimized by putting them on a moving mount that is always pointed toward the sun. Prototype scanning systems are relatively expensive and the motor and sensor systems are more likely to fail than is the solar-cell array. Moreover, the scanning motors consume electricity. One available scanner uses as sensors bulbs filled with Freon, a gas now considered environmentally hazardous. Under present conditions, we recommend a simple, static support. Manufacturers provide advice on the best angle for mounting a solar array in a chosen location but a good year-round guideline is to point the array directly toward the equator, tilting it at an angle equal to your latitude. For example, if you are located at 10 [degrees] south latitude, lift the south edge of the panel until the panel is tilted 10 [degrees] from horizontal.

Hybrid systems, which provide hot water in addition to electricity, have also been investigated. Although they work well for remote homesteads in northern climates they do not seem economically sound in tropical countries where the need for hot water is less urgent. Exceptions are remote clinics, hospitals, or other operations that need a reliable supply of hot water. Even low temperature steam can be made by a properly designed hybrid array. SunWatt Corporation and Alpha Solarco have developed packaged hybrid modules.

Solar cells are usually sold in panels that vary in size but are of standard voltage. Connecting individual cells in series adds the voltages of the individual cells,, while connecting cells in parallel adds their current-carrying capacity. Sixteen volts is a popular choice for a solar panel, because that output voltage is needed to charge a 12-V storage battery.

Storing and Converting the Energy

In some applications, such as the use of photovoltaic cells for pumping water for irrigation, the change in output of the cells through day and night is acceptable since the power is required only for a few hours in each 24-h period. For many applications, however, the solar-cell array should be used together with a battery storage system that can provide continuous power. During peak sunlight hours, the batteries are charged by the solar cells, which produce more power than is required by the load. During the night, the batteries discharge to operate lighting and other loads. Use of a diode is necessary to prevent the batteries from passing reverse current into the solar cells at night, and a voltage-regulating circuit is normally provided on larger systems to keep the batteries from being overcharged by the PV array. Some voltage regulators will also disconnect the load to prevent damage if the battery charge gets too low.

Lead-acid batteries specially developed for photovoltaic-system applications are generally used, but any deep-cycle lead-acid battery may serve if necessary. Automobile batteries are not highly satisfactory for this application because daily charge and discharge cycles greatly shorten their useful life. For some purposes, especially in remote locations, the more expensive nickel-cadmium batteries are preferred since they require less maintenance.

A solar-cell array with battery provides direct current (d.c.), which has many uses. A photovoltaic system for d.c. only is shown in Figure 3. For a simple arrangement of a few lights and a radio

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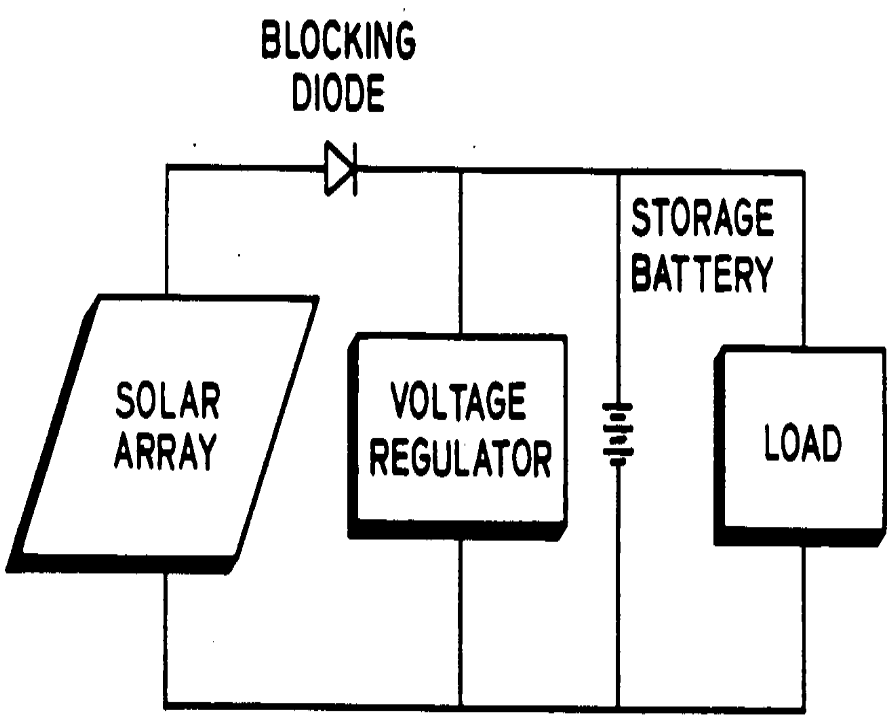

Figure 3. A photovoltaic system for direct current only.

or TV set, this is the preferred system. Incandescent lights for 12 V d.c. are available, and are almost twice as efficient as their 220-V or 110-V counterparts. Small 12-V TV's are very efficient also, and a small, portable radio draws very little power. However, fluorescent lights, refrigerators, etc., designed to operate on d.c. can be very much more expensive than their counterparts that operate from the 220-V or 110-V alternating-current (a.c.) mains in normal industrial and household use. It may therefore be desirable to include an inverter that converts the d.c. supply to the 50 Hz or 60 Hz a.c. needed by these appliances. Some loss of power results from the use of the inverter (at least 10%), but this may be justified if it leads to big savings in the cost of the appliances. Alternatively, the inverter can be used for only the a.c. appliances, while the rest of the load is operated directly from d.c.

Basic Costs

Photovoltaic arrays can now be bought for about $6 to $10 per peak watt. This price has fallen slowly but steadily over the last few years, and is expected to continue to fall. Adding battery storage (and regulator, if needed) adds 50% or more to this cost. The total cost is too high to compete with the local utility rates in most places, but is far cheaper than the installation and operating cost of a petrol or diesel generator. As a guideline, if a power line longer than one km must otherwise be built, PV or PV plus wind-generating systems is a cheaper way to get small to moderate amounts of electricity.

It is believed that photovoltaics will start to be used widely when the price falls to about $2 per peak watt in 1989 prices. At this level, and assuming that whole system costs fall at a similar rate, solar electricity will be competitive with centralized, fossil-fuel generating systems and will be used on a large scale both by utility corporations and by individuals who own rooftop arrays. Even now, solar cells are probably cheaper than diesel generators for most rural applications. And if prices fall as predicted, solar cells could be the most economical electricity source for all applications in remote locations of tropical countries, especially if combined with wind generators (W.J. Bifano 1982).

MEETING ENERGY NEEDS WITH SOLAR CELLS

In the next decade, applications of solar cells in developing countries will probably be mainly in rural villages. Many villages do not have a power line fed by a central grid system; the cost of extending a power grid to serve all villages would be prohibitive in large countries. However, pilot solar schemes are now in progress in most developing countries (W.A. Brainard 1982). See Table 1 for typical village power requirements for a number of activities that can be powered by solar cells.

Solar powered water pumps are increasingly used for irrigation and community water supplies. The outstanding advantage of a pumped system is the ease with which the water supply can be kept free of contamination. From the standpoint of community health, a pump can be the most important investment a village makes.

As an example, Arco Solar Inc., described a portable photovoltaic water supply for the village of Boera, Papua New Guinea (Arco

Solar Inc. 1982). The village has a population of about 1,000, and the system installed produces 440 peak watts, without battery storage. This system delivers about 5,500 liters an hour (L/h) in full sunlight and about 3,300 L/h under overcast conditions. Storage is provided by four tanks each of 5,500 L capacity that are normally filled by midday. The pump is then switched off by a float valve. The villagers pay about $0.01 per bucket of water. A portion of the funds is used by the community to maintain the system.

TABLE I: TYPICAL VILLAGE POWER REQUIREMENTS

Assumptions: 500 people, 100 homes. Sunlight equivalent of 5 hours noonday sun. Source: ref. 3.

APPLICATION ENERGY REQUIRED,
kWh/day

Water pumping (50 L/person-day) 4.7
Lighting - indoor (2 lights/home) 16.0
Lighting - outdoor (5 lights/village) 2.4
Television (20 sets/village) 1.6
Refrigerators (10/village) 10.0
Grain Grinder (1 kg grain/person-day) 6.0
Communications (1 two-way radio set/village) 0.4

Total kWh/day 41.1
Total kW Peak Required 10.7

Water for Drinking and Irrigation

Irrigation for agriculture is probably the greatest consumer of energy in rural areas of developing countries. Animal power and diesel-fueled pumps are the main competing technologies. The quantity of water required for irrigation may range from 5,000 to 13,000 cubic meters per hectare (cu m/ha) over the growing period, or 40 to 110 cu m/ha each day. The required pumping capacity is therefore about 4 to 10 L/second for each hectare, a typical farm being 1 to 3 ha (W.A. Brainard 1982).

As in the case of drinking-water supply, the amount of power required depends on the depth from which the water must be pumped. Usually this is less than 10 m, so the requirement is for a few hundred W/ha. If irrigation is to be economical, the cost of obtaining the water must be less than the value of the increase in crop production. Wright estimated that irrigation is not worthwhile unless the water costs less than about $0.05/cu m (W.A. Brainard 1982). He suggested that photovoltaic systems were two to four times more expensive than their economic yield for irrigation. The break-even point in favorable cases (water depth less than 5 m) probably already has been reached and the number of photovoltaic-powered irrigation systems is likely to expand in the near future.

Irrigation is important not only for food crops but also in the early stages of reforestation. Solar power may contribute to the reversal of deforestation, which has been drastic in such countries as India. Another indirect economic benefit of irrigation is that it may halt, or even reverse, the population shift from the rural villages to the cities by improving the quality of village life. And, according to a recent review, irrigation must increase by 250% over the next 25 years in order to support a growing world population (J.L. Crutcher 1982). Thus, the increased food requirements of world population growth leads to a prediction of increased use of solar cells.

Desalination

Photovoltaic-powered desalination units to produce fresh water from sea water have been installed in Saudi Arabia and Qatar (J.L. Crutcher 1982). They use reverse osmosis, in which the dissolved salt is driven through a membrane. Each liter of drinking water requires 8 to 20 Wh of electricity, which compares favorably with 2.4 kWh for a solar still and 200 kWh for a flash evaporation unit. The unit at Jeddah has been in operation since January 1981 and supplies 2,000 L per day from an 8 kW (peak) array and d.c.-powered pumps. The system does not use a voltage regulator; this raises efficiency but leads to fluctuating waterflow rates and pressures. The Jeddah unit produces water with a salinity of less than 200 parts per million (= 200 mg/L). In the Qatar unit, the salinity is below 500 mg/L: this relaxation in standards permits 6,000 L/day to be achieved from an 11.2 kW (peak) array. Desalination is, in general, economically viable only in relatively affluent communities that have a severe water shortage.

SunWatt Corporation has demonstrated a small PV/hybrid desalinator, based on evaporation and condensation cycles, that produces fresh water and electricity at the same time. However, production of such a machine on a commercial scale requires more research.

Refrigeration

PV-powered refrigerators for medical supplies, have become a regular component of pilot village schemes. Refrigerators that operate on d.c. are available, and it is also possible to buy a refrigerator with its own independent photovoltaic panel. The reliability of solar-cell systems is vitally important when storing vaccines and other medical supplies that would deteriorate rapidly if not kept cool. A typical refrigerator requires about 300 peak watts and consumes about 1 kWh/day. Experience with 20 refrigerator systems in different countries has shown that the units now available require very little maintenance except of the power supply itself (G.F. Hein 1982).

Flour Milling

The performance of a solar-powered grain mill at Tangaye in Burkina Faso has been well documented. The mill began operation in March 1979. The 1.8 kW solar array was used to mill grain for 600 families, relieving the village women of a daily one-to two-hour task. The early modules were not very reliable, but by 1982 the original system worked well 98% of the time (D. Elwell 1981). No problems of maintenance or operation were reported. The

system was increased in size in May 1981 to 3.6 kW, and an improved hammer mill was installed. By 1982, the mill was grinding 1.2 tons of flour per week and the cooperative that runs the mill demonstrated a small operating profit.

Lighting and Communications

Incandescent or the more efficient fluorescent lighting can greatly improve communal village life by providing increased opportunities for meetings and social events in the evenings. Battery storage is essential if lighting is included in a scheme. The price of the lights and the greater efficiency of d.c. should be compared with cheaper ballasts for a.c. fluorescent lights before deciding whether to buy an inverter; the inverter may be the component with the greatest cost and lowest reliability.

Because they require comparatively little power, television sets can be operated by solar cells. The value of TV in rural education is well documented in many locations, starting in 1976 with Cote d'Ivoire and India.

An emergency radio set is a useful addition to a village and has been included in the development plans of some countries. The Mexican government has installed a solar-powered, rural telephone station, and solar-powered telephones have also been used in Saudi Arabia. Solar power was preferred for a microwave communications link in Papua New Guinea. Telecommunications terminals and data-processing microcomputers can also be operated by solar cells. VITA has installed solar-powered packet radio systems where the computers communicate with each other via radio, in remote areas of Sudan and the Philippines. This paper was prepared, in part, in a remote U.S. location on a solar-powered word processor operating through a 2-kW inverter. These examples illustrate the variety of ways that solar cells can be used in communications in remote locations. As in other applications, the reliability of solar cells is their main advantage.

Local Industries

Can PV arrays assist the development of small industries? One recent review specifically covered small, rural manufacturers, in Mexico and the Philippines, employing fewer than 50 people and producing simple consumer products. Most industries were found to require too large an investment in photovoltaics to be economically viable at present. However, viable possibilities do exist in some industries that use small power tools.

Among small industries, an interesting possibility is the local manufacture of photovoltaic modules themselves. Small-scale, labor-intensive plants can make modules from purchased cells. They can even make the cells, from industrial grade silicon, using recently developed fabrication techniques. A VITA Volunteer recently helped set up the first factory in Africa to produce PV panels. Using purchased cells, the Moroccan plant turns out 100 panels per week. In plants like this, the economics of using a few extra workers to replace a large capital investment in automated equipment are very favorable. A detailed analysis of a 500-kW PV plant now being planned for India showed how 11 extra production workers can displace about $800,000 of capital investment. Small solar-cell modules to charge batteries for portable lights, radios, and other small electric appliances can be made in even simpler shops; it can be done on a village level.

Three relatively small-scale plant models at different levels of production are proposed below. Cost equivalents are for illustration and should not be used for planning.

o A small shop producing 5-W to 10-W solar battery chargers.

Solar cells, plastic for cases, etc., are purchased.

Output: 2,000 chargers per year, 8 per working day.

Personnel: 1 to 2 persons.

Capital: $25,000 startup, $32,000 per year material cost.

o Labor-intensive factory making 40-W, laminated PV modules.

Solar cells, glass, and other supplies are purchased.

Output: 1/2 Megawatt (MW) in modules per year (12,500 modules, 50 per day).

Personnel: 18 production workers.

Capital: $250,000 startup, $2,000,000 per year materials cost.

o Plant making solar cells from industrial grade silicon.

Using cheaper grade silicon, the plant casts polysilicon shapes, cuts them into square wafers, dopes them, adds metal contacts, etc.

Output: 1 MW per year (1,000,000 wafers, 4000 per day).

Personnel: 20 workers (6 highly skilled).

Capital: $2,500,000 startup, $3,000,000 per year operating.

SOME CRITICAL COMPARISONS

At present, photovoltaics cannot compete with centrally generated electricity except when power lines must be installed over long distances. They are therefore most likely to be applied in rural locations, especially in villages. Their flexibility in use, in large or small arrays, is a major advantage since a system can be carefully tailored to the specific application and expanded as needed. In comparing the cost-effectiveness of solar and diesel systems, particular or local economic factors may be decisive, even when maintenance costs and reliability are taken into account. Failure problems with the earliest modules appear to have been solved; thus, wind power is the only serious competitor of PV devices as a renewable source of electricity. An alternative that should also be seriously considered is solar thermal power.

Hot water or gas can be used to drive a Stirling engine, for example in irrigation, and some engineers argue that this is currently the most effective method. Refrigerators and air conditioners can also be driven by warm water, but need small electrically powered pumps. Here as elsewhere, one must choose from many alternatives the one that offers the best combination of cost and effectiveness.

The choice of solar cells or wind generators for electricity depends on the location. However, it is likely that a combination of these will become the major source of electricity in areas that are not supplied with a central grid that distributes, for example, hydroelectric or geothermal energy. The cost of solar cells is still high and there are few applications in which a strong economic benefit can be demonstrated to justify their introduction. However, there is no doubt that solar arrays can greatly improve the quality of rural village life. The next decade should see a great expansion in solar-cell utilization as prices fall to the predicted $1 to $2 per peak watt.

Ideally, developing countries can follow the lead of India, Morocco, and Mexico by starting to develop their own capacities for solar-cell production. Thus, a country can begin now to develop technological capabilities in a field where future demand seems certain.

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MANUFACTURERS

The main U.S. suppliers of photovoltaic modules and related equipment are listed below:

Alpha Solarco, 11534 Gondola Drive, Cincinnati, Ohio 45241

Arco Solar Inc., P.O. Box 4400, Woodland Hills, California 91365

Photocomm Inc., 7861 East Gray Road, Scottsdale, Arizona 85260

Solarex Corp., 1335 Piccard Drive, Rockville, Maryland 20850

SunWatt Corporation, RFD Box 751, Addison, Maine 04606

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