

PHOTOVOLTAICS: UNLIMITED ELECTRICAL ENERGY FROM THE SUN

Bulk electrical power generation using the available solar energy of a kilowatt per square meter will occur when photovoltaic cells decline in price below 10 cents per kilowatt-hour.

Jack L. Stone

The first practical solar cell was developed at Bell Laboratories¹ in 1954. With the advent of the space program, photovoltaic cells made from semiconductor-grade silicon quickly became the power source of choice for use on satellites. The systems were very reliable, and cost was of little concern. In the early 1970s, the disruption of oil supplies to the industrialized world led to serious consideration of photovoltaics as a terrestrial power source. This application focused research attention on improving performance, lowering costs and increasing reliability. These three issues remain important today even though researchers have made extraordinary progress over the years. This article details that progress.

What is photovoltaics?

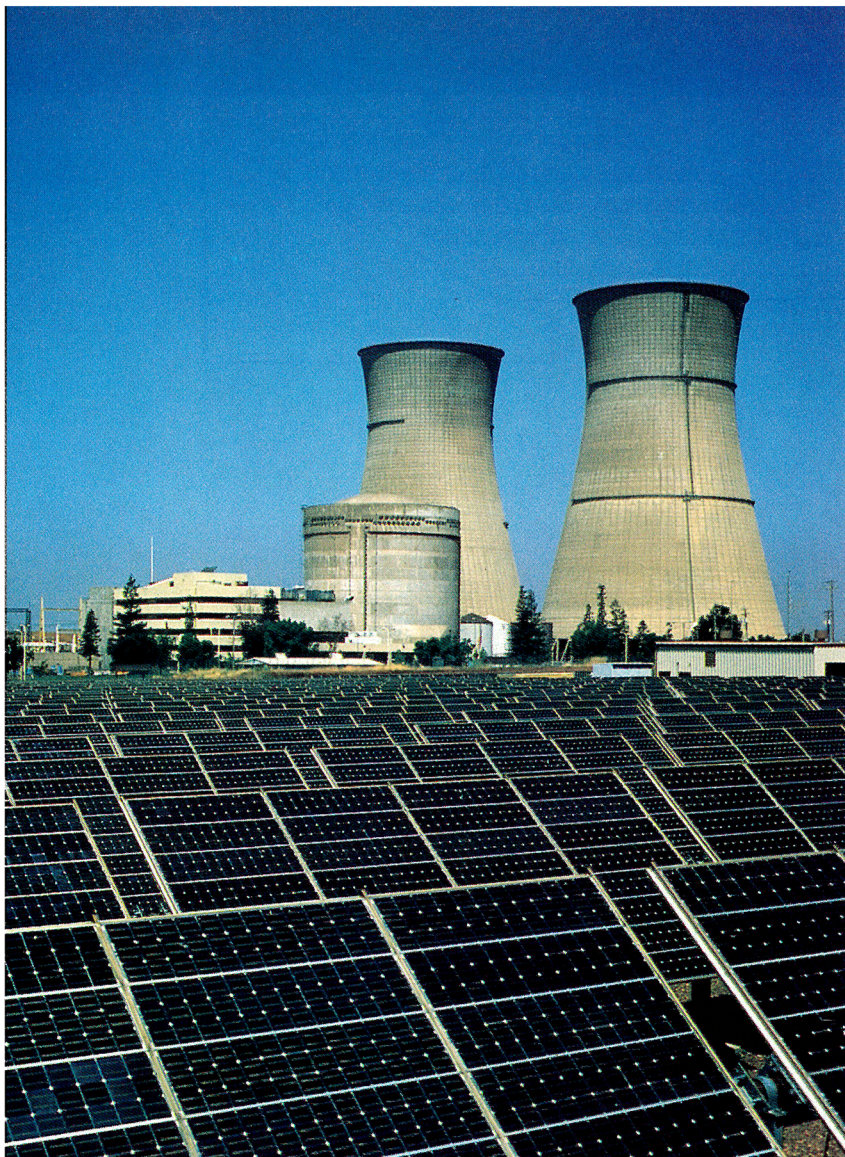
Photovoltaics is a high-technology approach to converting sunlight directly into electrical energy. The electricity is direct current and can be used that way, converted to alternating current or stored for later use.

Conceptually, in its simplest form a photovoltaic device is a solar-powered battery whose only consumable is the light that fuels it. There are no moving parts; operation is environmentally benign; and if the device is correctly encapsulated against the environment, there is

nothing to wear out.² Because sunlight is universally available, photovoltaic devices have many additional benefits that make them usable and acceptable to all inhabitants of our planet. Photovoltaic systems are modular, and so their electrical power output can be engineered for virtually any application, from low-powered consumer uses—wristwatches, calculators and small battery chargers—to energy-significant requirements such as generating power at electric utility central stations (see figure 1). Moreover, incremental power additions are easily accommodated in photovoltaic systems, unlike more conventional approaches such as fossil or nuclear fuel, which require multimewatt plants to be economically feasible.

To understand the many facets of photovoltaic power, one must understand the fundamentals of how the devices work. Although photovoltaic cells come in a variety of forms, the most common structure is a semiconductor material into which a large-area diode, or p-n junction, has been formed. The fabrication processes tend to be traditional semiconductor approaches—diffusion, ion implantation and so on. Electrical current is taken from the device through a grid contact structure on the front that allows the sunlight to enter the solar cell, a contact on the back that completes the circuit, and an antireflection coating that minimizes the amount of sunlight reflecting from the device. Figure 2 is a schematic depiction of a rudimentary solar cell that shows the important features.

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New and old sources of energy in Sacramento, California. In the foreground is the Sacramento Municipal Utility District's 2-megawatt photovoltaic power plant, which was constructed in two stages (1984 and 1986). The cooling towers in the background are from the now closed Rancho Seco nuclear generating station. **Figure 1**

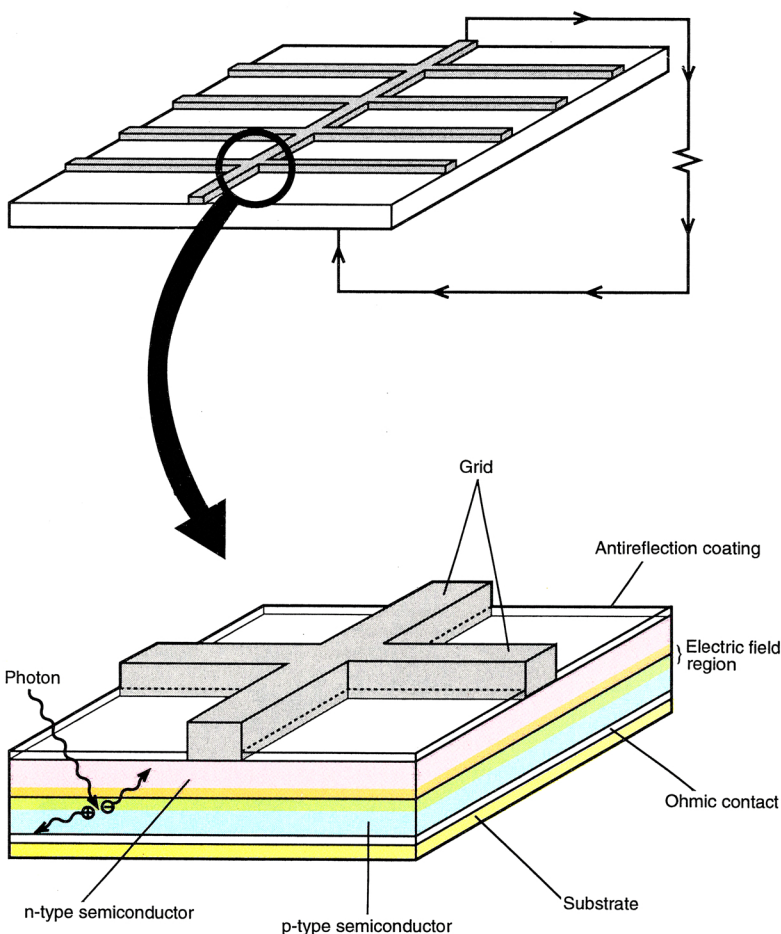
The fabrication of the p-n junction is key to successful operation of the photovoltaic device (as well as other important semiconductor devices). We will assume that the semiconductor material is single-crystal silicon. Although photovoltaic technologists today use many other varieties of semiconductors, crystalline-silicon concepts represent a reasonable compromise for this discussion because they are well known and understood by physics students.

Silicon is representative of the diamond crystal structure. Each atom is covalently bonded to each of its four nearest neighbors; that is, each silicon atom shares its four valence electrons with the four neighboring atoms, forming four covalent bonds. Silicon has atomic number 14, and the configuration of its 14 electrons is $1s^2 2s^2 2p^6 3s^2 3p^2$. The core electrons, $1s^2$, $2s^2$ and $2p^6$, are very tightly bound to the nucleus and, at real-world temperatures, do not contribute to the electrical conductivity. At absolute zero, as N silicon atoms are brought together to form the solid, two distinct energy bands are formed—the lower, “valence” band and the upper, “conduction” band. The valence band has $4N$ available energy states and $4N$ valence electrons and is therefore filled. Conversely, the conduction band is completely empty at

absolute zero. Thus the semiconductor is a perfect insulator at absolute zero.

As the temperature of the solid is raised above absolute zero, energy is transferred to the valence electrons, making it statistically probable that a certain number of the electrons will be raised in energy to such an extent that they are free to conduct electrical charge in the conduction band. These electrons are called intrinsic carriers. The amount of energy necessary to bridge the valence and conduction bands is referred to as the forbidden gap or energy gap E_g , which is 1.12 eV at room temperature for silicon. Even at room temperature, however, the amount of conductivity is still quite small. At 300 K there are 1.6×10^{10} intrinsic carriers per cubic centimeter; thus the material is still a very good insulator compared with a metal, which has approximately 10^{22} carriers per cubic centimeter.

To modify the conductivity to more useful values, one must introduce small controlled amounts of impurities into the host materials. By substituting, or “doping,” the silicon, which is in column IV of the periodic table, with either column-III materials (boron, aluminum, gallium or indium) or column-V materials (phosphorus, arsenic or antimony), one can increase and control precisely the



Schematic diagram of a rudimentary photovoltaic cell. The cell is a diode in which light generates the electromotive force. **Figure 2**

number of conduction band electrons or valence band holes (deficiencies of electrons).

A column-V dopant completes the covalent bond and leaves an additional, loosely bound electron that can be transferred to the conduction band by an energy of about 40–50 meV, termed the ionization energy. Column-III impurities leave the covalent bond deficient of one electron (that is, with a hole). An electron from the valence band can transfer to the empty site and satisfy the bond requirement. In effect the hole moves, because the transferred electron leaves behind a hole. The amount of energy required to thus place the hole in the valence band ranges from 45 to 160 meV.

By varying the density of the doping impurities, one can design the silicon to range from a poor conductor of electricity to a near-metallic conductor. Silicon that has been doped with column-III elements is called a p-type semiconductor; that doped with column-V elements is called an n-type semiconductor.

The p-n junction diode

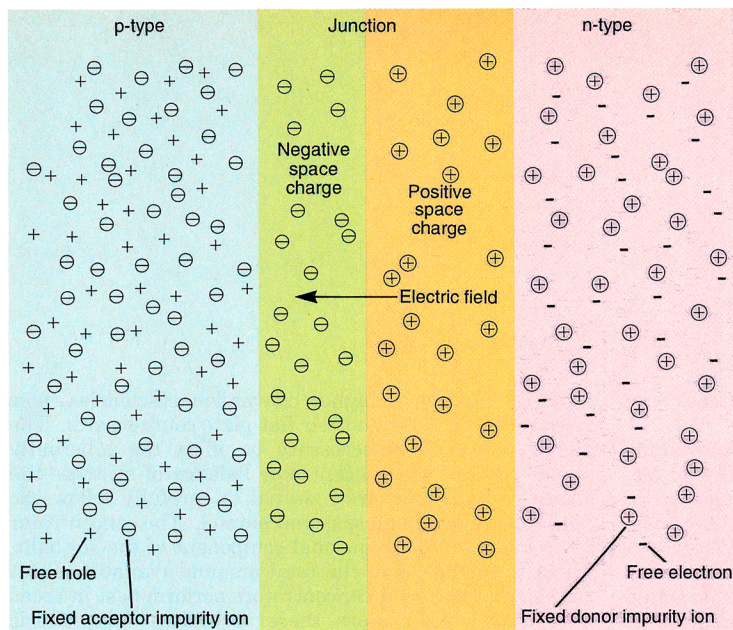
When a uniform p-type sample is metallurgically joined to a uniform n-type sample, the configuration produces the all-important p-n junction. Instantaneously the positive and negative electrical charges redistribute, establishing internal electric fields that determine, in part, the properties of the semiconductor diode. At the instant of formation, there exist on the n side, extending to the junction, uniform concentrations n_{n0} of mobile free elec-

trons and p_{n0} of mobile free holes. On the p side there exist uniform concentrations p_{p0} of mobile holes and n_{p0} of free electrons, also extending to the junction. The concentrations satisfy the relation

$$n_{n0} p_{n0} = n_{p0} p_{p0} = n_i^2$$

Here n_i is the intrinsic-carrier concentration at the given temperature of the material.

At the instant of junction formation, the concentration of electrons is much larger on the n side than on the p side. An analogous condition applies to the hole concentrations, which are larger on the p side than the n. The large difference in carrier concentrations sets up an initial diffusion current: Electrons flow from the n region into the p region, and holes flow from the p region into the n region. This flow of charge results in a region near the junction that is depleted of majority carriers—that is, of electrons on the n side and of holes on the p side. The fixed donor and acceptor impurity ions in this depletion region are no longer balanced by the free charges that were there. As a result, an internal electric field builds up with a direction that opposes further flow of electrons from the n region and holes from the p region. The magnitude of the field is such that it exactly balances the further flow of majority carriers by diffusion. The region around the junction is depleted of majority carriers, and a space-charge layer forms in the region of high electric fields, as shown in figure 3. Thus in the absence of externally



Junction region. Space-charge layers and an internal electric field form as a result of diffusion of majority carriers near a p-n junction to the region of opposite conductivity. (Adapted from J. P. McKelvey, *Solid State and Semiconductor Physics*, Harper & Row, New York, 1966; used by permission.) **Figure 3**

applied potentials, no current will flow.

Contact can be made with the two ends of the p-n junction to form a two-terminal device. A positive voltage applied to the p side relative to the n side encourages current flow across the junction. Conversely, a negative voltage applied to the p side relative to the n side further discourages current flow relative to the zero-voltage case. The former condition is referred to as forward bias and the latter as reverse bias. These two conditions can best be described in terms of the ideal-diode equation:

$$I = I_0 [\exp(qV/kT) - 1.0]$$

Here I is the external current flow, I_0 is the reverse saturation current, q is the fundamental electronic charge of 1.602×10^{-19} coulombs, V is the applied voltage, k is the Boltzmann constant, and T is the absolute temperature. Under large negative applied voltage (reverse bias), the exponential term becomes negligible compared to 1.0, and I is approximately $-I_0$. I_0 is strongly dependent on the temperature of the junction and hence on the intrinsic-carrier concentration. I_0 is larger for materials with smaller bandgaps than for those with larger bandgaps. The rectifier action of the diode—that is, its restriction of current flow to only one direction—is key to the operation of the photovoltaic device.³

If light is allowed to impinge on a p-n junction device, the equilibrium conditions of the device are disturbed. Minority carriers—that is, electrons in the p material and holes in the n material—are created in sufficient quantities to lower the potential energy barrier at the junction, allowing current to flow and establish a voltage at the external terminals. The availability of current and voltage produces usable power.

As shown in figure 4, the photovoltaic device can be modeled as an ideal diode in parallel with a light-induced current generator I_L , whose magnitude is a function of the generation of electron-hole pairs by the absorption of incoming light and the collection efficiency for these charge carriers. The current and voltage characteristics are modified by light to

$$I = I_0 [\exp(qV/kT) - 1.0] - I_L$$

There will be resistive losses due to series and shunt

resistance. A current-voltage diagram, like that in figure 5, characterizes the important operational parameters of the cell, among which are the short-circuit current I_{sc} , the open-circuit voltage V_{oc} , and the current and voltage at the maximum power point (I_{mp} and V_{mp} , respectively). The maximum power output is simply the product of I_{mp} and V_{mp} . However, various effects modify this amount of power by a term called the fill factor FF, defined as

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$$

For practical photovoltaic cells, the fill factor ranges from approximately 0.70 to 0.85. For a typical single-crystal silicon solar cell, we find, approximately, that $V_{oc} = 0.58$ V, $J_{sc} = 35$ mA/cm² and FF = 0.8. Thus a 100-cm² cell is capable of producing approximately 1.6 watts. Most practical applications would require more power. Fortunately, one can increase the voltage by adding more cells in series, and one can increase the current by wiring more cells in parallel.² As mentioned earlier, this modular nature of photovoltaic cells allows us to design systems to meet power requirements from a few watts to many megawatts. More importantly, one can make the additions incrementally, if required.

The solar resource

To determine how a given photovoltaic system will operate at a given geographic location, one must obtain a detailed characterization of the solar resource.

Earth's source of solar radiation—the nuclear fusion reactor 151 million kilometers from us—provides a bountiful, inexhaustible source of energy. On a typical land area on Earth, approximately 1000 W/m² of energy from photons is available for conversion into electrical power at solar noon. The solar radiation is reduced from the level outside Earth's atmosphere as a result of absorption by such gases as CO₂, water vapor and ozone. Before these various absorptions occur, the radiation above Earth's surface is 1367 W/m², defined as AM0, or air mass zero. On Earth's surface, when the Sun is directly overhead, the radiation that makes it through a cloudless atmosphere is labeled AM1. (In general, the air mass

number is $1/\cos \theta$, where θ is the angle of the Sun measured relative to overhead.)

To put all of this into perspective,⁴ a photovoltaic generating station 140×140 km in area at an average US location could generate all the electricity needed in the US (2.5×10^{12} kW-h/yr), assuming a system efficiency of 10%, a balance-of-systems efficiency of 81% and a system packing factor of 50%. Thus although the solar resource is dispersed in area, it is ample in reasonably small areas to provide whatever amount of photovoltaic power is required. Obviously, because the Sun does not shine at all times in any one location on Earth, some practical means of energy storage also is needed.

Semiconductor materials used to fabricate solar cells are sensitive to the color of the sunlight. In addition, certain materials absorb sunlight more effectively than others. Materials such as gallium arsenide and amorphous silicon are extremely efficient absorbers; thus only thin layers of such materials are needed to produce the same amount of power that a thicker layer of a material such as crystalline silicon would produce. (The thickness ratio is about 500:1 for silicon compared with amorphous silicon.) Because the amount of required material differs, the cost depends on the type of semiconductor used.

Another variable in choosing a semiconductor material is its bandgap, the energy required to raise a carrier from the valence band to the conduction band. The larger the bandgap, the more energy is required from the impinging light. Sunlight is made up of a continuum of colors, and much of it either will be too low in energy to produce free electrons and holes or will be too energetic and thus produce only wasteful heat in the material. Silicon, with a bandgap of 1.12 eV, can effectively use only the wavelengths in the range of about 0.4–1.1 microns.

More complex photovoltaic devices can use more of the spectrum. Multijunction solar cells operate at higher efficiencies than the more conventional, single-junction devices. As the junctions are connected in series, the current of each junction must match; hence the device current will be determined by the lowest junction current.

An additional consideration is whether the photovoltaic modules will be of the flat-plate or concentrator configuration. The most common photovoltaic systems employ flat-plate modules, which are either mounted so that they are fixed with respect to the Sun or tracked on one or two axes to follow the Sun during the day or during seasonal variations. In either case, flat-plate systems use both the normal and diffuse components of sunlight.

Concentrators use lenses or mirrors to focus the sunlight onto a smaller-area solar cell. Magnification ratios of 10–100 $\times$ (small to medium range) and 100–1000 $\times$ (high concentration) are common. Concentrator cells

typically operate at higher conversion efficiencies (now greater than 30%) than their flat-plate counterparts. The higher efficiency is necessary to offset the inherently higher costs of the concentrator balance of system—the lenses and the trackers required to carefully follow the Sun in its diurnal and seasonal motion. The concentrator devices use the direct-normal component of the sunlight, which is smaller than the total amount available to flat plates. Furthermore, concentrators perform best in areas with clear skies, where there is limited atmospheric interaction with the sunbeam—areas such as the desert in the southwestern US.

Performance efficiency

The figure of merit for solar cell performance is the conversion efficiency η , defined as

$$\eta = \frac{V_{mp} I_{mp}}{P_{in}}$$

Here V_{mp} and I_{mp} are again the voltage and current, respectively, at the point of maximum power. The input power P_{in} is

$$P_{in} = A \int_0^{\infty} F(\lambda) (hc / \lambda) d\lambda$$

Here A is the device area, $F(\lambda)$ is the number of photons per square centimeter per second per unit bandwidth incident on the device at wavelength λ , and hc/λ is the energy of each photon. The power output is given by

$$P_{out} = V_{mp} I_{mp} = FF V_{oc} I_{sc}$$

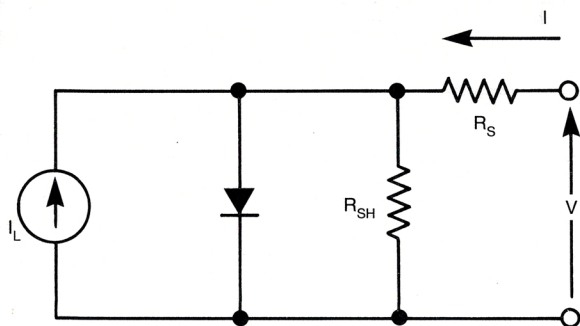
where the fill factor FF is given approximately by

$$FF \approx \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1.0}$$

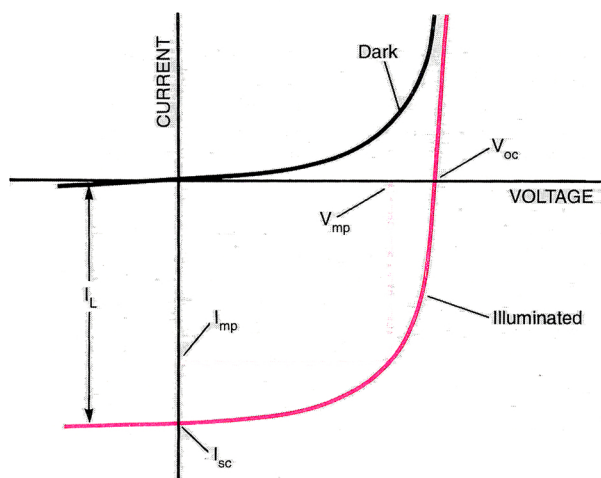
with

$$v_{oc} = V_{oc} \frac{q}{nkt}$$

where n is the diode ideality factor. Hence, the fill factor is only one factor in defining² the open-circuit voltage V_{oc} . The conversion efficiency η is simply P_{out}/P_{in} . One can calculate the maximum theoretical efficiency for a variety of semiconductor materials.⁵ Because the short-circuit current and open-circuit voltage vary in opposite directions as a function of bandgap (I_{sc} decreases with increasing E_g , and V_{oc} increases with increasing E_g) and the fill factor follows V_{oc} , the efficiency will exhibit a maximum value, occurring at a bandgap of approximately 1.5 eV. Using reasonable device parameters for single-junction solar cells, one calculates a maximum theoretical efficiency of 29%.



Generator as a model for a photovoltaic cell. A photovoltaic device can be modeled as an ideal diode in parallel with a current generator. The current is a function of the generation of electron-hole pairs by the absorption of incoming light and the collection efficiency for these charge carriers. **Figure 4**



Current-voltage curves for a p-n junction diode in the absence of light and when illuminated. (Adapted from ref. 2; used by permission.) **Figure 5**

Because of its importance for describing and comparing the performances of photovoltaic devices, efficiency must be measured carefully. In the past, and to a certain extent even today, efficiency results have been controversial. The most important factor affecting the accuracy of the efficiency measurement is the light source used to illuminate the cell. One typically uses a light source that has a carefully controlled spectrum. (AM1.5 has been chosen as the standard for flat-plate measurements.) This so-called solar simulator must be accurately duplicated by each group hoping to make the measurement, or critical correction factors must be applied that take into account a number of factors characterizing the differences in spectral quality among the various solar simulators.

For each photovoltaic material the simulator must duplicate what the cell experiences in the real world under natural sunlight. Control solar cells, or standards, can be very helpful in correcting for the material differences. Additionally, one must accurately know and be able to duplicate from measurement to measurement the intensity of the light and the junction temperature. Another critical factor in determining the accuracy of an efficiency measurement is the definition of the area of the cell, as the short-circuit current measurement is strongly dependent on the cell area. Much discussion has gone into determining whether the total area, the active area or the aperture area should be used. The active area is used only with small, laboratory-scale devices. Aperture and total-area standards are used with commercial-sized cells and modules.

Solar cell materials

Single-crystal silicon has been the material of choice for

high-performance, highly reliable solar cells since the successful deployment of silicon photovoltaic systems for space power. Most of the terrestrial photovoltaic power systems sold today are also crystalline silicon. The need to lower the cost of terrestrial photovoltaic power has focused research efforts on alternative materials as well as on less expensive means of producing solar-grade silicon.

Crystalline silicon is made by growing large cylindrical single crystals, called boules. The boules are sliced into thin wafers, from which photovoltaic devices are made. Slicing is an expensive and material-wasteful process. Several approaches have been investigated to minimize the cost of the original silicon material and to eliminate the slicing step.

A less expensive material, polycrystalline silicon, bypasses the expensive and energy-intensive crystal growth process. The molten silicon is instead cast directly into either cylindrical or rectangular ingots. The polycrystalline material has a large number of crystallites separated by grain boundaries. The material has poorer crystalline quality, and light-induced electron-hole pairs can recombine at the grain boundaries without producing current in the external circuit. Although polycrystalline materials result in less efficient solar cells than crystalline silicon, they are sufficiently cheaper that they are commercially viable. The cast material must still be sliced, however, leading to a loss of about half of the material. Improvements in sawing techniques such as multiple-wire saws continue to reduce the loss in producing thinner wafers.

Another approach to producing less costly materials is to avoid most of the sawing altogether. Several techniques that produce silicon in sheet form have been

developed. The first commercial success was the edge-defined film-fed growth (EFG) ribbon process, in which polycrystalline silicon is grown by extracting the crystallizing silicon melt through a graphite die. By this technique, thin ribbons of polycrystalline silicon can be grown either as multiple separate ribbons or as polygons of material that can be separated into silicon blanks for fabrication into finished solar cells with minimal loss of material. An alternative approach has been to grow the ribbon from parallel supporting dendrites (like a soapy water film grown between wires). By carefully controlling the thermal profiles, one can grow a film of nearly single-crystal material. Other techniques, such as horizontal ribbon growth and spin casting, have also been demonstrated. Regardless of the approach, ultimately the cost of silicon solar cells will depend on the starting material.

The lowest-cost approach would be to minimize the required amount of semiconductor material. Thin films have been developed that are only a few micrometers thick. Such films are produced by a number of vapor-deposition approaches carried out with in-line, highly automated systems. The techniques are adaptable to a number of semiconductor materials that are optimized for solar cell operation. It has been shown that silicon, with its bandgap of 1.12 eV, is not optimal. Materials with bandgaps nearer to 1.5 eV, such as GaAs and CdTe, have higher theoretical efficiencies. Thin films are cheaper than crystalline structures but typically have lower efficiencies. Ultimately, however, thin films will be necessary for producing low-cost electricity, because the bottom line—the cost per watt—is more important than the efficiency.

Performance characteristics

Because of the ever changing nature of photovoltaic technologies, the following discussion of state-of-the-art efficiency results should be taken as representative, not absolute. The numbers quoted have been measured under exacting conditions at the National Renewable Energy Laboratory and hence are good for comparisons.⁶ Standard reporting conditions used for terrestrial flat-plate device measurements are 1000 W/m² total irradiance, ASTM E892 or IEC 904 AM1.5 global spectrum and 25 °C device temperature.

The highest-efficiency single-junction solar cells are made from crystalline silicon and GaAs. Silicon cells of 23% efficiency and GaAs cells of 25% efficiency have been confirmed. When the same materials are used in concentrator applications, the efficiencies increase to 28% and 29%, respectively. The highest efficiency that has been confirmed is 34% for a GaAs–GaSb stacked cell operating at 100-Suns concentration—light concentrated

to an intensity 100 times that of ordinary sunlight. For 1-Sun conditions, the efficiency of polycrystalline silicon is approximately 18%; that of cells made using the edge-defined film-fed growth-ribbon process, 14%; and that of dendritic web cells, 15.5%. (Dendritic web cells are built from single-crystal films grown between two dendritic seed crystals.)

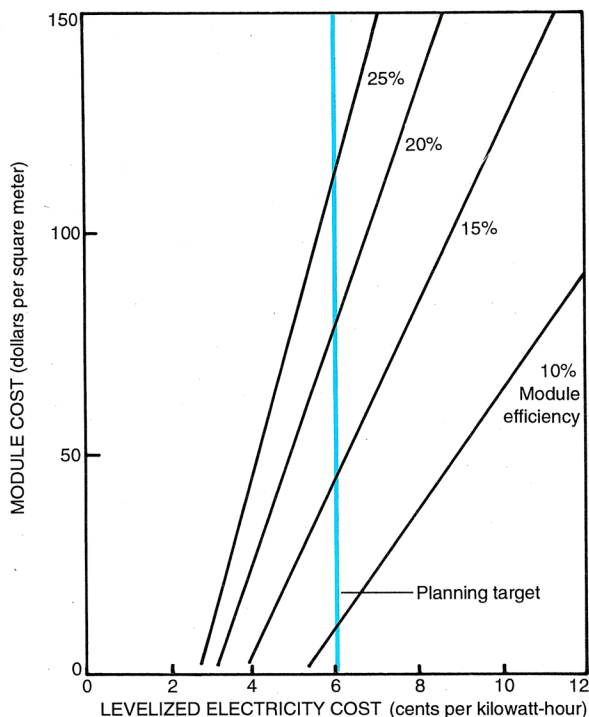
The highest thin-film cell efficiency has been confirmed at 15.8%, for cadmium telluride. Thin films of silicon on ceramic substrates have yielded efficiencies of 15.7%; copper indium diselenide, 12–13% (almost 16% has been achieved by the addition of gallium); and amorphous silicon, 12% before light soaking (amorphous silicon efficiencies fall off for a time before stabilizing). Research continues, and efficiency increases are expected in all materials.

Economics of photovoltaics

For photovoltaics to be widely used, the costs must be competitive with those of conventional forms of electricity. In the US, the average price for electricity is 6–7 cents per kilowatt-hour. Today photovoltaics generate electricity at 20–30 cents per kilowatt hour; therefore the costs must come down by about a factor of 5 to compete in the bulk electricity market.

A number of factors influence photovoltaic energy costs. Foremost are the module efficiency, lifetime and cost per unit area. The US Department of Energy chose a target of 6 cents per kilowatt-hour for its terrestrial photovoltaic program.⁷ Figure 6 indicates the interrelationships of cost and module efficiency that lead to specific electricity costs, given a 30-year lifetime for the module and making a number of economic assumptions. From these curves it is clear that lower-efficiency modules have to cost less than higher-efficiency modules to produce the same cost of electricity. Hence there is a premium on higher efficiency. Similar curves exist for concentrator systems, but higher efficiencies are required to offset the higher balance-of-system costs associated with the necessary lenses or mirrors and Sun trackers. In both cases, efficiency can be traded off against area-related costs (such as land, wire and support structure) to achieve the same cost of electricity.

The annual worldwide commercial production of photovoltaics amounts to about 60 MW, divided approximately equally among the US, Japan and the European Community. Most of the markets are of the high-value variety—that is, markets where today's photovoltaic systems are competitive with traditional ways of providing electrical power. These applications are largely remote from the electrical grid, serving such needs as water pumping, remote communication, refrigeration, signal lights, emergency lighting, pipeline corrosion protection



Module costs and efficiencies as a function of 30-year levelized (adjusted for inflation) electricity costs for fixed flat-plate photovoltaic systems. **Figure 6**

and village power. The competition typically is with diesel generators and with extension of electrical transmission lines. The cost of grid extension is such that if a power requirement lies more than about half a kilometer from the electrical line, photovoltaics will be cost-effective compared with line extension.

As the cost of photovoltaic systems declines, the number of cost-effective applications increases. The ultimate application, bulk electrical power generation, is expected to occur within the next 10 to 20 years, when photovoltaics decline in price below about 10 cents per kilowatt hour. Various utility niche markets are expected to grow before these large-power markets do.

Market growth will be tied to the continuing decline in photovoltaic costs relative to conventional supplies. The industry will need to build larger, more cost-effective production plants that take advantage of available economies of scale. Investment in these new, large plants will require identification of sustainable markets. Many high-value applications taken together, including international rural electrification projects, could provide the necessary market pull.

The electric utilities in the US will require extensive field experience with photovoltaic systems before they will commit to large investments in power plants. Operation and maintenance data, as well as reliability data, are absolute necessities for making the technology credible with the utilities. The process of obtaining such data has begun at the Photovoltaics for Utility-Scale Applications (PVUSA) project in Davis, California, and other cities. Through this large, evolving utility-connected photovoltaic demonstration project a national public-private partnership is assessing and demonstrating the viability of utility-scale pho-

tovoltaic generating systems.

Several other grid-connected installations are undergoing evaluation by City of Austin Power and Light in Texas (300 kW), by the Sacramento Municipal Utility District in California (2.4 MW) and by the 3M Company's research center in Austin, Texas (a 300-kW concentrator system). Validation in such actual utility operating environments is the first step for utilities in defining the value of photovoltaics in their systems.

Future

The demonstration of higher performance, lower cost and better reliability in today's photovoltaic systems is leading many different end users to assess the value of these systems for their particular applications. Aggregation of these applications will lead industry to commit to larger, more cost-effective production facilities, leading to yet lower costs. Public demand for environmentally benign sources of electrical energy will hasten adoption of photovoltaics. How quickly these adoptions occur will be dictated by the economic viability of photovoltaics with respect to the competing options. It is no longer a question of if, but of when and in what quantity, photovoltaic systems will gain adoption. Clearly the energy system of the future has become today's consideration.

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