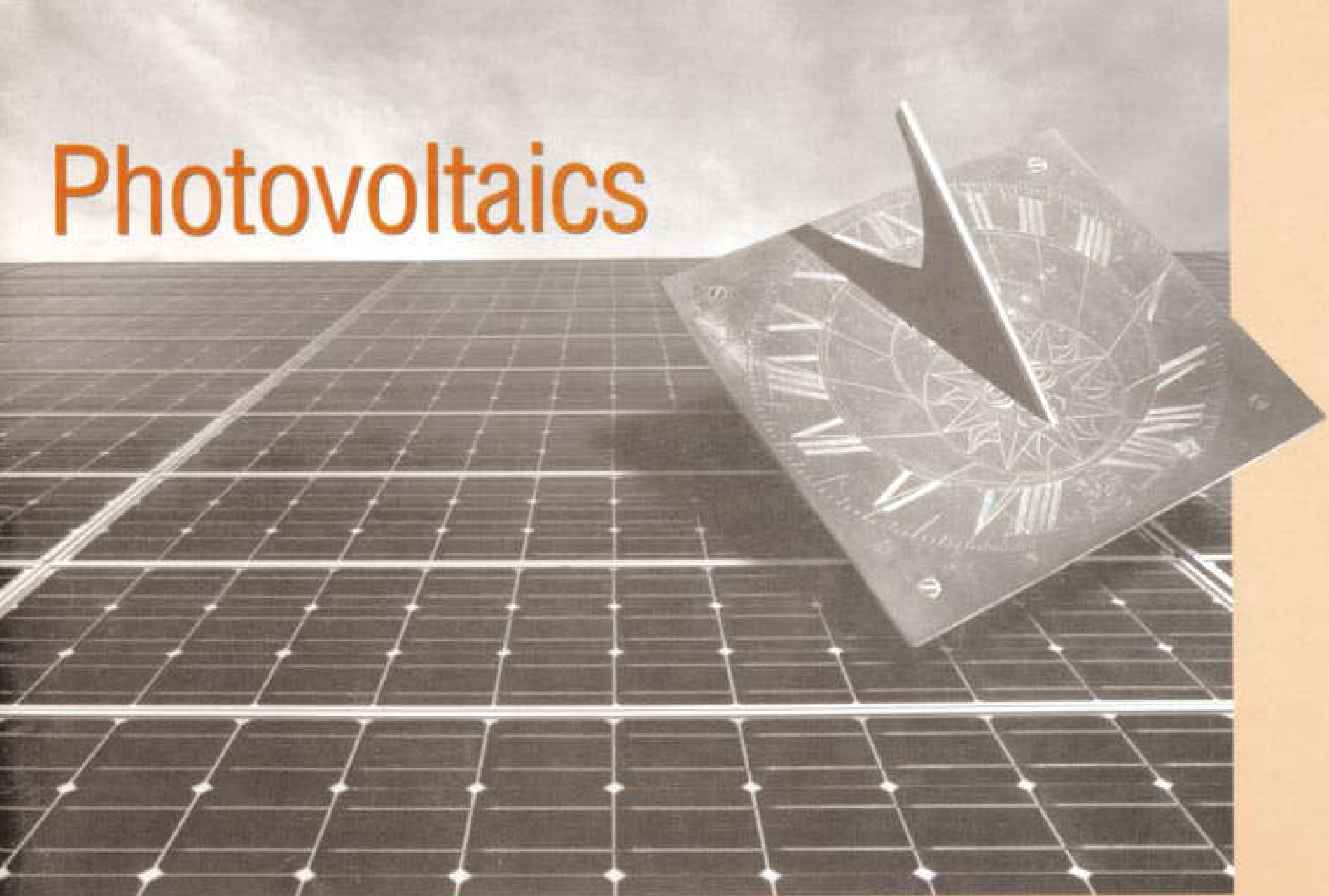
Photovoltaics



Advancing Toward the Millennium

Introduction

Photovoltaic devices directly transform the sun's energy into electricity. As we approach the new millennium, this promising technology is becoming increasingly cost competitive with traditional energy sources — such as oil, gas and nuclear fission — in a growing number of applications.

The Power of Choice

Photovoltaic (PV) systems have a number of economic and technical advantages over established sources of power. Their high reliability means that photovoltaics is often the power of choice for critical applications that require a consistent, predictable energy supply. Their low maintenance requirements — little servicing and no refueling — makes them popular in remote locations, where PV systems have long been cost competitive. High reliability and low maintenance translate into low life-cycle costs when compared with the alternatives, including power-grid extensions, and electric utility companies have found that the power output of PV systems correlates well with peak, daytime electricity consumption. Because the systems are modular and easily transportable, local power requirements can be met relatively quickly when compared with the time it takes to construct new fossil-fuel power stations.

Photovoltaic systems also have several environmental and social benefits. Few power-generation technologies have as little impact on the environment as PV. During operation, PV produces no air pollution, hazardous waste or noise, and requires no transportable fuels. Because their energy source (sunlight) is free and abundant, PV systems can provide guaranteed access to electrical power while reducing our trade deficit and avoiding the cost of maintaining energy supply routes in politically volatile regions such as the Middle East. Plus, the domestic PV industry creates new jobs and strengthens U.S. competitiveness.

About This Document

This document describes the state of photovoltaics in the closing years of the 20th century. It was produced for the U.S. Department of Energy (DOE) using data from both DOE-sponsored researchers and industry sources. The document opens with a 10-page overview, followed by an in-depth analysis of the industry and technologies. Illustrative case studies are used throughout.

Millions of people around the world already depend on photovoltaic electricity, a highly versatile and reliable source of power.

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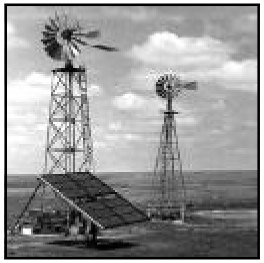


Electricity from the Sun

Overview

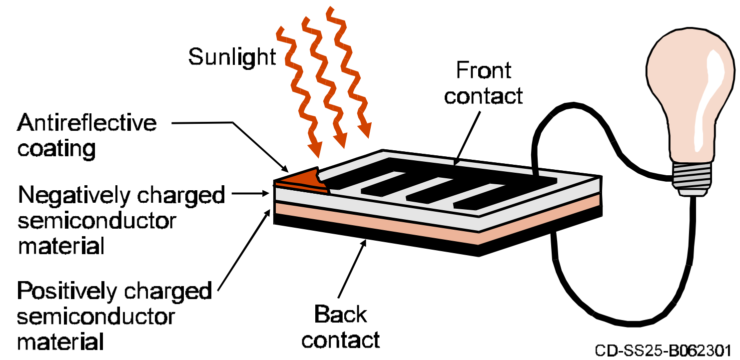
Photovoltaics is the direct conversion of light (photons) into electricity (voltage). Certain materials naturally release electrons when they are exposed to light, and these electrons can then be harnessed to produce an electric current.

The photovoltaic effect was observed as long ago as 1839, and was first applied commercially toward the end of the 19th century in light-measuring devices. It is only in the past 40 years, however, that photovoltaics has been used as a source of power.

Photovoltaic (PV) cells, also called solar cells, are made from the same semiconductor materials used in computer chips. The ability of semiconductors to conduct electricity varies with their temperature and the type of impurities they contain. This variable conductivity is a very useful property.

All solar cells have at least two layers: one that is positively charged and one that is negatively charged. The electric field across the junction between these two layers causes electricity to flow when the semiconductor absorbs photons of light and releases electrons. The greater the intensity of the light, the more power is generated by the cell.

Electrical contacts are attached to the front and back of the cell to enable it to become part of an electrical circuit. The back contact usually consists of a solid layer of aluminum, molybdenum or other metal. This isn't possible on the front surface (which faces the sun) because a solid layer of metal would prevent sunlight from getting through to the cell. For this reason, the front contact is usually laid down as a grid consisting of many thin, conductive metal fingers spreading out across the cell's surface.



A typical solar cell. When incoming photons of light strike atoms in the semiconductor material, some electrons are knocked loose. These free electrons can be harnessed to produce electricity.

Over 98% of solar cells are made with silicon, which is a shiny gray material. Left untreated, the surface of the PV cell acts like a mirror, reflecting back more than 30% of the incoming light, so an antireflection coating is added to the top surface of the cell.

Most silicon solar cells are quite brittle, so several cells are wired together and enclosed in a rugged, protective casing called a module or panel. A group of these modules is called an array.

Photovoltaic modules produce DC (direct current) electricity, which must be converted to AC (alternating current) electricity to run standard household appliances. The amount of power produced by an electrical system is measured in watts (W), kilowatts (kW — thousands of watts) and megawatts (MW — millions of watts). The maximum power output of a photovoltaic array (on a clear, sunny day) is typically expressed as kilowatts of peak capacity power (kW_P), and power output over time is measured in kilowatt-hours (kWh).

The Range of Applications

Wherever there is sunlight, there is energy. Photovoltaic systems can be used to turn this energy into electricity anywhere on Earth — from tropical rain forests to the polar ice caps, from the Sahara Desert to New York City — or even in outer space.

Photovoltaic generation of electricity was born in the 1950s, and first came into the public eye when solar cells were used to power communications equipment on board the Sputnik (1957) and Vanguard (1958) orbital satellites. The need for a highly reliable, light-weight power source on spaceships and satellites was an important driving force in the early evolution of photovoltaic systems, and the tremendous technological progress made during the 1960s helped to establish their credibility for terrestrial applications.

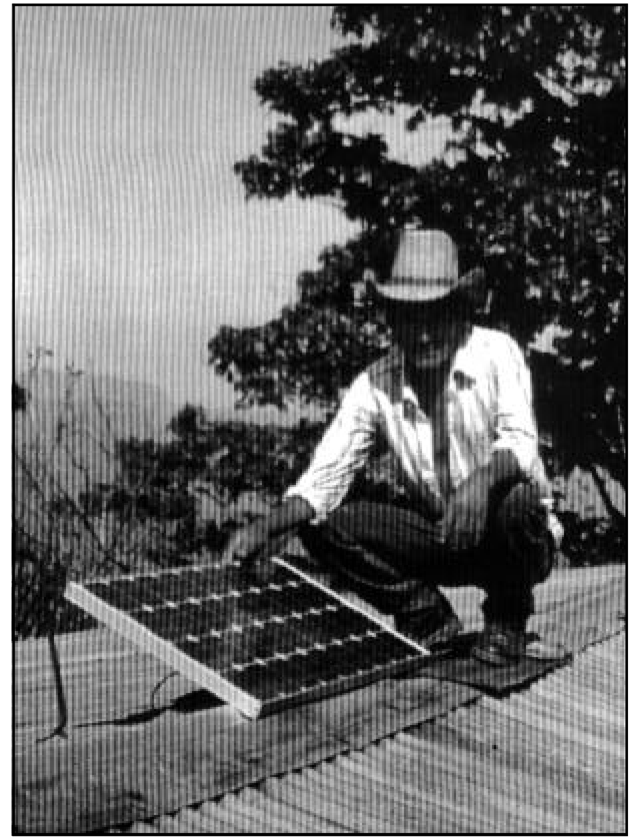
The Russian space station Mir, with PV panels extended, photographed shortly before the U.S. space shuttle Atlantis docked with it in July 1995. Photovoltaics has been used to power satellites since the late 1950s.

Here on Earth, the amount of solar energy available to generate photovoltaic power is about 10,000 times greater than total world energy use today. In the United States, the world's largest consumer of electricity, PV modules covering only 0.3% of the land area would take care of the entire nation's power requirements. For comparison, this is only a quarter of the area currently taken up by roadways.

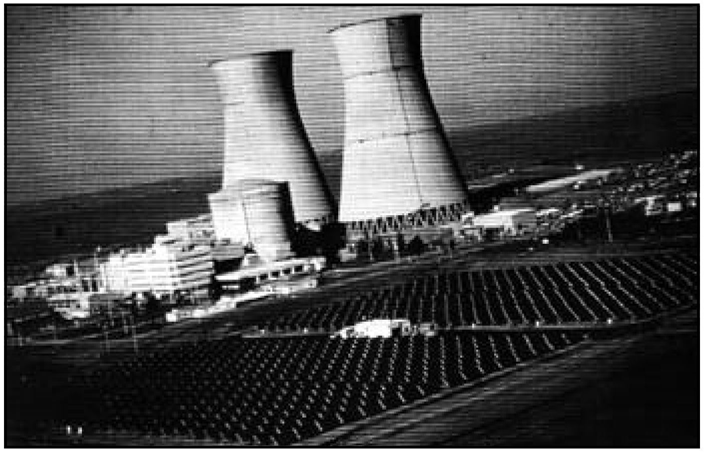
Photovoltaic systems are unlikely ever to become our *only* source of electricity. But as production costs continue to fall, PV is being used in an ever-expanding range of commercial applications.

One of the better-known uses of photovoltaics is in consumer electronics, the low-power end of the spectrum of PV applications. Today more than a billion calculators, and several million watches, portable lights and battery chargers are powered by photovoltaic cells generating tiny amounts (less than 1 watt) of DC electricity.

Millions of people rely on photovoltaics every day without realizing it. Television, radio and telephone systems are all dependent on photovoltaics because PV is the preferred source of power for communications satellites, remote telecommunications



This Honduran farmer's PV system powers four lamps, a radio and a television. With technical assistance from Enersol Associates, Inc., an international nonprofit organization, a local coffee cooperative installed 100 such systems in 1994. By replacing polluting kerosene lamps, each PV system will eliminate 3-6 tons of greenhouse gases over its 20-year life. Enersol's solar-based rural electrification program in Honduras is supported in part by Sandia National Laboratories.



Changing times: The Sacramento Municipal Utility District operates this 2-MW_p PV system on the grounds of its now-closed Rancho Seco nuclear power plant in California. The system produces enough power for 660 homes in the Sacramento area. As the cost of photovoltaics continues to decrease, this environmentally benign technology is becoming increasingly attractive to electric utility companies.

repeaters, and the fiber-optic amplifiers used in telephone and cable-TV networks. This is partly due to PV's excellent reliability and low maintenance requirements; plus, in remote areas, stand-alone PV systems are often the most cost-effective solution.

If the electricity grid is far away, the cost of extending power lines can be prohibitive, and while alternative stand-alone systems — such as diesel generators — may be cheaper initially, they typically require a fair amount of expensive maintenance and regular shipments of fuel. Because of these factors, PV is rapidly becoming the power supply of choice for remote, small-power applications: running communications equipment, pumping water for livestock and crop irrigation on farms, and providing electricity for household appliances in remote homes and cabins. In Norway alone, more than 50,000 vacation homes are powered solely by photovoltaic electricity.

Compared to conventional generators, PV systems are reliable, quiet, odorless, safe and, because they require no fuel, they are both environmentally benign and self-sustaining. Small-scale PV systems are also quite compact. Many of these advantages have proven to be decisive for applications in which dependable power is needed in extreme conditions. The U.S. Coast Guard has installed over 20,000 PV-powered navigation aids because they are the most dependable power source for harsh marine environments; the armed forces use photovoltaics to charge battery packs during field operations; and portable PV systems have been used to provide emergency power for medical clinics and essential communications following natural disasters. Because PV systems are nonpolluting, they have been used to provide power in environmentally sensitive areas across the globe, from Yellowstone National Park in the United States to the jungles of Borneo.

Municipal Applications: Median Irrigation in Florida

Photovoltaics can be the least expensive way to bring electricity to a site even when power lines are less than a stone's throw away. This was the case in Reddington Shores, Florida, where the city government, in conjunction with the Florida Power Corporation, installed 12 PV-powered median irrigation systems along busy streets.

Each of the 5-watt photovoltaic systems supplies electricity to a controller and low-power water-valve actuators. Battery backup provides sufficient storage for four days of operation.

Although power lines were on average only 40 feet from the irrigation controller and actuators, bringing grid electricity to the median would have involved boring under heavily traveled roadways. The cost to install grid-powered irrigation systems was estimated at $2,200 for each system, totaling $26,000 for the whole project. And the cost of purchasing and installing the 12 photovoltaic systems was only $15,000, 42% less. The decision to opt for photovoltaic technology was an easy one, and both the city and the utility company have been very satisfied with the performance of the systems.

Manufacturers have sold thousands of such PV-powered irrigation systems to farmers, ranchers and municipal governments across the country. In order to avoid monthly utility bills, more and more communities are considering replacing existing grid-connected irrigation control devices with systems powered by photovoltaics.

But by far the largest market for photovoltaics is providing power to the more than two billion people who still have no electricity in their homes — 40% of the world population.

Because of the enormous cost of extending the electricity grid to outlying areas, rural electrification programs in developing nations are increasingly turning to photovoltaics. By 1995, roughly 250,000 households in developing countries were using photovoltaics to run equipment such as lights, radios, televisions and water pumps. In Brazil, Mexico and the Philippines, local utility companies are installing photovoltaic systems in remote provinces because they provide the most cost-effective solution.

Photovoltaics is also being used in conjunction with other sources of power to provide for the electrical needs of entire villages. Such hybrid systems typically incorporate wind and diesel generators in addition to PV panels.

The cost of generating electricity from sunlight is falling steadily, and will continue to fall as the technology matures. And as we deplete global reserves of coal and oil, the cost of these conventional fuels will inevitably rise. Renewable sources of power such as photovoltaics could eventually take over from fossil fuels as an important source of electrical energy. But it is difficult to predict how long this transition will take.

Some utility companies have chosen to get in on the ground floor, investing in photovoltaic research and pilot projects now. This research has already proved the value of photovoltaics in several applications, and they are now gathering the hands-on experience they will need to move into mainstream generation of photovoltaic electricity as that option becomes increasingly competitive with other energy technologies.

Home Power Applications: The Solectrogen House in California

Photovoltaics can readily be used in combination with other sources of electrical power. Such hybrid power systems typically are designed to take full advantage of any available renewable energy sources — such as sunlight and wind — while using a more conventional energy source for backup power.

Hybrid systems can be designed to run individual homes or entire villages. In either case, the fact that they use a mixture of energy sources makes their power output highly dependable.

The Solectrogen House, an off-grid home near San Francisco in California, incorporates a hybrid power system and several energy conservation features. The house meets its energy requirements with a combination of photovoltaics, wind energy, liquid petroleum gas (LPG) and solar thermal water heating.

The primary source of electricity for the house consists of 50 polycrystalline PV modules with a total output of 3 kW_p. The electricity generated by the PV array passes through a DC power center that incorporates fuses, breakers and lightning protection to the standard of the National Electric Code. Electricity is stored in 24-volt lead-acid batteries, which receive additional charge from two 1-kW_p wind generators mounted on a nearby hill. During the winter, when the output from the renewable energy systems is not sufficient to meet the entire demand of the house, an LPG-powered generator kicks in. The engine starts automatically when battery voltage drops below 23 volts, and stops when the battery is fully charged. There is standard AC wiring throughout the house, and a power conditioner converts the 24-volt DC output from the batteries to AC at 120 volts.

This modern California home operates completely independently of the utility system.

Agricultural Applications: Livestock Watering in Colorado

Photovoltaic systems are particularly cost effective in remote areas where power lines are either nonexistent or very expensive to maintain. For example, KC Electric Association, a rural electric cooperative in eastern Colorado, serves a 4,000-square-mile territory of wide-open spaces, with an average of only two consumers per mile of line. About half of its sales are to irrigation customers. In 1990, the cooperative began using photovoltaics as a more practical and affordable alternative to replacing damaged distribution lines or installing new ones.

KC Electric loses hundreds of distribution poles and power lines every year to winter storms. The most severe weather occurs during March and April — calving season — when water delivery is especially critical. Power to submersible pumps at the wells had to be maintained, and PV was the answer.

An installation at a well site owned by rancher Bill Bledsoe illustrates the cost advantages of PV. Bledsoe's existing windmill-powered system had to be replaced because it wasn't producing enough water in the summer. KC Electric installed a 600-watt photovoltaic system that reliably delivers 3,500 gallons of water per day from 170 feet below the surface. The life-cycle cost of the PV system was one-fifth that of extending a power line to the well.

A PV-powered water-pumping station operating on the Bledsoe ranch in eastern Colorado.

Developing an Eco-Resort in the Caribbean

You don't have to convince Stanley Selengut about the merits of environmental sensitivity. In the 1970s this New York developer built a resort on land within a U.S. National Park in the U.S. Virgin Islands. The resort won the 1978 Environmental Protection Award and attracted more customers than it could handle. Selengut's Maho Bay development is now one of the most profitable resorts in the Caribbean.

In 1992 Selengut took environmentally sustainable design one step further when he decided to build a new resort, called Harmony, on land adjacent to Maho Bay. Constructed of recycled building materials, with minimal disruption to the local ecology, Harmony became the world's first luxury resort powered exclusively by photovoltaic systems and wind energy.

The 12 Harmony living units feature 24-volt electrical systems and energy-efficient appliances powered by roof-mounted photovoltaic panels with battery storage. The whole development shares a single wind generator for supplemental power.

Visitors to Harmony learn that living off the electricity grid can be comfortable and easy, and monitors installed in every unit enable the more curious guests to see how much electricity they consume each day.

The Harmony resort was built using photovoltaics to power construction equipment. The intention was to incorporate the construction power components into the Harmony resort's energy system after construction was completed, but the system proved to be so much more reliable than eithe diesel generators of the local electricity grid that Selengut decided to keep it as a portable system for future projects.

The PV Industry: Coming of Age

It wasn't until the energy crisis of the 1970s that photovoltaic technology gained recognition as a source of power for non-space applications. Today, with the terrestrial PV industry not much more than 20 years old, photovoltaics is a well-established, proven technology with an extensive international network of manufacturers and distributors. In the United States alone, more than 850 companies are involved in the manufacture and sale of photovoltaic modules and system components.

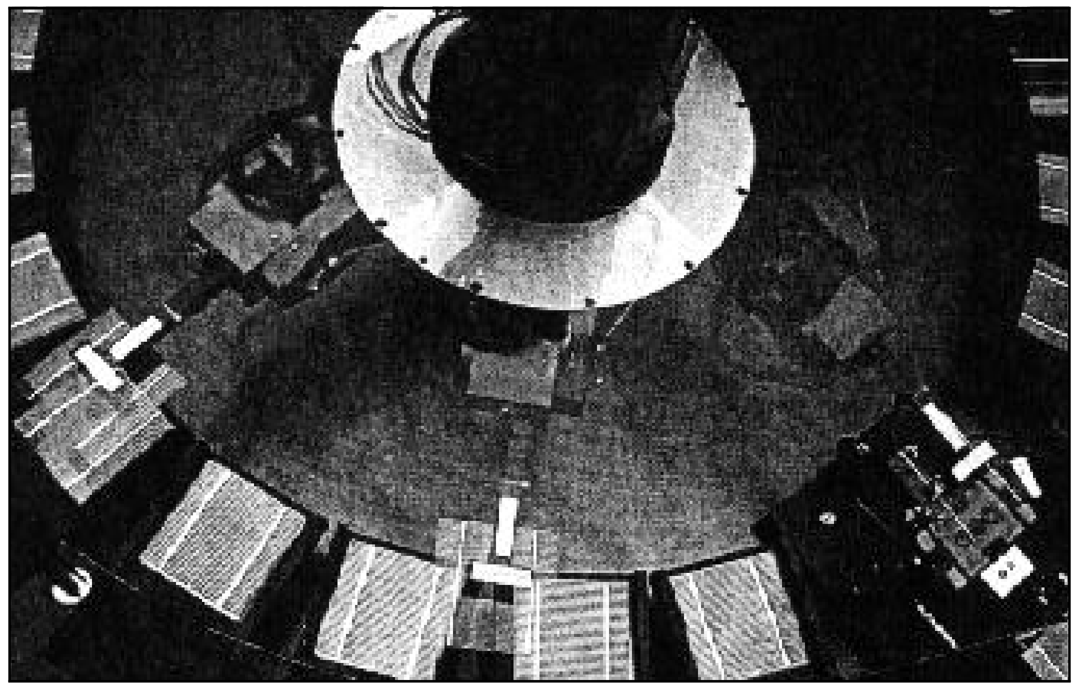
As the industry has grown, prices have tumbled. Technological advances coupled with declining manufacturing costs have brought the retail price of terrestrial PV modules down to less than 1% of their price in the early 1970s, from $500 per watt in 1972 to less than $4 per watt in 1995. During this period, the price of electricity from photovoltaic systems has fallen 68% for every tenfold increase in production, a trend that seems likely to continue.

As prices have dropped, making photovoltaic products increasingly more affordable, new markets have opened up both at home and abroad. The United States is still the biggest consumer of photovoltaic systems, but this is changing as developing countries realize the tremendous benefits of photovoltaic technology. By 1994, India was vying with the United States for status as the biggest PV market in the world; sales of photovoltaic modules to customers in India had grown to 80% of sales in the United States.

This situation is very much to the advantage of U.S. businesses. The United States is the world leader in photovoltaic research and manufacturing, accounting for 43% of global PV module production in 1995. This was well ahead of its closest regional competitor, Europe, which captured 26% of the market, and even further ahead of its closest national competitor, Japan, which captured only 24% of the global market in the same year.

The growing international popularity of photovoltaics is creating an increasingly buoyant domestic PV industry: U.S. production in 1995 was up 103% from 1991, compared with a global increase in production of only 47% during the same four-year period. In other words, U.S. businesses are increasing their share of the global market in photovoltaics.

The PV industry appears to be approaching a critical mass, where its own momentum could help to ensure its success.



Crystalline silicon production equipment operated by Mobil Solar Energy Corp. (now ASE Americas, Inc.)

Part of the increase in U.S. production has been at the expense of European output. Several photovoltaic manufacturing facilities in this country are owned by European parent companies, and there has been a trend for these companies to shift their operations to the United States in recent years, partly encouraged by lower U.S. labor rates.

Approximately 70% of U.S. production of PV modules is exported. Maintaining dominance in photovoltaic technology and manufacturing is part of the solution for a healthy U.S. economy, not least because it helps to improve our ailing balance-of-trade deficit.

And as the world market grows, U.S. companies stand to corner major profits and to generate

Golden Photon's facility for manufacturing cadmium telluride PV modules in Golden, Colorado

Business Opportunities for PV Distributors

As the domestic and international markets for photovoltaics have grown, so have the entrepreneurial opportunities for PV distributors, brokers, mail-order businesses and local dealers.

There is currently a total of 680 distributors of photovoltaic products in the United States, with another 175 businesses supplying related products such as batteries, power conditioners, mounting hardware and tracking systems. And there is plenty of room for more investors in this potentially lucrative market sector.

Each type of distribution business requires a different level of venture capital (to purchase and warehouse photovoltaic devices and supporting equipment, for example) and customer contact.

At one end of the scale, mail-order distributors can function as "box-shifters," providing low prices but usually limited service, whereas local dealers are generally expected to have enough expertise to design and install a PV system that meets the needs of the customer. Service agreements and performance guarantees are especially important when installation is part of the package. PV brokers are somewhere in between, working with clients to match the best available technology to their specific needs, and acting as an intermediary between the client, suppliers and local installers.

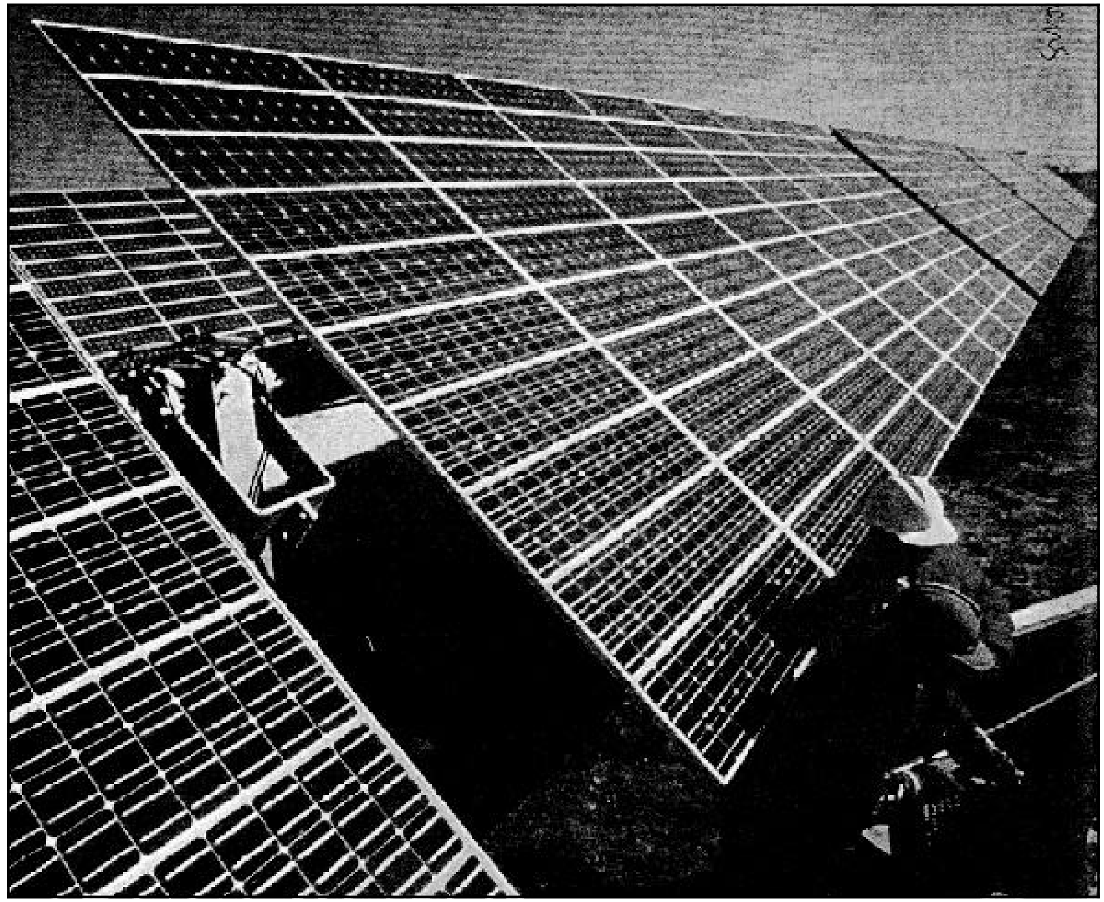
In 1994, U.S. companies produced and shipped photovoltaic cells and modules with a total capacity of 26 MW_p. Only 31% of these PV devices were sold directly to end users and specialty module manufacturers, creating tremendous opportunities for independent PV distributors. Just over 50% of 1994's output was sold to wholesale distributors, 9% to installers, 5% to retailers and 5% to exporters and other buyers.

substantial employment opportunities. A 1992 study prepared for the U.S. Department of Energy — *Economic Impacts of a Photovoltaic Module Manufacturing Facility* — found that every $100 million in sales of photovoltaic modules creates or supports 3,850 jobs in the United States.

Responding to steadily growing demand, U.S. PV module manufacturers are scaling up their production facilities to take advantage of emerging markets. Expansion in manufacturing capacity in the late 1990s is in the order of 55 MW_p of module capacity. To get an idea of the scale of this investment, the total output of PV modules shipped by U.S. manufacturers in 1995 was only 35 MW_p. This growth in capacity is completely unprecedented in the history of the commercial photovoltaics industry, and reflects a new confidence by major industry players that the demand for photovoltaic devices is about to take a significant upturn. Although much of this demand will come from overseas markets, a sizable volume of modules will be absorbed by expansion in the utility photovoltaic program here in the United States.

The photovoltaics industry appears to be approaching a critical mass, where its own momentum could help to ensure its success. Expansion in output by individual manufacturers leads to economies of scale that reduce production costs. Manufacturers can then afford to charge less for PV products, which means that more people can afford to buy photovoltaic sytems.

If the anticipated growth in demand materializes, the new millennium holds a bright future in store for PV manufacturers and consumers alike.



Technicians running tests at the 500-kW_p solar plant operated by Pacific Gas and Electric Company (PG&E) in Kerman, California. This PV facility, which uses modules made by Siemens Solar Industries, is part of an ongoing investigation into the benefits of using solar power to support the utility distribution grid. The facility began operating in April 1993, just six months after construction began, demonstrating that extra power capacity can be added quickly by installing photovoltaics.

The Cutting Edge of R&D

Worldwide, about 750 professional, scientific and engineering personnel are directly engaged in research and development (R&D) on photovoltaics. Most of that research is focused on materials and technologies that promise to have commercial applications in the foreseeable future. The cutting edge of research, sharpened by the promise of financial return, is to make PV more cost competitive in lucrative energy markets. That means cutting the cost of photovoltaic electricity.

Cost-Reduction Strategies

Reducing the cost of photovoltaic electricity involves: (1) improving the efficiency of PV cells at converting solar energy to electricity, and (2) lowering manufacturing costs for PV systems and components. Since efficiency and cost are related (see sidebar, opposite), the two major avenues of progress are to:

- Reduce the manufacturing cost of naturally high-efficiency but higher-cost PV technologies (such as single-crystal silicon and concentrators)
- Improve the sunlight-to-electricity conversion efficiencies of naturally low-cost but low-efficiency PV technologies (such as thin films).

Automated production: Energy Conversion Devices can maintain very high product quality (uniformity varies less than 1%) and cell yield (greater than 99%) with its amorphous silicon thin-film production machine.

The silicon used in PV cells is more than 99.9999% pure and is consequently very expensive. Crystalline silicon solar cells have to be cut from large ingots of silicon, wasting some of the silicon as sawdust. Improved slicing techniques and emerging ribbon-growth processes are reducing the amount of silicon needed.

Thin-film solar cells are potentially less expensive to produce, partly because they use less semiconductor material, and partly because they have a simpler manufacturing sequence. However, the manufacturing sequence can require more sophisticated fabrication processes. If their efficiency can be improved and their manufacturing advantages can be realized, thin films will become the dominant technology for the majority of applications.

The growing use of automated production benefits all PV technologies through economies of scale in manufacturing and reduced defect ratios.

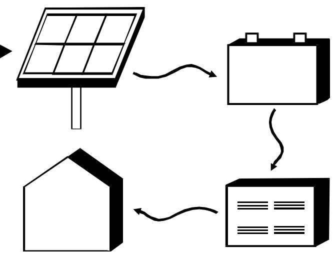
Priorities in Photovoltaics R&D

A comprehensive R&D program is an essential element in keeping U.S. companies at the forefront of global advances in photovoltaic technologies. Across the country, universities, industry research teams and national laboratories are addressing every level of the product development cycle by:

- Investigating PV processes and materials
- Developing more efficient solar cells
- Finding ways to improve manufacturing processes and module design
- Marrying photovoltaic technology to an ever-expanding range of applications
- Conducting user education programs and full-scale demonstrations of the viability of PV.

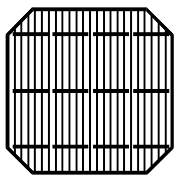
Photovoltaic Systems and Research

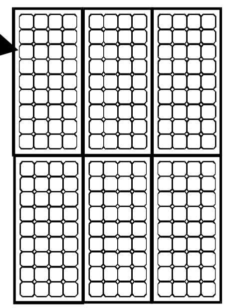
Photovoltaic systems incorporate many different components. PV modules are typically assembled into arrays, which are then mounted on structures that point them toward the sun; they may also need to be connected to batteries and inverters to supply AC electricity, depending on the type of electrical load. Current research spans everything from these end-user components down to interfaces and materials within the solar cell itself.



Balance of Systems (BOS)

The BOS can include wires, power conditioners, batteries, safety devices and tracking systems that keep the PV modules tilted into the sun as it moves across the sky. These components can cost more than the modules, so ongoing efforts to reduce BOS costs are very important.



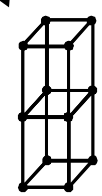


Modules and Arrays

Crystalline silicon PV modules must provide the fragile silicon cells with considerable structural support and protection from the elements, and efforts continue to strengthen the delicate interconnections among individual solar cells within each module. Thin films typically are much more resilient although they, too, require encapsulation.

Solar Cell Design

There are many different approaches to improving solar cell design. One option is to make the surface of the cell less shiny, so that it reflects less light away — more light can then be absorbed and converted to electricity. Another possibility is to reduce the shading caused by the front electrical contacts, which block some of the sunlight, thereby lowering the cell's efficiency — one strategy is to use transparent metal oxides instead of a solid metal grid.



Materials Research

Research aims to: (1) improve the characteristics of well-established materials, such as enhancing the flow of electricity across boundaries between crystals in polycrystalline silicon, and (2) explore the characteristics of promising new materials, such as cadmium telluride and copper indium diselenide (both used in thin films).

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The Cost-Efficiency Trade-Off

The ultimate aim of PV research is to lower the cost of photovoltaic electricity, which involves increasing system efficiency and cutting system cost. But the solar cells with the highest sunlight-to-electricity conversion ratios are also the most costly.

The most expensive and most efficient solar cells are made from large, single crystals of silicon. Cheaper but less efficient cells can be made by casting ingots from polycrystalline silicon or by growing silicon crystals in sheets (ribbons). The cheapest, least efficient option is to deposit very thin layers of amorphous (noncrystalline) or polycrystalline semi-conductor materials onto an inexpensive substrate such as plastic, creating a thin-film cell. Lenses can be used to concentrate the sunlight falling on a cell, thereby increasing its power output but, again, a price is paid for this improvement.

Engines of Growth

Market Forces

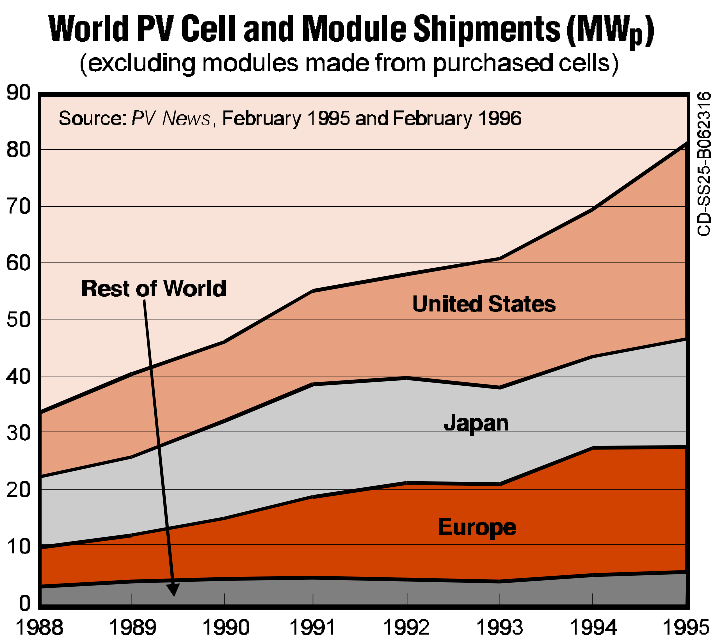
The terrestrial photovoltaics industry has witnessed tremendous growth since its birth in the early 1970s. A variety of political and economic forces have been responsible for this.

In the early days, the availability of investment capital was especially critical. The terrestrial market for PV was virtually nonexistent, and a deep financial chasm separated the technology of the time from the potentially lucrative markets of the future. A substantial investment in R&D was required to bridge that chasm. Motivated by escalating oil prices and runaway energy costs, the U.S. government stepped in to provide development financing. This initial injection of capital helped to get the domestic PV industry started, and government support continues to be important in helping to bring experimental photovoltaic technologies to market. Additional financing came from petroleum companies looking to diversify their energy portfolios and, by 1983, annual private investment in PV had surpassed government funding.

The promise of long-term financial rewards is another important engine of growth. The potential for turning a profit in the PV industry has risen steadily as production costs have fallen but, until recently, the volume of sales was too low for companies to reap any significant financial returns. This is changing as the international power market opens up and U.S. electric utilities step up their deployment of photovoltaic systems.

Consumer demand is, ultimately, the most important market force governing the growth of the PV industry. Healthy demand makes it easier to attract venture capital and makes the industry more profitable. Demand is determined by the price of PV systems, the value placed on the technology, and the availability of financing mechanisms that make it easier for people to buy PV.

Consumers are also voters, and voter pressure is becoming an increasingly important factor in political decision-making about energy resources. Now that the promise of cheap electricity from nuclear fission has been overshadowed by the human and environmental risks involved, a growing number of governments are exploring renewable sources of electrical power. This has been especially true in Europe, where environmental consciousness took a dramatic upswing following the disastrous meltdown of the Chernobyl nuclear plant in



1986. European consumers are demanding safe, environmentally benign alternatives to electricity from fossil fuels and nuclear power, swinging the political pendulum over to photovoltaics and other low-impact energy solutions.

Other political considerations continue to affect the growth of the PV industry. For example, although national energy security is less of an issue today than it was during the series of oil crises that shook the United States in the 1970s, reducing dependence on foreign oil is still a factor in explaining continued government support.

While the global market for photovoltaics shows a steady upward trend (see graph on facing page), the industry is still too young to reliably predict demand from one year to the next. This uncertain market makes production planning difficult, especially for the smaller PV companies that don't have substantial financial reserves to draw on. Overproduction in any given year means additional costs that have to be borne by the units actually sold, while underproduction means lost sales — either way, profits suffer.

Because it takes time to gear up for extra production, insufficient supply can sometimes be a limiting factor in the marketplace. This was the case in the United States in 1995 when, according to the *Photovoltaic Insider's Report*, "Business was so strong that several manufacturers reported shipment delays because production capacity couldn't keep up with demand." Not wanting to be caught in this situation again, "Virtually every U.S. module producer is now in the midst of large manufacturing capacity expansion programs." Once this expansion is complete, U.S. manufacturers will be able to respond to unforeseen surges in demand much more quickly.

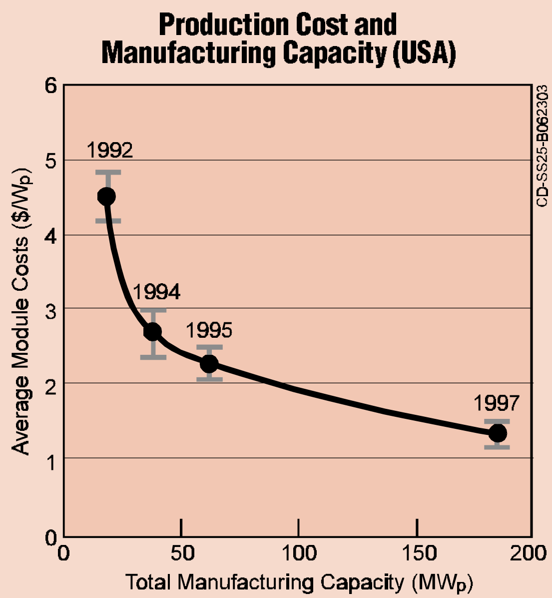
Solar Alliances: Strengthening U.S. Competitiveness

Since the mid-1970s, the U.S. solar industry has forged strategic partnerships with federal and state government agencies to develop promising PV-related technologies.

Because PV companies provide jobs to local economies, several states and municipalities have incentives encouraging them to locate within their jurisdictions. Virginia, for example, pays a cash subsidy of up to $0.75 per watt (on the first 6 MW_p of production) to PV module manufacturers building factories in the state.

Most PV research today is cost-shared by industry and the National Photovoltaic Program, which is planned and managed by the U.S. Department of Energy (DOE). Research is conducted by industry and university teams, as well as by DOE's support laboratories (the National Renewable Energy Laboratory and Sandia National Laboratories). These solar alliances have played a critical role in assisting U.S. companies to bring new technologies to market.

One example of this type of collaboration is the Photovoltaics for Utility-Scale Applications (PVUSA) program, a cooperative research effort between DOE, the Electric Power Research Institute (founded by the utility industry), the California Energy Commission and a dozen utility companies. PVUSA was established in 1986 to test and assess the technical viability and costs of large-scale PV systems, including the 500-kW_p Kerman array (see page 9). Another example, the Utility Photovoltaic Group (UPVG), was formed in 1992 to accelerate the implementation of photovoltaic technologies in utility applications. By 1995, UPVG included over 90 utility companies, representing 45% of the country's electricity production.



In addition to such broad-based cooperative ventures, DOE is supporting individual U.S. companies directly through programs such as the Photovoltaic Manufacturing Technology (PVMaT) initiative, the Thin Film Partnership Program and PV Building Opportunities in the U.S. (PV:Bonus). These programs provide a total of $35-$40 million each year to leading-edge U.S. companies. PVMaT focuses on optimizing commercial manufacturing processes with the aim of reducing module costs and boosting production capacity (see graph, above). The Thin Film Partnership aims to accelerate the commercialization of low-cost thin-film modules, and PV:Bonus develops products that can routinely be deployed in buildings (see page 17). By establishing these programs, DOE has developed a strong pathway for new PV technologies to make rapid progress from the lab to full market implementation.

Beyond Niche Markets

Strengthening Traditional Strongholds

Photovoltaics originally gained a foothold in highly specialized applications, such as satellite power and battery chargers for the armed forces. Space satellites need a lightweight, reliable and long-lasting energy source; because sunlight is the *only* readily available energy source in space, photovoltaics is an ideal match to this need. Today's military personnel are using a growing variety of battery-powered equipment, such as communications transceivers and night-vision glasses (see photo, below). During covert operations, these battery packs have to be recharged as quietly as possible from a portable energy source; again, photovoltaics is the perfect match.

Stand-alone photovoltaic systems provide power to telecommunications equipment such as this in remote locations all over the world.

In high-value niche markets such as these, PV is the most affordable option, despite being expensive. This is largely because there is no acceptable alternative to photovoltaics for these applications. In space, for example, the alternatives would be to power each satellite with the heat produced by radioactive materials (unpopular due to safety concerns) or to send astronauts up on periodic refueling missions (complicated and very expensive). Neither solution compares favorably with the simplicity and ease of deploying PV systems. The military and space markets continue to provide a strong impetus for specialized research since the expense of developing applicable PV technologies can immediately be passed on to the buyer — price is (almost) no object.

Other traditional strongholds of photovoltaic technology are remote power applications and consumer goods. Again, these are high-value markets for PV because of the high cost of alternatives.

Photovoltaics has been used to power remote telecommunications repeater stations since the mid-1970s. As with the space program, the need was for a self-contained, reliable power source requiring almost no maintenance, one that could be placed in remote locations. Many of these repeater stations are located on remote mountain tops that are not accessible by road. It was the savings in maintenance and fuel supply costs, not the cost of energy, that made these photovoltaic systems competitive.

A similar need led to the large-scale deployment of photovoltaics by the U.S. Coast Guard. Since 1984,

Portable photovoltaic battery chargers have been put to good use in a variety of military applications.

approximately 20,000 navigational aids — primarily warning buoys and shore markers — have been converted from disposable batteries to PV power with rechargeable batteries. The reduction in maintenance visits and battery costs saves the Coast Guard over $8 million each year.

In 1980, the Japanese opened up the small-power consumer market by starting to produce solar-powered calculators and watches. This turned out to be a highly profitable market for PV because of the relatively high cost of batteries. In the mid-1980s, U.S. manufacturers entered the market for PV-powered consumer goods with an emphasis on small, lightweight PV modules for walkway lights and battery chargers.

There are many more examples of situations in which photovoltaic systems have long been cost effective for users. Using photovoltaics to power remote homes and cabins avoids the (often prohibitive) cost of stringing power lines from the electricity grid; this is also the case with PV-powered irrigation pumps at remote well-sites on farms and ranches, and photovoltaic systems are routinely used to power roadside warning signals and emergency call-boxes. All of these markets are growing steadily.

This utility-independent home in New Jersey is powered by a 1.8-kW_p photovoltaic array.

The Growth of the U.S. PV Industry

In the United States, business interest in photovoltaics was awakened by the invention of the first silicon solar cell at the Bell Telephone Laboratories in 1954. Most early attempts to commercialize the technology failed, however, because photovoltaic electricity was then prohibitively expensive compared to electricity from conventional power sources. But photovoltaics quickly proved itself to be cost effective in space, and the 1960s saw the development of a small PV industry to serve the space program. Five U.S. companies entered the field during that decade, three of which dropped out again. Although the annual market for PV grew from 7 kW_p in 1960 to 80 kW_p by 1970, this was not enough demand to support five manufacturers.

With the first Arab oil embargo in 1973, finding alternative sources of energy suddenly became a matter of national security. The continuing oil crisis fueled a major effort by the U.S. government and industry to make photovoltaics more affordable. As many electric utilities switched their power stations from burning oil to gas and coal, federal support for renewable energy stimulated the growth of a terrestrial PV industry. By 1979, the U.S. photovoltaics industry comprised more than a hundred companies producing approximately 1.5 MW_p (1,500 kW_p) of modules.

In the 1980s, as oil became more plentiful and the energy crisis abated, the federal government relaxed its emphasis on renewable energy, including photovoltaics. In some areas of research, private funding began to take over from government programs. Investor purchasing of stocks in PV companies took off, bringing a major infusion of capital to the industry, and Wall Street's continuing interest in photovoltaics is an increasingly important source of financing for smaller PV companies.

By 1995, photovoltaics had become a vibrant, billion-dollar industry, with over 850 U.S. companies involved in the manufacture and sale of PV modules and components. U.S. production in 1995 totaled 35 MW_p, almost three-quarters of which was exported.

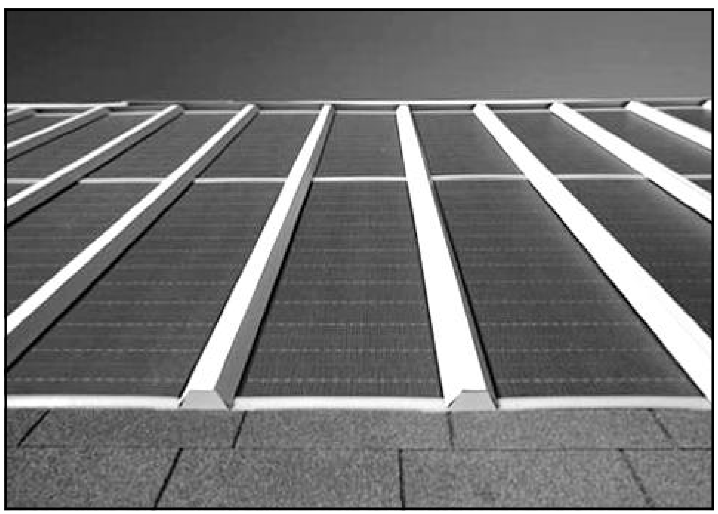
One of 30 PV-powered school-zone flashers in Carrollton, Texas

Military and space applications are still specialty markets, characterized by low sales volume, very high prices and a considerable amount of application-specific R&D. This was true for most of the early uses of photovoltaics. But as the other markets for PV have grown, many of them can no longer be considered to be true niche markets. Sales are up, prices have tumbled and similar modules are used in a wide range of installations.

The industry has grown by successfully courting these high-value, traditional strongholds of photovoltaics. Building on this success, the PV industry is now diversifying into potentially high-volume, mainstream markets.

Entering the Mainstream

As manufacturing costs fall and its track record grows, photovoltaics is becoming increasingly accepted into mainstream applications. Federal, state and municipal planning departments are using photovoltaics for a wide variety of stand-alone applications; its use in grid-connected buildings is expanding at home and abroad; utility companies are using photovoltaics to supplement the power grid and reduce peak demand by consumers; and photovoltaics has been incorporated into experimental mini-grids powering entire villages in the developing world (see page 22).



These roof-mounted PV panels replace conventional roofing shingles while supplying electricity to the building and the utility power grid.

Urban Applications

Photovoltaics is cost effective in a growing number of urban applications. As PV technology moved into the cities from remote homes and isolated areas, it gradually gained acceptance, to the point where it has now become a factor in the decision-making process of mainstream politicians and municipal planners. Across the country, from California to New York and from Texas to Montana, city planners have installed PV-powered systems, dispelling the myth that photovoltaic systems require a “sunbelt” climate to work effectively and efficiently.

In urban areas, the cost of extending conventional utility service to a site is sometimes prohibitive when compared to the photovoltaic alternative. Installing power lines and service drop equipment (e.g., transformers), digging up streets and rerouting traffic can cost a lot of money, even for relatively small applications. Photovoltaic systems, on the other hand, can be installed without any of these costs and with minimal environmental disruption.

In Carrollton, Texas, a suburb of Dallas, city officials had 30 PV-powered school-zone flashers installed at a cost of $102,000 (see photo, left). Installation of grid-connected flashers would have cost $210,000. Serving 15 schools, the battery-backed flashers are extremely reliable, and have roused considerable praise from city residents.

In Orange County, California, several cities banded together to install 1,100 PV-powered emergency call boxes along urban highways. These cellular-phone systems cost a total of $4.5 million, 57% less than the $10.5 million projected cost of installing grid-connected call boxes with identical capabilities.

And in West Kendall, Florida, a west Miami suburb, the local community association saved $52,000 by installing photovoltaic street lighting. This does not take into consideration the ongoing savings from not having to pay monthly utility bills for the lights. Residents have been very satisfied with the performance of the systems. In fact, when utility power was out for 33 hours because of Hurricane Andrew

Thin-film photovoltaic modules used as exterior cladding on a factory facade

in 1992, the only street lighting in the community came from these 26 photovoltaic lights.

Photovoltaics for Buildings

Buildings consume approximately two-thirds of the electricity generated in the United States. By locating a photovoltaic system on a building, its demand for grid electricity can be reduced, saving on electricity bills.

The overall demand for electricity within a distribution system fluctuates during a given 24-hour period, typically peaking in the afternoon. For many commercial buildings, especially offices, there is a good match between this peak demand and the output of photovoltaic systems. This is especially true on warm days, when the need to run air-conditioning equipment coincides with the time of day when solar radiation is at its strongest. Home owners have also demonstrated a willingness to have utility-owned, grid-connected PV systems installed on their rooftops. Although residential demand peaks during the evening, such residential systems feed photovoltaic electricity back into the electricity grid, helping to offset peak demand in other parts of the utility's distribution network.

Several different approaches are being used to incorporate PV into buildings. The simplest method is simply to mount unmodified PV modules on rooftops, as has been done for over 20 years. These modules can be connected to the grid or used to drive equipment such as cooling fans directly. But the greatest potential for growth in this market will come from standardized building materials that double as photovoltaic modules. Examples include roofing shingles, exterior cladding, windows and skylights that incorporate solar cells. One U.S. manufacturer is developing modular homes with PV modules integrated into the roofs; another is developing AC power modules that will free architects and designers from the issues of inverter sizing and DC wiring. As they enter mass production, such "architectural" PV modules will significantly strengthen the economic appeal of installing photovoltaic systems; because they serve two functions, the cost of conventional building materials is avoided.

Incorporating photovoltaics into building materials is technically complex, requiring joint development among several normally separate elements of the building industry. Despite this, a 1995 study by Arthur D. Little, Inc. — *Building-Integrated Photovoltaics (BIPV): Analysis and U.S. Market Share* — found that grid-connected, building-integrated PV systems should be cost effective in many U.S. installations by the year 2005.

Electric Utilities

The large-scale generation of electric power is the most important long-term market for photovoltaics in the United States. Utility companies, destined to play a major role in this emerging market, have formed a number of alliances — notably the Utility Photovoltaic Group — to gain hands-on experience with using photovoltaic technologies. A 1993 study by the Electric Power Re-

This electric-vehicle recharging station in South Florida is powered by a grid-connected PV array mounted on the roof. Excess power from the modules is fed back into the utility grid.

The Boston Edison "Impact 2000" home incorporates a 4-kW_p utility-connected photovoltaic array.

search Institute found that more than 100 utilities now routinely use photovoltaics in more than 60 specific applications. Examples that haven't already been mentioned include providing power to switches on transmission lines and providing cathodic protection to prevent the corrosion of metal structures such as bridges and pipelines.

Utility deployment of photovoltaics is following a natural progression, from small, stand-alone systems to bulk power generation.

1. Stand-Alone Systems

For stand-alone applications, typically less than 10 kW_p, photovoltaic systems offer a number of significant advantages to utility companies. Because of their light weight, modularity and portability, PV systems can be erected quickly and easily, without the need for expensive service equipment. PV systems are quiet, nonpolluting, don't have to be supplied with fuel or water, and eliminate the need for transmission lines.

Grid-independent PV systems are already the most cost-effective source of power when extending transmission lines is prohibitively expensive (remote installations) or difficult (some urban sites), when line-maintenance costs are high (extreme winter weather, heavily treed areas), or when the demand is so small that the potential revenue doesn't justify the cost of providing service.

2. Grid-Connected Buildings

As indicated under *Photovoltaics for Buildings* (page 17), current research shows a high correlation between the electricity generated by photovoltaic systems and the daily power requirements of large commercial utility customers. Several utilities have installed photovoltaic arrays on commercial buildings to evaluate their ability to smooth out the fluctuations in demand for grid electricity. This is sometimes referred to as "demand-side management" or "peak shaving" because it can help a utility to reduce the load demanded by the customer during peak periods. The peak load for commercial customers could be as much as 50 kW_p.

Utilities are also installing PV arrays on residential buildings. The incentive in this case is a little different, since residential demand generally doesn't match photovoltaic output. With extensive deployment, grid-connected residential systems could help alleviate overall demand on the utility grid. For now, however, the main advantage lies in the free real estate offered by utility customers with experimental PV modules mounted on their rooftops. This factor is especially important in densely populated areas such as Japan (page 24), where real estate is in short supply.

3. Utility Grid Support

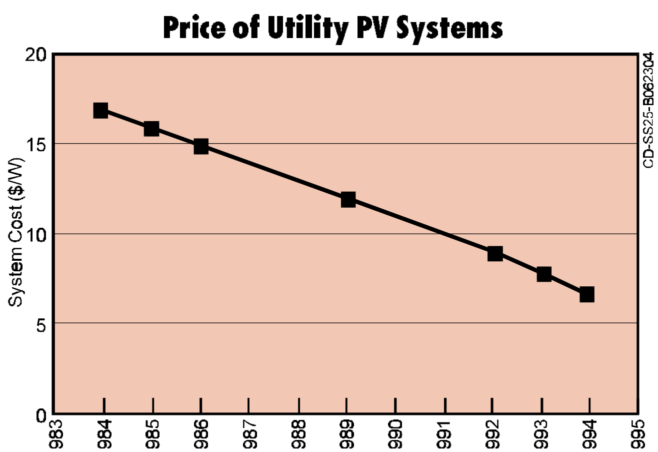
Power lines are designed to carry a certain amount of current. When demand at the end of a distribution grid grows beyond design specifications, utilities are faced with the prospect of having to replace long stretches of line to avoid thermal overloading or voltage sag. This is so expensive that the alternative of installing PV systems (at 500-1,000 kW_p) near the new source of demand is nearly cost effective today, provided there is a match between the supplemental load and photovoltaic output. The same economics are valid for extending the life of thermally overloaded substations.

Pacific Gas and Electric Company, the country's largest investor-owned utility, has found that it can cost twice as much to distribute power as it does to generate it in the first place. This significantly improves the economic appeal of photovoltaic systems for grid support.

4. Peaking Power Plants

Because the overall demand for electricity isn't constant, and because power plants are expensive to run, electric utilities are forced to operate a variety of power plants to match the load. "Baseload" power plants (typically nuclear or coal-fired) are so-called because they operate around the clock to meet the utility's baseload. "Intermediate" or "cycling" plants meet most of the extra daytime load and turn off at night, and "peaking" plants (typically gas turbines or hydroelectric systems) operate only when demand is at its highest, usually for just a few hours a day.

Peaking power plants are the most expensive for a utility to operate, so they are the most likely candidates to be replaced by photovoltaic systems in those parts of the country where there is a close match between photovoltaic output and peak electrical demand. There is still more research to be done, but peaking photovoltaic power plants could be phased in as early as 2005, especially if utilities change their rate structures to reflect the higher cost of peak electricity.



The Utility Photovoltaic Group has documented the steady reduction in the cost of utility PV systems during the past decade.

5. Bulk Power Generation

Photovoltaics could eventually make inroads into the bulk (baseload) power market as the utility industry rethinks its current structure. Existing utility networks have just one large, centrally located power station supplying the baseload needs of the entire grid. In the future, utilities are likely to move to a "distributed generation" model, in which a number of smaller power stations — such as PV plants — are located near major customers to supplement the electricity supplied by the central power plant. Grid support is one aspect of this vision. The distributed utility model reduces transmission and distribution losses, improves power quality and enhances system reliability.

Recouping the Cost of Using PV

Individual utilities are finding that they can cover the additional cost of using photovoltaic energy through "green-pricing" strategies. With green pricing, customers agree to pay a little more on their utility bill each month, or make a one-time contribution to a renewable energy fund, as a way of supporting greater investment in alternative energy technologies. Under the Sacramento Municipal Utility District's "PV Pioneers" program, for example, customers offer the use of their rooftops for PV panels that provide electricity to the utility grid. They also pay a $4 surcharge on their monthly electricity bill to support the use of solar power. The utility purchases, owns, installs and maintains the systems. Over 300 4-kW$_P$ PV systems have been installed under this initiative. Such green-pricing strategies have also been introduced by Detroit Edison and Public Service Company of Colorado.

The international market for photovoltaics is expanding as electricity becomes an essential

Risk Assessment

The oil crisis of the mid-1970s taught us that, when it comes to energy reserves, access is power. Unlike conventional fuels, solar energy cannot be controlled — it is freely available to any individual, company or nation that chooses to harness it. When planning for an uncertain future, factors like this can have a significant influence on investment decisions.

Utility companies typically calculate the return on their investments over a period of 20 years or more into the future. Over the long term, dependence on conventional fuel involves significant risk: prices are highly unstable with a definite upward trend. Photovoltaics, on the other hand, has minimal risk because of its proven, unbroken trend of declining prices. Its high reliability translates into predictable and low operating costs, and the nonpolluting nature of the technology means that utilities choosing photovoltaics are free from the threat of new government regulations concerning emissions.

For the average person, predictability is preferable to risk. When choosing a mortgage, for example, most people willingly pay the premium for a fixed rate to avoid the risk associated with a variable-rate mortgage. Similarly, most consumers would pay more to safeguard their electricity rate charges from potentially dramatic fluctuations due to changing fuel costs.

When the relative risks associated with different energy technologies are adequately factored into cost-benefit calculations by utility analysts, photovoltaic technology emerges as a more attractive option than a straightforward comparison of present-day costs per watt might indicate.

International Interest in Photovoltaics

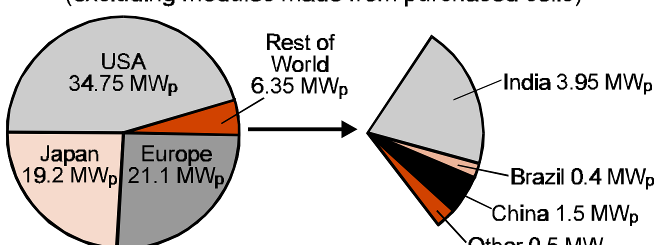
With support from the U.S. Department of Energy, the Brazilian energy ministry is installing PV systems such as these in several northeastern and Amazonian states.

resource for fueling economic growth in the developing world. Demand is growing, and growing fast. It is estimated that China, for example, will require an additional 137,000 MW of power during the last half of the 1990s, India will need 75,000 MW and Mexico 27,000 MW. This compares with anticipated growth in U.S. demand of anywhere from 6,000 to 20,000 MW.

Developing countries currently account for about 30% of global energy use, and are expected to account for over half of the increase in global energy consumption during the next 30 years. In addition to the demands of industry in these nations, an expanding population with a growing desire for basic services — such as lighting, clean water and irrigation pumping — and an increasing appetite for electrically powered consumer goods puts heavy pressure on local governments to keep pace with the demand for electricity.

Although photovoltaic technologies are not yet sufficiently cost competitive in the United States to have attracted widespread investment by utility companies, the situation is different in many other countries, where electricity costs typically are much higher than they are in the United States. This is especially true in less densely populated regions, where the costs of running power lines from one remote village to another can be prohibitive. Besides, the governments of many developing nations are unable to afford the high cost of building and operating new centralized power plants and transmission grids.

1995 World PV Cell and Module Shipments
(excluding modules made from purchased cells)



Total World Shipments = 81.4 MWp

Source: *PV News*, February 1996 CD-SS25-B062314

Photovoltaic systems are proving to be the most cost-effective solution for bringing electricity to many rural villages (see example on page 22), and major international lending institutions like the World Bank (see sidebar on page 25) are making development funds available to interested governments. This funding is fueled by growing international concern over atmospheric pollution and global warming, which photovoltaics can help to ameliorate since it is an environmentally "clean" technology. The countries that currently are the most active in installing photovoltaic systems are Brazil, China, India, Indonesia, Mexico, Russia and South Africa.

Although developing nations are fast becoming the greatest source of demand for photovoltaic systems, they are responsible for less than 8% of global PV module production (see pie chart, left). Until such time as they acquire significant production capacity of their own, developing countries represent a wide-open market for existing PV manufacturers. The United States leads the world in PV output, and approximately 70% of U.S. production of photovoltaic modules is exported, so the growing international market means more jobs and increasing revenues in this sector of U.S. industry.

Some of the more forward-thinking governments in the developing world are already taking steps to avoid long-term dependency on foreign expertise in renewables power generation. India, for example, which currently is the world's second-largest market for photovoltaics, is doing everything it can to encourage foreign PV companies to develop projects together with local companies in joint ventures (see sidebar, right). The government also requires that eventual in-country manufacturing be part of any bilateral agreement. India's insistence on technology transfer and domestic value-added could well be a sign of things to come, and it is important for U.S. manufacturers to get in on the ground floor to ensure a solid presence in developing countries as their demand for renewable energy expands.

Investment in photovoltaic systems continues to grow in the industrially developed world, too, with most interest focused on the great potential for photovoltaics in buildings.

In Germany, for example, the federal government pays up to 70% of the cost of fitting grid-connected PV systems to residential rooftops. This so-called "Thousand Roofs " program met with such a warm reception that, shortly after its inception in 1990, the target was expanded to include some 2,500 installations. Its success has spawned similar initiatives in other European countries, including Austria.

Scandinavia has a large, existing market for small, stand-alone PV systems because of the great popularity of family-owned vacation cottages. Most of these cabins are located off-grid, where PV systems are an ideal source of power. In Finland, for example, there are about 200,000 off-grid summer houses, of which 20,000 are now PV-powered, and

Opportunities in India

The Republic of India, with more than 900 million inhabitants, is the largest trading partner of the United States. A growing middle class of over 200 million people means that the demand for goods and services should increase dramatically in the years to come. In addition, more than 72,000 Indian villages currently are without electricity, representing a large potential market for renewable energy technologies such as photovoltaics.

The Indian government has demonstrated its commitment to bringing renewable energy to these villages by implementing financial protocols that encourage foreign investment. U.S. companies are now allowed to maintain a majority (51%) ownership in joint ventures with Indian companies. In addition, domestic excise duties and sales taxes are generally waived on PV systems and components, and import duties paid are granted 100% depreciation in the first year for income tax purposes.

The government is also providing other monetary incentives to encourage the widespread installation of photovoltaic systems. It pays 55% of the cost of PV modules, and loan assistance for the balance is available from the Indian Renewable Energy Development Agency at low interest rates, with a two-year moratorium on repayments and an eight-year total repayment period.

Several U.S. organizations, including the Electric Power Research Institute (EPRI), which carries out research projects for the U.S. utility industry, and the Department of Energy's National Renewable Energy Laboratory, have developed bilateral agreements to accelerate the use of renewable energy in India.

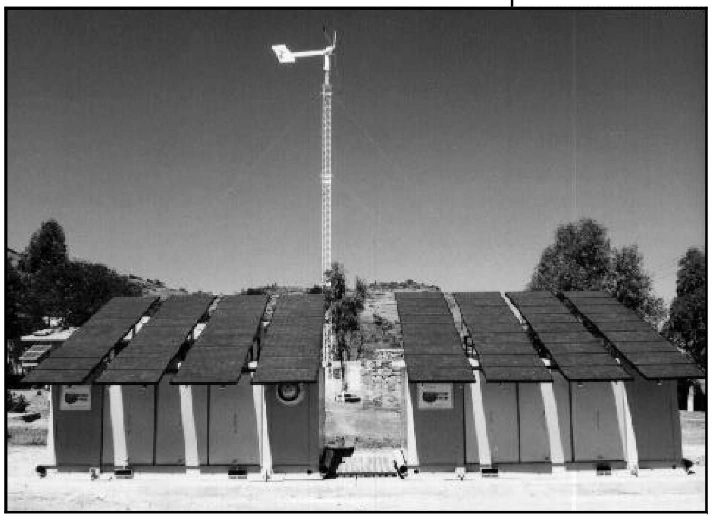
George Preston, EPRI vice president for generation, has said that EPRI sees India as an ideal location for the expanded use of renewable energy technologies because of:

- Its plentiful renewable energy resources
- The close match between the small, modular nature of renewable energy systems and the needs of India's remote villages
- The general shortage of electricity generating capacity in India
- The desire of Indian companies and agencies to work with U.S. organizations.

Photovoltaics is rapidly gaining favor among the various renewables, partly because of the simplicity of system installation. Renewable Energy Systems (RES), the Indian government venture tasked with distributing World Bank loans (see sidebar, page 25), is gradually shifting its focus away from promoting wind toward photovoltaics. The reason? Officials at RES are finding that solar power projects are more cost effective and can be implemented more quickly than wind power projects.

The Economics of Bringing Photovoltaic Electricity to the Global Village

Two billion people — 40% of the world population — still don't have electricity in their homes. Many of them live in rural villages situated far from the reach of the electricity distribution grid. People not served by a power grid often rely on fossil fuels — such as kerosene and diesel — for many of their energy needs. Transporting these fuels to remote locations can be expensive and difficult, and maintenance of fossil-fuel-driven generators can be problematic. Another issue is that fossil fuels are often imported, leaving domestic economies vulnerable to global price fluctuations and, as happened in the 1970s, disruptions in supply.



This centralized, hybrid power system provides electricity to the village of Santa Maria Magdalena in Mexico. Incorporating a 4-kW_p photovoltaic array, a 4-kW_p wind turbine and an 18-kW_p diesel generator, the system is designed to support loads of 45 kWh per day. The village has a utility-grade distribution network that supplies electrical power to 43 homes, three schools, two stores, a church and an auditorium.

In contrast, photovoltaic energy is a clean and economical alternative that is not dependent on a foreign source of fuel. Many developing countries are located in the tropics and have high levels of sunshine year-round, providing them with a free and abundant energy supply that is locally available. Using photovoltaics to generate electricity from sunlight is simple, requires no moving parts and has been proved reliable in tens of thousands of installations worldwide. Photovoltaics may also be the most cost-effective means of supplying basic services when its life-cycle costs are compared to typical alternatives, such as the use of kerosene and candles for lighting, or extending a power line from the electricity grid.

Although they often don't have the financial resources to extend centralized power networks to rural areas, local governments have a strong incentive to find a way to provide electricity to the rural poor. In many cases, the lack of access to basic services, together with the meager economic opportunities in the countryside, encourage people to move into the cities in search of a better life. Photovoltaics can provide the power necessary for electric lighting, health clinics, television, water pumping and purification systems, and can supply power for cottage industries in rural areas. When these things are available locally, the desire or necessity of moving to already overcrowded urban centers can be diminished.

Photovoltaic electricity is sometimes dismissed as a power-supply option because it has a relatively high price per kilowatt-hour (kWh) when compared to traditional sources of energy, especially grid-supplied electricity. However, the important issue is not so much what photovoltaic electricity *costs*, but rather what the service it provides is *worth* to the user when compared to the alternatives.

Rural households in the developing world typically require only a small amount of electricity — generally just enough to power a few electric lights and a television or radio for three to four hours in the evening. In most cases, the revenue from such small energy usage does not cover the actual costs of generating and distributing electricity from a conventional power plant.

In the Dominican Republic, for example, the price of electricity to households already connected to the utility grid can be as low as $0.11/kWh (in 1993 dollars). But this doesn't reflect the high cost of stringing copper wire across the countryside to remote sites. If a home with a typical electrical load (6 kWh per month) were located only one mile from the grid, it would cost the utility company over $11/kWh to provide electricity (when amortized over a 30-year period at 10% interest, assuming a line installation cost of $7,500 per mile). Because the true cost of providing grid service is prohibitive, and because government subsidies are limited, large segments of the developing world remain without access to electricity.

Instead, rural populations rely on other energy sources such as kerosene and candles for lighting, vehicle batteries to run televisions, and dry-cell batteries for radios and cassette-players. Although these lighting and electricity sources can be purchased in small enough quantities to be affordable, rural households are actually paying very high prices for these basic services. In the Dominican Republic, the average monthly combined price for these energy sources is on the order of $1-$2/kWh; dry-cell batteries typically cost $30-$60/kWh. In contrast, a typical 50-watt, single-module photovoltaic system can supply these loads for about $0.75/kWh — higher than the cost of grid-supplied electricity (if it were available on-site), but lower than the actual cost of the alternatives. (The figure of $0.75/kWh assumes a $700 installed cost, plus replacement of a $45 battery every 18 months over a 20-year system life.)

Thus, despite common perceptions, small photovoltaic systems can offer a cost-effective alternative to traditional energy sources in many situations in the developing world. They provide cleaner, safer, more reliable and more convenient services for a life-cycle cost that is comparable to, or less than, what households are already paying.

The system economics described here can vary widely from one village to the next, and from one country to another. Many villages already have electrical mini-grids supplied by diesel generators. In some cases, these generators have significant reliability, repair, maintenance or fuel-supply problems. This is prompting some governments and local utilities to experiment with reducing the load on the generator (or supplementing its output) by adding photovoltaic (and wind power) systems to the grid.

One reason for adding PV is to keep pace with the growing demand for electricity in the village. Like all technologies for generating power, PV systems have design limits on the loads they can handle. But in a mini-grid or stand-alone situation, these load limits are particularly critical. One of the problems with providing dependable electricity to people who haven't had it before is that they start to come up with an ever-growing number of uses for power. Once electrified, they tend to buy more electrical equipment, pushing system design limits. In a PV-wind-diesel hybrid power scheme in the village of Xcalak, Mexico, the local utility has implemented a creative solution that effectively addresses this issue without having to expand capacity. Users are charged $0.34/kWh for the first 36 kWh consumed per month. Thereafter, the tariff doubles to $0.68/kWh. This kind of fee structure curtails load growth and helps to impose user discipline in energy conservation.

By 1995, hybrid village-power systems incorporating photovoltaics had been installed in Mexico, Pakistan, Indonesia, Saudi Arabia and Egypt. Although such systems are not currently cost effective when compared with diesel-only solutions, the experience gained from these sites is helping to lay the foundation for more widespread use of hybrid village-power systems in the future.

Primary source: "Solar Photovoltaics for Development Applications" by Lisa W. Shepperd and Elizabeth H. Richards, issued by the U.S. Department of Energy's Sandia National Laboratories, August 1993.

PV module and system growth in developing countries and the Third World, where enormous markets for PV exist, is limited only by financing to pay for installation.

— *Photovoltaic Insider's Report*, February 1996

Norway already has 50,000 PV-powered vacation homes.

On the other side of the world, Japanese interest in photovoltaics has been growing steadily since the early 1980s. In a country where land is at a premium, grid-linked PV systems on buildings are the most feasible way to implement photovoltaic technology. In 1994, the national government initiated an ambitious program to install 62,000 PV systems (totaling 185 MW_p) on residential rooftops by the year 2002.

A member of the Vietnam Women's Union (VWU) making her down payment for a home PV system. In a joint venture with the Solar Electric Light Fund, the VWU set up a revolving credit fund that enabled 100 homeowners in southern Vietnam to purchase solar lighting systems in 1995. Over 80% of Vietnam's population is without electricity.

Financing PV Installations

In the developing world, the widespread implementation of photovoltaic technology has been hampered by its relatively high up-front capital costs. Users are, in effect, required to pay for 20 years of electricity all at once — something that the typical rural household simply cannot afford. The situation is reminiscent of the U.S. housing market earlier this century: it wasn't until the 1930s that banks in this country began to offer mortgages enabling people to finance the purchase of their own homes. Before then, people had to come to a private financial arrangement with the seller or buy their homes outright.

Because of a domestic shortage of investment capital, the governments of developing countries have traditionally looked to outside sources of funding for energy development projects. However, a number of factors have made it difficult to obtain the support of the international financial community for small-scale photovoltaics installations:

- Lending institutions often have a lack of awareness about photovoltaic technology.
- The infrastructure necessary to maintain PV systems often doesn't exist in the recipient country.
- Administrative factors — several small projects are more costly to administer than a few, larger, centralized-power projects (even though smaller projects are often technically more viable).
- The photovoltaics industry is relatively young, and many PV manufacturers and marketing companies have limited experience with obtaining financing for international projects.

The lack of financing options is currently the biggest factor limiting the expansion of photovoltaics into the developing world. But the situation improves every year. Awareness and infrastructure issues can be tackled through education, thereby making it easier to get external financing, and several nonprofit organizations and international lending institutions have initiated creative financing arrangements to improve access to photovoltaics. The sources for project funds include:

- Loans from international (multilateral) development banks, such as the World Bank and the United Nations Development Program
- Grants from international (bilateral) aid organizations and regional development banks, such as the International Fund for Renewable Energy and Energy Efficiency
- Special funds set up to facilitate loans for PV applications, such as the World Bank's FINESSE program (see sidebar, right)
- Nongovernmental organizations — both aid organizations and local cooperatives — which have raised seed money (often no more than $2,000 to $20,000) to establish a revolving loan fund
- Federal and state governments in the developing countries themselves, which are increasingly open to sharing the costs of PV installations with local utility companies and end users.

There are two different approaches to making PV systems more affordable to end users. In most cases, the user buys the system by making a cash down payment (typically 10%-20% of the total system cost) and then making installment payments over a number of years. The alternative approach is for the end user to lease the system, paying a monthly usage fee to a third party which owns and maintains the equipment — this method is used by electric utilities in the Philippines. Either method achieves the objective of dividing the total system cost into affordable monthly payments, bringing PV within reach of an ever-increasing number of people.

Financing by International Development Banks

Organizations that traditionally fund large, energy-related projects have begun to recognize the superior economics of photovoltaics for remote homes and villages. With funding from various international aid organizations and lending institutions, many national governments are beginning to provide PV systems to homes that have no electrical power. Such programs are currently under way in Brazil, China, India, Indonesia, Mexico, the Philippines, Sri Lanka and Zimbabwe.

The World Bank is the largest and most important of the international lending institutions providing funding for development projects. It is actually a consortium of several banks, each with a separate focus, such as the International Finance Corporation, which mobilizes capital for direct lending to the private sector; and the International Development Agency, which provides concessional loans to poorer countries using funds contributed by national governments.

FINESSE, which stands for Financing Renewable Energy for Small-Scale Energy Users, is a World Bank initiative started in 1989 to facilitate funding of smaller energy projects by large multilateral development banks. Such institutions typically won't consider small projects, partly because the costs of evaluating and administering the projects are prohibitive. FINESSE packages several small projects into financing portfolios of sufficient size to appeal to large lending institutions. The existence of bundling mechanisms such as this helps to ensure a healthy market for PV.

In 1991, responding to growing concern over global environmental degradation, the World Bank joined forces with the United Nations Environment Program and the United Nations Development Program to create the Global Environmental Fund (GEF). The GEF provides grants and concessional funds to developing countries for projects aimed at addressing climate change, desertification, deforestation, biological diversity, ozone depletion and protection of international waters.

The GEF has recognized the great value of photovoltaics in addressing several of these concerns. At the fringes of deserts in Africa and Asia, for example, villagers cut down trees to burn for fuel. This depletes the surrounding forests, causes the desert to expand and adds carbon dioxide — a greenhouse gas — to the atmosphere. Because PV is a non-carbon energy source able to replace wood- and oil-based power and energy needs, it can help to reduce the rate of desertification and deforestation while mitigating global warming. From 1991 to 1995, the GEF awarded $112 million to renewable energy projects, including photovoltaics. It is also developing a PV "Green Carrot" program to fund three companies or consortia with the most innovative proposals for accelerating PV technology and expanding commercial applications in the developing world. The awards are $15-$20 million each.

In 1996, the Indian government began disbursing $250 million in World Bank loans to promoters of photovoltaic and other renewables power projects. PV projects were granted the lowest interest rate of all (2.5%) over 8- to 10-year terms, with the Indian government paying 90% of the project costs for photovoltaic systems installed under this scheme. This kind of joint support from a national government and an international development bank will have a tremendous impact on the proliferation of photovoltaic power systems in the developing world.

Complete Photovoltaic Systems

Photovoltaic Technologies

Most people who use photovoltaics are not just interested in solar cells; they want a complete photovoltaic system to meet their specific needs. The photovoltaic cell or module only generates the electricity; other components — called the "balance of systems" — are needed to store, deliver and condition that electricity to match the electrical load.

By themselves, individual solar cells don't produce significant amounts of power — typically no more than 1 or 2 watts. To produce more power, several cells can be connected together and encased in a protective shell to form a module. Modules can then be connected to other modules to produce the correct voltage, current and power for the application.

A combination of modules is called an array. Arrays can be mounted on a fixed rack — the cheapest and most reliable solution — or they can be mounted on a tracking system that allows the array to follow the sun as it moves across the sky. Tracking systems make more efficient use of available sunlight.

Another way to increase power output is to use a lens to concentrate sunlight onto small, high-efficiency cells. This approach minimizes the amount of expensive semiconductor material used, but does require the use of a tracking system.

A photovoltaic module produces DC electricity in direct proportion to the amount of sunshine striking it. If the user needs a constant amount of electricity, or needs it when the sun is not shining, then a system for storing electricity must be provided. Batteries generally require a charge controller to protect them from being overcharged by the PV array or overdischarged by the load. And if the user needs AC electricity — to power conventional household appliances, for example — an inverter must also be used.

Grid-connected photovoltaic systems don't need batteries because the utility grid can be used for backup power. They do, however, require much more elaborate power conditioning. Grid-connected inverters have to regulate the flow of electricity from the utility to the load, from the PV array to the load, and from the array to the utility grid, matching the utility's AC wave form.

Today, balance-of-system components represent only about half the cost of a complete PV system yet, according to U.S. Department of Energy research, they are responsible for 99% of system repairs. While PV modules typically operate 20 years or more without any problems, inverters fail on average once or twice a year. Furthermore, about 15% of the electricity generated by photovoltaic modules is lost during conversion and transmission through balance-of-system components.

Although other system components are just as important to the viability of commercial products, the primary focus of photovoltaic research is to bring down the cost of electricity produced by PV cells and modules. Cell efficiency is an important factor, and so is manufacturing cost. This section examines key developments and turning-point issues in both of these arenas.

Dominant Solar Cell Technologies

The drive for lower cost and higher efficiency has spawned many different approaches to generating photovoltaic electricity, but virtually all (95%) of today's commercial PV modules are made using one of three solar cell technologies: single-crystal silicon, cast polycrystalline silicon and amorphous silicon thin films.

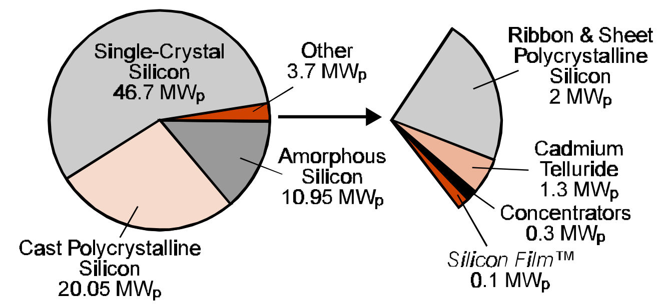
Crystalline silicon technology is the most mature and best understood photovoltaic technology, with a 40-year development history. Cells made from large, single crystals of silicon currently dominate the world market, accounting for 57% of global sales in 1995. Laboratory cells have reached efficiencies of 24%, and it is predicted that the efficiency of production modules will reach 22% by 2010. Cast polycrystalline silicon, which is cheaper to produce but a little bit less efficient, was used in approximately 25% of the PV modules sold in 1995. Both of these technologies involve sawing large ingots of silicon into thin wafers, which are then processed into solar cells. Unfortunately, much of the silicon is lost as sawdust in the process. By growing silicon crystals in ribbons or sheets that are already wafer-thin, the need for slicing can be minimized; still in development, this technology accounted for just under 3% of sales in 1995.

Thin films made with amorphous (noncrystalline) silicon captured almost 14% of the world market in 1995. Inexpensive to manufacture and fairly resilient, most of these modules are used in low-power consumer electronics. Cell efficiencies are somewhat limited, however, because the absence of a crystal lattice makes it more difficult for electricity to flow through amorphous silicon. The best laboratory cells have reached 11%, while commercial modules hover around 7% efficiency. Semiconductor materials other than silicon are also being investigated for use in thin films: copper indium diselenide shows considerable promise for the long term, and modules made with polycrystalline cadmium telluride are already commercially available, accounting for almost 2% of sales in 1995.

By sandwiching different types of semiconductor materials together in one multilayered (stacked) cell, more light energy can be absorbed by the cell. A growing number of amorphous silicon modules are made in this way. Stacked cells using other semiconductor materials have reached efficiencies greater than 30% in the laboratory, but none has yet been incorporated into production modules.

Together, all of the other photovoltaic technologies accounted for only 0.5% of the global market in 1995. This includes concentrator systems as well as novel, proprietary processes such as that used in making *Silicon Film*™, a type of thin film that incorporates polycrystalline silicon.

1995 World PV Cell & Module Shipments by Technology



Total World Shipments = 81.4 MWp

Source: *PV News*, February 1996 CD-SS25-B062313

PV Production Module Conversion Efficiencies (%) — Current and Projected

Cell Type	1995	2000	2010
Single-Crystal Silicon	15	18	22
Polycrystalline Silicon	14	16	20
Ribbon and Sheet Silicon	14	17	21
Concentrators (silicon cells)	22	25	30
Amorphous Silicon (including stacked cells)	7-9	10	14
Copper Indium Diselenide	7-9	12	14
Cadmium Telluride	7-9	12	14
Silicon Film™	8-10	12	15

(Source: Paul Maycock in *Solar Today*, Nov./Dec. 1995)

Crystalline Silicon Solar Cells

Silicon has been used in photovoltaic devices since the early 1950s. Although other materials have been found to have higher theoretical conversion efficiencies, there are significant technical and financial hurdles to implementing these alternatives. With so many years of research behind it, the properties of silicon are now very well-documented, and it would be extremely expensive to bring the knowledge about alternative materials up to an equivalent level.

While amorphous (noncrystalline) silicon is leading the thin-film revolution, most photovoltaic cells today are made with crystalline silicon. With its relatively high efficiency, stability, competitive cost and proven track record, crystalline silicon is likely to remain the dominant solar cell technology into the next millennium.

Scientists at AT&T's Bell Laboratories demonstrating one of the first silicon solar cells in 1954. This team was able to produce a solar cell with a conversion efficiency of 6%, establishing photovoltaics as a viable source of electrical power.

Obtaining Silicon for PV Cells

Silicon is the most abundant mineral in the Earth's crust, sand and quartz being two of its most common forms. In addition to its importance for PV, silicon is also the heart of the modern microelectronics industry. Virtually all computers, televisions, radios and other electronic devices use integrated circuits and other components fabricated from silicon.

The semiconductor-grade silicon used to produce solar cells and integrated circuits has to start out virtually 100% pure. (Specific chemical "impurities" are added later to improve conductivity.) Sand is not a good source of pure silicon since the silicon is chemically bound with oxygen and other impurities, but high-grade deposits of quartzite (rock quartz) can contain over 90% silicon. This quartzite is processed into metallurgical-grade silicon (98%-99% pure) which is then refined to produce semiconductor-grade silicon, a material that is at least 99.9999% pure.

About 15,000 tons of semiconductor-grade silicon are produced annually for the computer industry. Photovoltaic cells are usually made from the less expensive scrap silicon discarded by manufacturers of electronic devices. But more and more of this waste silicon is being absorbed by the semiconductor industry, pushing up the price. In 1995, silicon made up approximately 20% to 40% of the total cost of producing crystalline silicon PV modules.

From Crystals to Solar Cells

About half of the solar cells made today are cut from large, single crystals of silicon. Although performance has improved tremendously during the intervening years, this is essentially the same technology as that used in the earliest silicon solar cells over 40 years ago.

The use of silicon in photovoltaics was made possible by the development, during the 1940s and 1950s, of the Czochralski (pronounced *cho-kralski*) process for growing large, single crystals of silicon (see illustration, opposite). These crystals are required to have an extremely small number of defects in the atomic structure of the crystal lattice.

Such defects reduce the cell's performance. Although other methods of growing crystals have been developed, Czochralski silicon is still the most popular raw material for manufacturers of single-crystal silicon cells.

Once a cylindrical ingot of silicon has been grown, a special saw is used to slice the ingot into thin wafers, which are then processed into solar cells. Sawing wastes about 20% of the valuable crystal material as sawdust. Silicon is also wasted because the wafers are cut thicker than they have to be for optimum photovoltaic performance. This is because crystalline silicon wafers are very brittle, and thicker cells are more resistant to breakage during the manufacturing process.

To create an electric field, the wafer must carry a positive charge on one side and a negative charge on the other. This is accomplished by treating the silicon with two different chemicals in a process called "doping." Boron is diffused throughout the crystal by adding it to the molten silicon before the ingot is drawn. The cut wafers are later doped on one side only with phosphorus. The phosphorus diffuses a short distance into the wafer, creating a very thin layer that has more free electrons than the layer that contains only boron. Electrons carry a *negative* charge, so the phosphorus-doped layer is called "n-type." Boron increases the presence of weak atomic bonds that are short of one electron. These bonds, or "holes" as they are called, have a *positive* charge, so boron-doped silicon is referred to as "p-type" silicon. In the n-type layer, the phosphorus overrides the effect of the boron. An electric field forms across the junction (known as the "p-n junction") between these two layers. Electrical contacts are then attached to each side of the wafer, so that the cell can be connected to an electric circuit, and an antireflection coating is applied to the top surface of the cell.

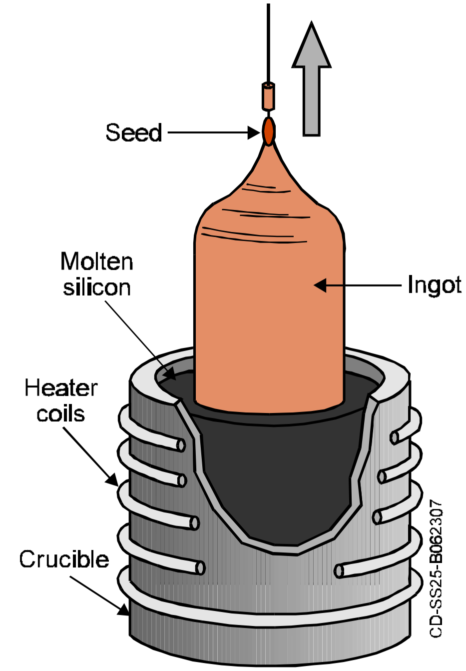
Although all crystalline silicon cells have these same elements in common, modifications in cell design are steadily increasing the efficiency of single-crystal cells and cutting the cost of their manufacture.

Improvements in Cell Design

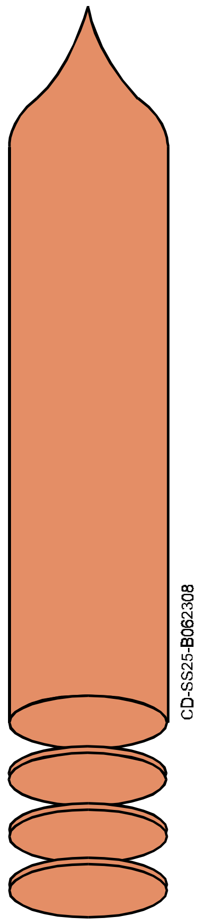
The strength of the photovoltaic effect is determined by the amount of light penetrating the semiconductor material. Untreated silicon cells are so shiny that they reflect back more than 30% of the incoming light, and traditional cell designs incorporate front-contact grids that cover 3% to 5% of the surface, shading the silicon wafers below. Both of these issues have been tackled in an effort to improve cell performance.

A couple of different methods are used to reduce the reflectance of the top surface. Depositing a single layer of silicon monoxide reduces surface reflection to about 10%, and adding an additional layer of another substance can reduce reflection to less than 4%. Another way to reduce reflection is to texture the top surface of the cell with an inexpensive chemical etching process: light that has an 80% chance of being absorbed by a flat surface will have a 96% chance of being absorbed by a textured surface. The highest-efficiency cells today incorporate two antireflection coatings as well as a textured surface, a combination that can cut reflection to less than 2% of incoming light.

Several innovative approaches are being tried to reduce shading by the front-contact grid. In the *micro-grooved cell*, a laser beam is used to cut thin, vertical slits into the top surface of the cell; electrical contacts are then inserted into these slits. This approach allows for excellent conduction, because the contacts have quite a large surface area, while significantly reducing shading. In the *emitter-wrap-through cell*, both positive and negative contacts are



The Czochralski process for making large crystals of silicon. A small seed of silicon with a perfect crystal structure is brought into contact with some molten silicon in a crucible, and is then slowly withdrawn (moving less than one inch per hour). The molten silicon sticks to the seed and cools, gradually solidifying in the same molecular pattern as the seed crystal. In this way, the crystalline structure of the seed is extended into the solidifying silicon. As the seed is raised, it pulls a cylindrical single crystal of silicon behind it. The finished ingot typically weighs in the order of 500 pounds and measures about 5 inches in diameter.



After a cylindrical ingot of single-crystal silicon has been grown, it is sawn into thin wafers for further processing into photovoltaic cells. The sawing process wastes about 20% of the silicon as sawdust.

attached through the back of the cell, avoiding any shading of the front surface. A variation on this theme, the *point-contact cell*, incorporates a pattern of small, isolated n- and p-type patches that are diffused through the silicon wafer. Metal contact points are applied only to the center of these patches, again through the back of the cell.

In the manufacturing arena, the crystalline silicon industry is moving in the direction of using larger cells. Traditionally, circular wafers have been trimmed to a square shape so that more semiconductor material could be packed into a module. This is because there is virtually no dead space between square cells. But manufacturers have found that they save more by eliminating the cost of sawing wafers into squares than they lose by spending more on the extra glass and framing required for the bigger modules necessary to accommodate circular cells. Modules made with round wafers also run cooler because of the white space in between the cells. The integrated-circuit industry is producing silicon wafers up to 10 inches in diameter, and several PV companies have taken advantage of these larger wafers to use larger cells in their modules.

Polycrystalline Silicon

While single-crystal silicon remains unchallenged as the most efficient flat-plate technology available today, it is also the most expensive. Solar cells made of polycrystalline silicon material — consisting of several small crystals — have become popular because they are less expensive to produce. Cast polycrystalline silicon was used in approximately 25% of the PV modules sold in 1995.

The manufacture of most polycrystalline cells begins with a casting process in which molten silicon is poured into a rectangular mold. Casting produces a square block of polycrystalline silicon that is approximately 8 inches on each side (see illustration on opposite page). This ingot is then sliced into the 4-inch-wide square wafers that are used to make solar cells. Being square, these cells can efficiently be packed into a rectangular module.

Although polycrystalline cells are cheaper to produce, they are not quite as efficient because: (1) they contain more impurities, and (2) the electricity flowing through them has to jump across the boundaries between crystals. The cost-efficiency trade-off means that the "per watt" cost of electricity from polycrystalline cells is about the same as from single-crystal cells. Their lower efficiency

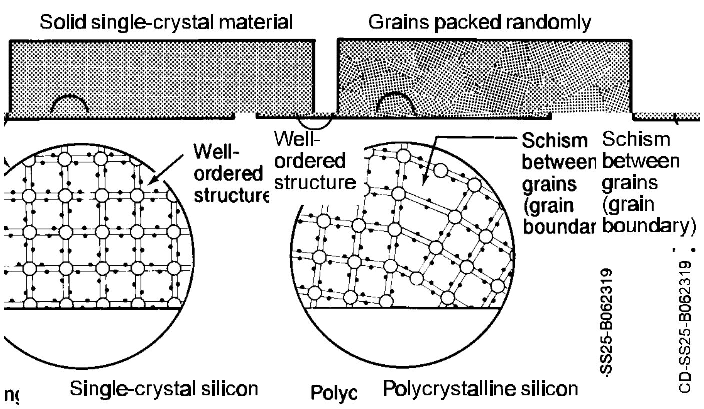
Photovoltaic modules being installed on the roof of the covered swimming pool used for the 1996 Summer Games in Atlanta, Georgia. This 311-kW_p, polycrystalline silicon system from Solarex Corporation and Solar Design Associates is connected to the utility grid.

means that polycrystalline modules have to be a little larger to achieve the same power output.

The crystals, or "grains," in polycrystalline silicon are typically quite large, around 3/8 inch across. For this reason, polycrystalline material is sometimes referred to as "semicrystalline," and much of the photovoltaic literature uses these terms interchangeably. Because the material is made of more than one crystal, it is also sometimes called "multicrystalline."

Even very small crystals of silicon can make successful solar cells. One company is developing thin-film solar cells made by growing a thin layer of polycrystalline silicon on a proprietary, low-cost substrate. The individual crystal grains in these *Silicon Film*™ cells are only about 40-100 microns in diameter, about the thickness of a human hair.

A number of different techniques are being used to improve the performance of polycrystalline silicon. Poor conduction at the grain boundaries is one issue that has received considerable attention. One approach to this problem is to modify the crystal lattice by annealing (heating and cooling) the material. This changes the naturally randomly oriented grains into larger, more columnar ones, so there are fewer grain boundaries. Introducing hydrogen into the wafers, in a process called "passivation," has been found to improve the flow of electricity across the grain boundaries that remain.

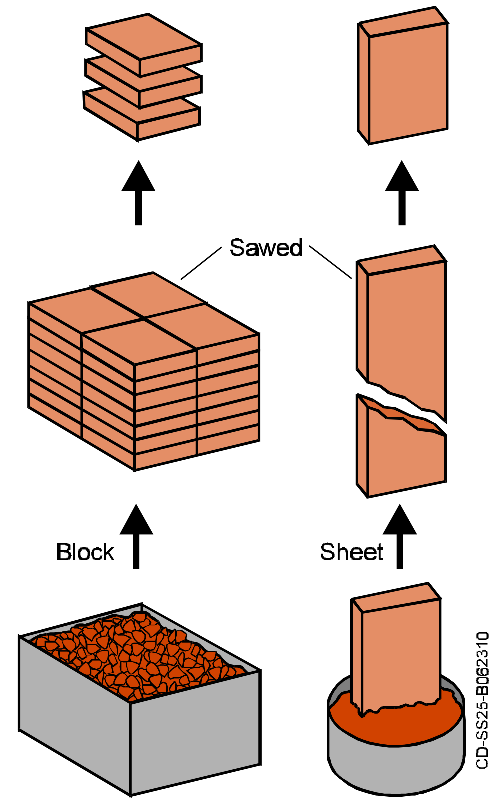


Single-crystal silicon (left) is structurally uniform, with no disturbances in the orderly arrangement of atoms. Polycrystalline silicon (right) is made up of several crystals or grains, and its molecular structure is disrupted at the interface where one miniature crystal ("grain") meets another. It can be difficult for electricity to jump across these grain boundaries, which is why electricity travels through solid, single-crystal silicon more easily.

As with single-crystal silicon cells, the top surface of polycrystalline cells has to be treated to reduce the amount of sunlight reflected away. The chemical etching process used with single-crystal cells is not suitable for polycrystalline materials, which today are mechanically etched. A promising approach to reducing reflectance is to deposit a textured film directly onto the top surface of the cell. Applying a coating is quicker and less expensive than mechanical texturing, and cells produced in this way match the performance of conventionally produced cells.

Ribbon and Sheet Silicon

One way of virtually eliminating the sawing step associated with other types of crystalline silicon is to grow strips of polycrystalline silicon that are already wafer-thin and the right width for use in solar cells (see illustration, right). These ribbon-growth technologies are cost competitive with casting techniques and show great potential, particularly because of the high efficiency (13%-14%) of current production modules.

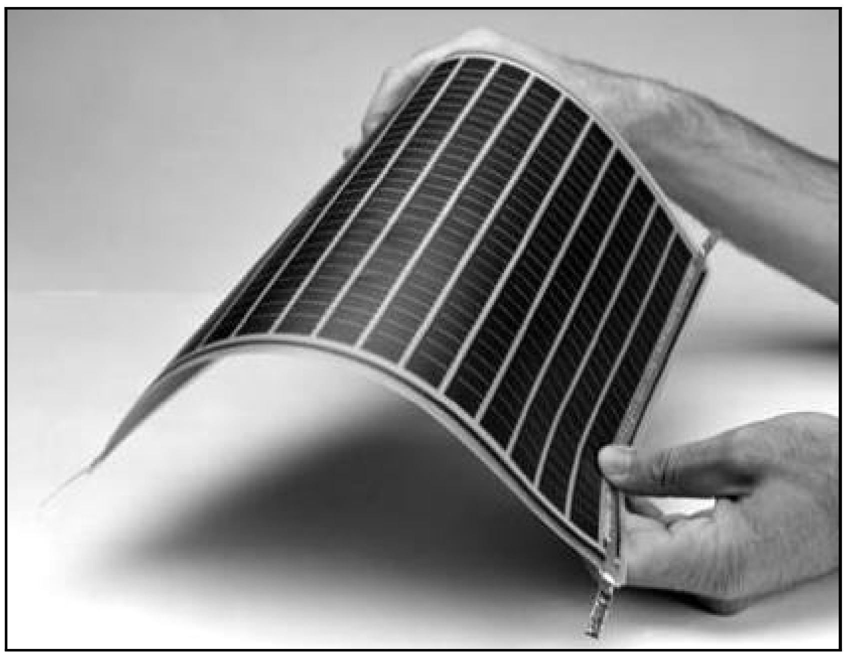


Two ways to make square polycrystalline cells for PV modules. Casting, on the left, involves slicing large ingots of silicon into square wafers. Ribbon-growth methods involve growing thin, rectangular strips of silicon that only have to be cut on two ends to produce a wafer.

Thin-Film Solar Cells

The development of photovoltaic thin films has largely been motivated by the substantial cost savings possible with this technology. They are also lighter, more resilient and easier to manufacture than crystalline silicon modules.

Thin-film modules are constructed by applying extremely thin (down to 1 micron thick) layers of photosensitive semiconductor material to a low-cost backing such as glass, plastic or thin, flexible steel sheets. They require much less semiconductor material per photovoltaic device than crystalline silicon modules, so the materials cost is correspondingly lower, and their light weight means that they require less structural support. Thin-film manufacturers can also make use of existing industrial processes, such as those used to manufacture and coat glass, instead of having to design all of their production equipment and procedures from scratch. And thin films require less labor-intensive handling because they are produced as large, complete modules, not individual cells that have to be mounted in frames and then wired together.



Thin-film modules, such as this one made with amorphous silicon, can be deposited on a variety of low-cost substrates, including glass and flexible plastic sheets.

Instead of physically assembling the semiconductor material, electrical contacts, an antireflection coating and protective layers, thin films are made by sequentially depositing separate layers of these elements directly onto the chosen substrate. The substrate, typically glass or plastic, provides structural support and usually doubles as the top protective layer of the module, already saving a step over the manufacture of crystalline silicon modules.

The first coating applied to the substrate is the front electrical contact. Instead of using a metal grid to collect the current, this contact consists of a thin layer of a transparent metal oxide, such as tin oxide or zinc oxide. These oxides conduct electricity very well, and can even be textured to double as antireflection coatings.

In a typical thin-film manufacturing plant, the coated substrate is then fed into an environmentally sealed, continuous-flow processing machine, which applies each of the semiconductor layers in turn. The use of this machine cuts down on the amount of handling, saving on labor and minimizing the opportunity for contamination. It also uses little energy and is potentially able to produce modules several square feet in size, much larger than the 4-inch-square wafers typically produced with crystalline silicon technology.

A thin base layer of metal — usually aluminum or silver — is sometimes added in the machine. This layer serves as a back contact and also reflects incoming light back up through the semiconductor materials, making the best use of light passing through the module. Individual cells are then formed by scoring through each layer (down to the substrate) with a laser beam. In other cases, the laser scribing is done *before* adding the back contacts, which can then be screen-printed onto the module in the same pattern as the scribed cells.

Thin films are highly versatile because they conform to the structure, shape and flexibility of the substrate. This unique property is what enables thin films to be used in innovative new products such as photovoltaic roofing shingles.

Amorphous Silicon

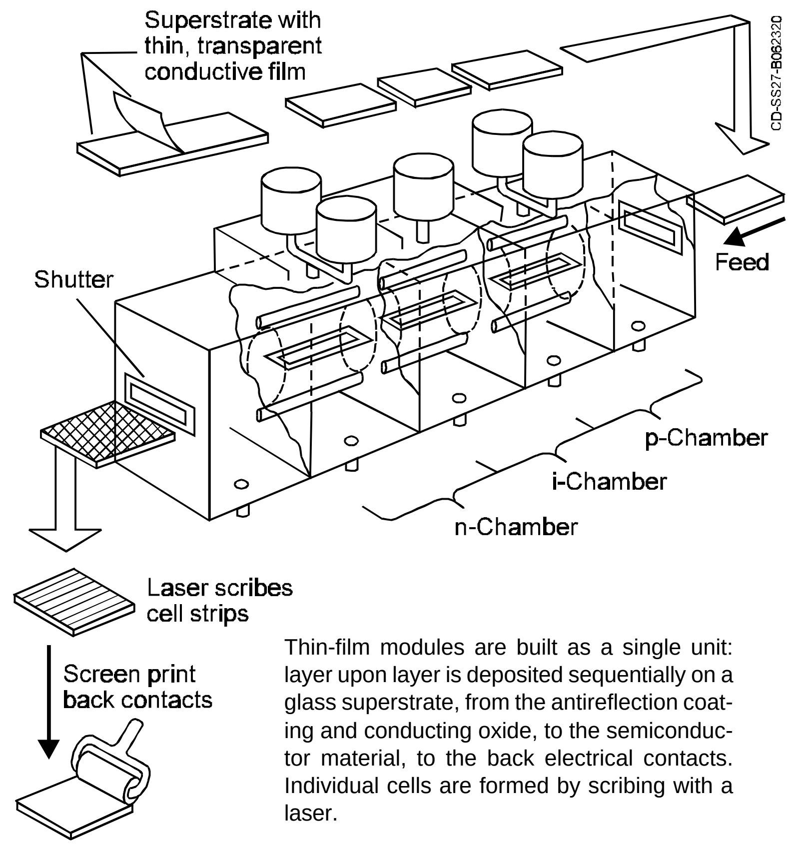
The most fully developed of the thin-film technologies, amorphous silicon, has been around only about half as long as crystalline silicon technology. Originally used for optically sensitive coatings on copying machine drums, it wasn't until 1974 that researchers discovered that they could use amorphous silicon in photovoltaic cells. Remarkable strides have been made since then, and amorphous silicon is receiving considerable attention from laboratory researchers and manufacturers alike.

According to industry analyst Paul Maycock, most of the 750 professional, scientific and engineering personnel directly engaged in PV research around the world are working on amorphous silicon. And about half of the total expansion in PV module manufacturing capacity currently under way in the United States is in thin-film amorphous silicon. The efficiency of commercial modules continues to improve, going from around 3.5% in the early 1980s to 7% by the mid-1990s, and prototype modules have been produced with efficiencies as high as 10%. In 1995, amorphous silicon was used in approximately 14% of the PV modules sold worldwide.

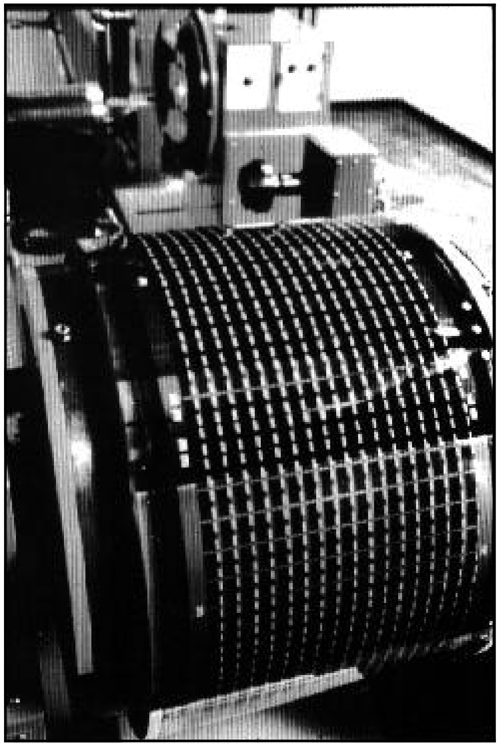
Amorphous solids, such as common glass, are materials in which the atoms are not arranged in any particular order. They do not form a crystalline lattice at all, and contain large numbers of structural and bonding defects. This disorganized structure makes it much more difficult for electricity to move through the substance, even more so than with polycrystalline material, limiting its efficiency. Adding hydrogen significantly improves electrical conductivity, however, and amorphous silicon films include about 10% hydrogen.

A potential handicap with amorphous silicon is the fact that the number of atomic defects increases with exposure to sunlight, which reduces efficiency even further. Scientists have, however, found ways to construct amorphous silicon modules whose conversion efficiencies stabilize after an initial breaking-in period. The initial decrease in efficiency is around 10% to 20%, and amorphous silicon efficiencies nowadays are reported in terms of "stabilized efficiency."

The poor mobility of electrons through amorphous silicon is made even worse by doping. To overcome this, amorphous silicon cells are designed with an undoped ("intrinsic") layer sandwiched in between doped p-type and n-type layers. The top p-layer is made so thin and relatively transparent that most light passes right through it into the intrinsic layer, where free electrons are more easily



Thin-film modules are built as a single unit: layer upon layer is deposited sequentially on a glass superstrate, from the antireflection coating and conducting oxide, to the semiconductor material, to the back electrical contacts. Individual cells are formed by scribing with a laser.



Energy Conversion Devices has been manufacturing rolls of film, such as this one made from multi-junction amorphous silicon alloys on steel sheet, since 1993.

generated. The top p-layer and the bottom n-layer induce an electric field across the intrinsic layer in a manner similar to the way an electric field is induced across the p-n junction of a crystalline silicon solar cell.

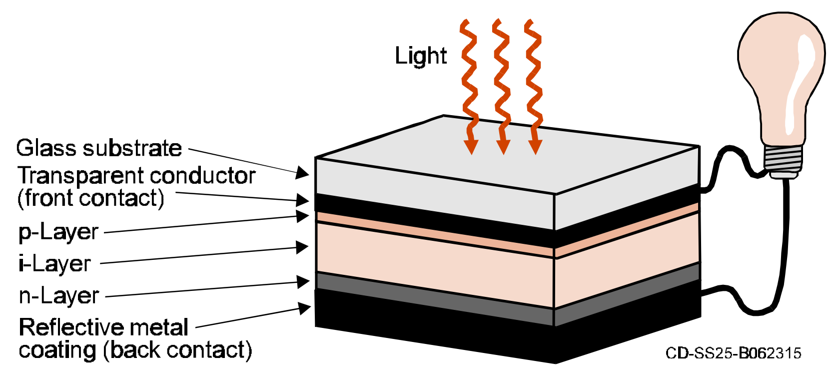
Despite these apparent disadvantages, amorphous silicon also has some important properties that explain its popularity. To begin with, it absorbs solar radiation 40 times more efficiently than single-crystal silicon, which means that a film only 1 micron thick can absorb 90% of the usable solar energy. Amorphous silicon thin films can therefore be made using less than 1% of the expensive semiconductor-grade silicon required by single-crystal or polycrystalline devices, saving substantially on materials costs. They also have a higher output voltage than crystalline modules and are more tolerant of high temperatures, such as those encountered in direct-mount rooftop applications. In fact, the efficiency of amorphous silicon modules degrades less at higher operating temperatures due to a self-annealing effect. Another factor is that the method used to manufacture amorphous silicon modules can easily be adapted to produce cells with multiple layers (see page 36), which are significantly more efficient than single-layer cells. A growing proportion of amorphous silicon modules are being produced with multilayered cells.

Polycrystalline Thin Films

Thin films can also be made using a number of different *polycrystalline* materials. One example of a polycrystalline thin-film technology is *Silicon Film*™, which uses silicon; other suitable materials include cadmium telluride and copper indium diselenide.

Cadmium telluride is already commercially available, and is widely regarded as having the best long-term prospects of any thin-film photovoltaic technology, partly because it is the easiest to manufacture. Modules can be produced using a variety of very common industrial processes, such as electrodeposition and spray pyrolysis, that do not require expensive capital equipment. Electrodeposition involves passing electricity through a solution containing ions of the required elements, which then attach themselves to an electrode (which acts as a substrate). This is the same process used to add gold plating to jewelry. With spray pyrolysis, a solution containing the necessary elements is sprayed onto a hot substrate; the heat then causes the chemicals to react and stick to the substrate while the solvent evaporates.

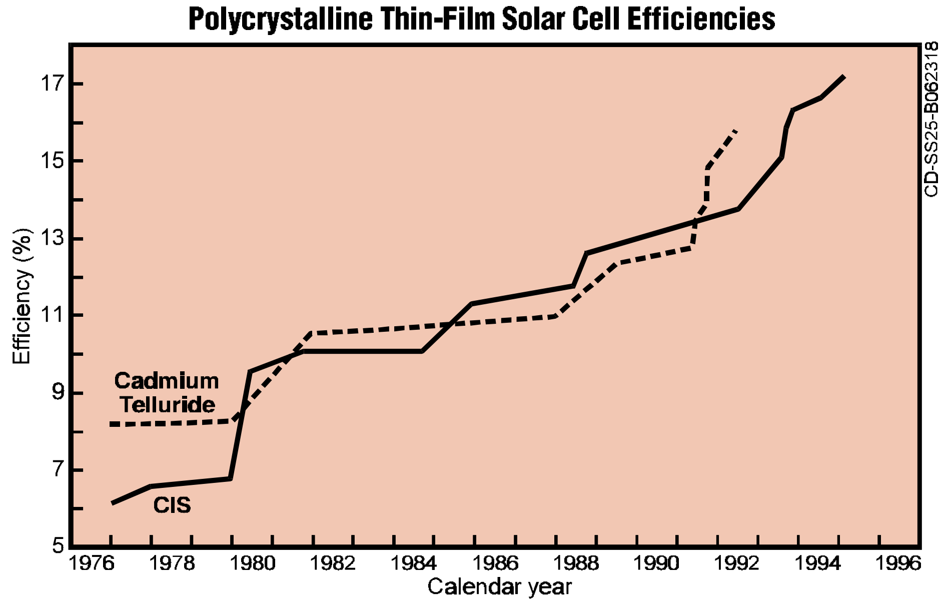
Initial concern over the use of cadmium — the same toxic metal used in nickel-cadmium batteries — has faded. The amount of cadmium used in these PV modules is very small, and existing manufacturers have implemented excellent waste-handling strategies: Suppliers take back in-plant wastes for resmelting, and plans exist for eventual recycling of the modules.



The typical amorphous silicon solar cell employs a p-i-n design, in which an undoped intrinsic layer (i) is sandwiched between a p-layer and an n-layer.

Copper indium diselenide (CIS) is a promising photovoltaic compound, partly because it is extremely good at absorbing light: 99% of the incoming solar energy is absorbed by the first micron of the material. Also, unlike other thin films, outdoor reliability has never been an issue. CIS modules exhibit remarkably stable conversion efficiencies over the long term, an important criterion for commercialization. Ordinarily consisting of three elements — copper, indium and selenium — in combination, the highest efficiencies in laboratory CIS cells have been attained by adding the element gallium, which also has the effect of improving the cell's tolerance to any variations in chemical composition that arise during manufacture.

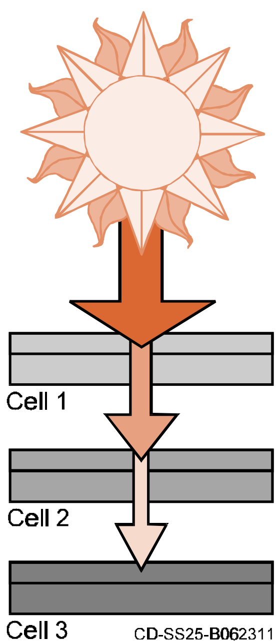
CIS is the performance leader in thin-film photovoltaics: the best laboratory cells have reached over 17% efficiency, almost as high as the best polycrystalline silicon cells, which currently are less than 18% efficient. This proves that thin films can perform exceedingly well. As with any relatively new technology, the key to progress lies in transferring laboratory advances to commercial production. A variety of manufacturing techniques can be used, including the electrodeposition and spraying methods used with cadmium telluride. Another popular method involves heating small amounts of each element to the point where the atoms vaporize; they then condense on a cooled substrate to form a CIS layer. All of these methods were developed in the computer-related thin-film industry, and show considerable potential for low-cost production.



The best one-of-a-kind laboratory cell efficiencies for thin films now approach the best efficiencies achieved by polycrystalline silicon. Researchers at the University of South Florida have developed cadmium telluride cells that approach 16% efficiency, while scientists at the National Renewable Energy Laboratory have developed small-area CIS cells with efficiencies approaching 18%, the highest efficiency of any thin-film cell in the world. These achievements, once thought impossible, are the basis for expecting thin films to become the dominant solar cell technology in the future.

John Jordan and Scot Albright of Golden Photon holding a prototype cadmium telluride module, made by spray pyrolysis. Golden Photon delivered a 25-kW_p array incorporating modules such as this to the U.S. Navy in January 1996; at the time, this was the largest cadmium telluride array in the world.

Solar Cells in Layers



A multijunction device stacks individual single-junction cells on top of each other in descending band-gap order. The top cell captures the high-energy photons and lets the rest of the photons through to be absorbed by the lower-band-gap cells below.

Different photovoltaic materials absorb different parts of the solar spectrum. Most solar cells are made with only one type of photovoltaic semiconductor material. This wastes the energy contained in those parts of the spectrum that the cell cannot absorb. One approach to reducing the cost of photovoltaic electricity is to improve cell efficiency by capturing more of the solar energy spectrum. This is accomplished by constructing multilayered cells that use a combination of semiconductors, each of which is sensitive to different wavelengths of light.

Light at the blue end of the spectrum has a shorter wavelength and more energy than light at the red end of the spectrum. When light strikes a photovoltaic cell, only some of the photons have sufficient energy to knock electrons free from their atoms. These free electrons are said to be in the "conduction band" because they enable the material to conduct electricity. The energy required to move an electron from its atom to the conduction band is called the band-gap energy.

Photovoltaic materials with lower band-gap energies can exploit a broader range of the sun's energy spectrum. This is because even relatively low-energy ("red") photons will have sufficient energy to free electrons from their atoms, enabling the cell to produce electricity. But low-band-gap materials also produce low voltages, which is not always desirable.

The most efficient photovoltaic cells incorporate materials with both high and low band-gap energies (see diagram, left). These multilayered cells actually consist of two or more cells on top of each other. Each component cell has its own junction (interface) across which an electric field is formed, so the complete multilayered cell is usually referred to as a multijunction device or cell.

Multijunction cells are made in one of two ways: monolithic or mechanically stacked. Monolithic multijunction cells are made by sequentially growing all of the necessary layers of materials for two cells and the interconnection between the cells, one layer on top of another. With mechanically stacked multijunction cells, different cells are made separately, stacked on top of one another, and stuck together with transparent adhesive.

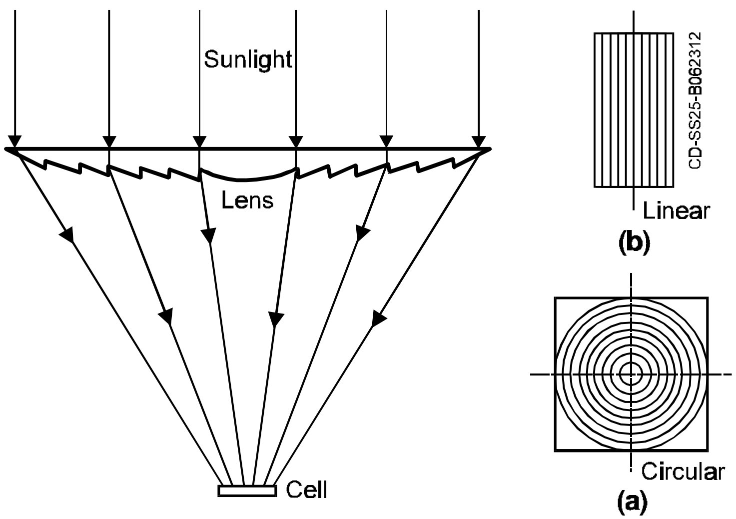
Thin-film multijunction devices are usually made monolithically. The process is relatively straightforward and requires very little energy, so such devices are relatively inexpensive to fabricate, typically costing only 10%-20% more than a single-junction cell. Performance improvements far outweigh the modest increase in expense.

In some cases, higher efficiencies result even if the same semiconductor materials are used for the top and bottom cells. This is the case with amorphous silicon multijunction cells, which have higher stabilized efficiencies than regular amorphous silicon thin films (see page 33). This is partly because there is less light-induced degradation in very thin amorphous silicon cells with extremely thin intrinsic layers, such as those used to make up multijunction devices — hence the higher stabilized efficiency. Even greater improvements in efficiency can be achieved by alloying the amorphous silicon with materials such as carbon or nitrogen to vary the band gap of each component cell.

Concentrators

Another approach to reducing the cost of photovoltaic electricity is to use optical lenses and/or reflectors to concentrate the sunlight falling on the solar cell. The greater light intensity means that more power is generated by the cell, so a given amount of power can be produced using a smaller quantity of semiconductor material. This reduces cost because the solar cell is the most expensive component in a photovoltaic system. Another, incidental, advantage of concentrators is that cell efficiency increases slightly under concentrated light.

Laboratory efficiencies of almost 33% have been reached by a concentrator incorporating a multijunction solar cell based on gallium arsenide (see page 38). This is the highest verified efficiency for any type of photovoltaic device.



A Fresnel lens, the most common lens used in concentrator systems, can be designed to focus light at a point (a) or along a line (b). The lens is made from a sheet of plastic that typically is flat on the upper side and that has sawtooth grooves on the bottom. If the grooves are etched in parallel ridges (b), they concentrate light along a line or strip of solar cells. If they are etched in concentric circles (a), they concentrate light at a point.

Most concentrators use inexpensive Fresnel lenses (see diagram). These plastic lenses are lightweight and can be mass-produced by casting them in molds at very reasonable cost. Line-focus Fresnel lenses can intensify solar radiation up to about 50 times, whereas point-focus concentrators can achieve concentration ratios up to 500.

In a collaborative venture with the City of Austin, the 3M Company installed this 300-kW_p linear concentrator system on the multistory parking garage adjoining its research facility in Austin, Texas. Designed by ENTECH, Inc., and manufactured by 3M, this computerized, two-axis tracking system features curved Fresnel lenses.

Compared to flat-plate systems, a drawback with concentrators is that they have to be used with tracking systems to keep them pointed into the sun. The higher the concentration ratio, the more critical precise focusing becomes, and the more precise the tracking system has to be. Two-axis trackers, which move up and down as well as side to side, are used with most concentrating systems. Modern two-axis trackers are quite reliable and require little maintenance, but they are also relatively expensive.

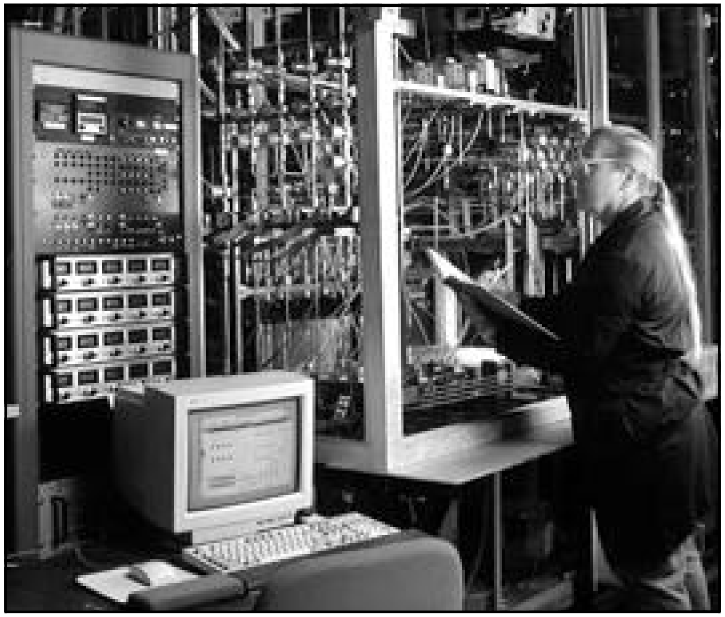
Another drawback with concentrators is that they can use only direct sunlight. The diffuse portion of sunlight, the part that you can see on a cloudy day, is not available to concentrators because it cannot be optically focused. Concentrator systems therefore operate most effectively in sunny, dry climates that experience fewer cloudy days.

Advanced Photovoltaic Technologies

During the 1990s, photovoltaic research has taken the technology to new frontiers. Dramatically increased cell efficiencies and entirely new applications have been made possible by recent laboratory advances. Two of the new technologies seem particularly likely to have important commercial uses in the not-too-distant future.

High-Efficiency Cells

While silicon is still the most popular photovoltaic material in use today, solar cells of the future are more likely to use a group of substances known as "III-V" (three-five) materials. These materials are so called because they consist of elements in groups three and five of the periodic table in chemistry, including gallium (Ga), indium (In), arsenic (As) and phosphorus (P).



This equipment, located at the U.S. Department of Energy's National Renewable Energy Laboratory, is used to make sophisticated, high-efficiency photovoltaic devices. A single commercial reactor of this type would be capable of producing as much as 500 MW_p of solar cells for concentrators per year.

The development of III-V alloys — such as gallium arsenide (GaAs) and gallium indium phosphide ($GaInP_2$) — has made possible record-breaking efficiencies for multijunction devices and concentrator systems. Cells incorporating these materials have reached laboratory efficiencies of 30% under one sun, and nearly 33% under concentrated sunlight. It should be possible to achieve sunlight-to-electricity conversion efficiencies approaching 35% under one-sun illumination and 40% with concentration.

Gallium arsenide, the most important III-V compound, has a number of very useful properties. It has an ideal band gap (see page 36) for use in single-junction solar cells; it is highly absorptive, requiring a cell only a few microns thick to absorb sunlight; it is relatively insensitive to heat, which makes it particularly suitable for use in concentrators, where cell temperatures can get very high; and it is very resistant to radiation damage, a significant advantage in space.

Although they are still very expensive, these materials are already cost effective in space applications because of their ability to endure high-energy radiation and because of the great amount of power they can produce in relation to their weight. In fact, the latest communications satellites are being powered by III-V solar cells. Here on Earth, III-V materials are cost effective in concentrator systems, where the photovoltaic cells are so tiny that the cost of the material is considered secondary to its performance.

Electricity From Heat

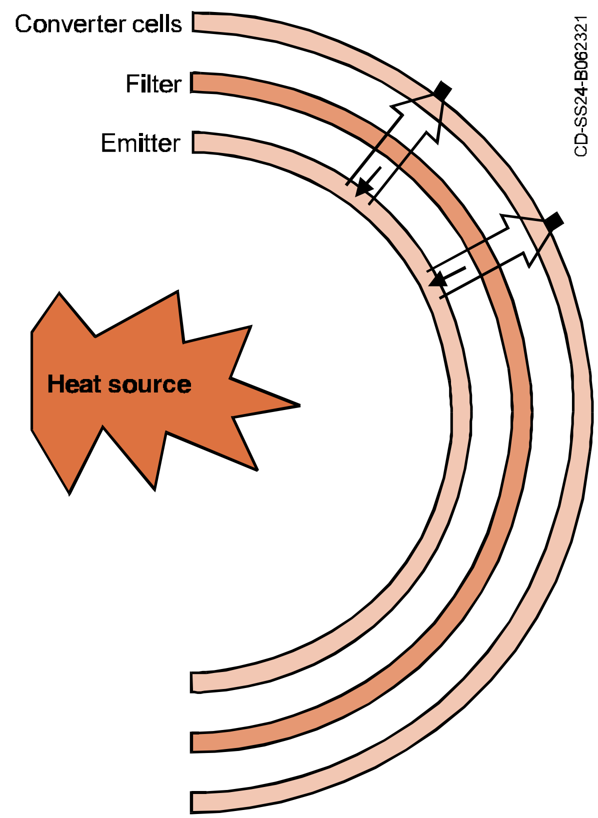
The process of generating electricity from heat has traditionally required several stages. A fluid medium such as water is first heated to produce steam; the steam then turns a mechanical turbine, which spins a magnetic-field generator. Alternatively, heat energy can be converted to mechanical energy by "burning" fossil fuel in an internal combustion engine. But now there is a cleaner, quieter, simpler way to produce electricity from heat without the need for any of these intermediate steps.

Thermophotovoltaics (TPV) uses solid-state electronic devices to convert radiant heat energy to electricity in much the same way as solar cells convert sunlight to electricity. While conventional photovoltaic devices use primarily visible light, a TPV converter uses the invisible, longer-wavelength infrared radiation emitted by a "glowing" hot object. The object can be heated by combustion of a fuel such as natural gas or propane, or by virtually any other high-temperature heat source.

TPV became a viable power-generating technology when researchers developed the ability to carefully tailor the band gap of a cell to match the type of incoming radiation. This made it possible to "tune" the converter cells to the temperature of the emitter, significantly improving the heat-to-electricity conversion efficiency of the device.

Overall fuel-electric conversion efficiencies in the range of 10%-20% should be readily attainable. This is comparable to the efficiency of small gasoline and diesel generators — but TPV has some important advantages. With no moving parts, TPV systems are relatively maintenance-free and quiet when compared with portable generators and, because they use complete combustion in a continuously burning flame, TPV devices also run much cleaner — with virtually no carbon monoxide and very low hydrocarbon emissions.

Several firms are actively developing products based on TPV technology. Potential near-term uses include gas furnaces that generate their own electricity for self-ignition (so that they can keep running during a power outage), and portable generators and battery chargers for remote-home, recreational or military field use.



TPV systems use a heat source to heat an emitter so that it "glows" with infrared radiation. A filter allows usable radiation to pass through to the converters (which generate electricity directly) but reflects longer-wavelength radiation back to the emitter, keeping it hot.

The Future of Photovoltaics

As production grows and the international market expands, improvements in materials, cell design and manufacturing processes offer increasingly efficient and less expensive photovoltaic modules. At the same time, the needs of end users and the ingenuity of system designers is fostering an ever-expanding range of applications, both at home and abroad.

Growing Markets

The United States leads the world in shipments of photovoltaic power modules, and its share of this market is increasing. This means that U.S. companies are well placed to take advantage of the steady growth in the international demand for power, especially from developing countries not yet committed to extensive, centralized electricity distribution grids. Photovoltaics can play a major role in extending basic services to people in the developing world, but the availability of suitable financing mechanisms will play a critical role in determining the rate of market penetration.

On the domestic scene, the greatest expansion in demand is likely to come from the utility sector. Photovoltaic systems are already being used to support local electricity grids through grid-connected buildings and PV-supported substations. It is clear that photovoltaics will soon offer utility companies a realistic alternative to peaking power stations, with bulk power applications not far over the horizon. Current concerns about global warming — which many scientists believe is aggravated by burning fossil fuels — could accelerate the introduction of photovoltaics for both peaking and baseload utility requirements.

Both domestic and international consumer markets are also likely to continue to grow, although this will not necessarily help U.S. industry a great deal, since Japan still has the edge in supplying photovoltaic cells for consumer products.

Key Technologies

Terrestrial photovoltaics, derived as an answer to the 1970s oil crisis, has been commercialized in less than 20 years. The technology is still very young, and it is difficult to accurately predict the changes that could take place as photovoltaics becomes more commonplace over the next 20 years. But we can identify the factors that are likely to shape future developments.

Materials utilization is one factor that is likely to become increasingly important as the technology matures. Analyzing a variety of mature industries indicates that the ultimate cost limit is associated with materials costs. This suggests that the low materials usage of thin films may become decisive, pointing to a bright future for this technology.

Despite some significant obstacles, amorphous silicon has already established itself as a viable

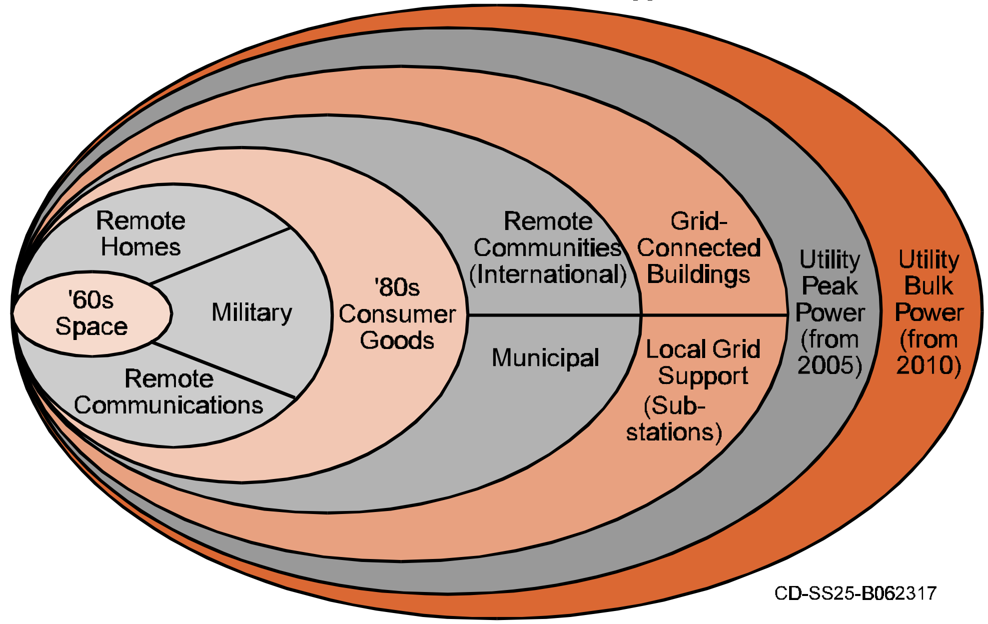
An aerial view of the Brundtland Center in Toftlund, Denmark. Opened in the summer of 1995, this high-tech office building makes use of several energy efficiency and renewable energy technologies, including the country's largest photovoltaic array. Semitransparent solar cells are integrated into the glass of the atrium roof, providing partial shading while producing 11,500 kWh of electricity at 220 volts AC.

competitor to wafer-based crystalline silicon devices. Once it becomes better established in the marketplace, amorphous silicon is likely to make good progress and could even come to dominate the world photovoltaics market. Meanwhile, the next generation of thin films — CIS and cadmium telluride — shows stronger technical performance (efficiency and stability) and promises similar or lower manufacturing costs. The goals for truly inexpensive photovoltaics are ambitious (30-year module life, 15% efficiency and a price around $0.50 per watt), but thin films seem capable of reaching, or even exceeding, these goals.

Before photovoltaics can be used for generating baseload utility power, significant strides must be made in the way electricity is stored. PV systems have to generate all of the electricity required over a 24-hour period during the hours of daylight, which means that a tremendous amount of energy must be stored for a long time — at least 12-16 hours, depending on latitude and season. Excess utility power is traditionally stored electrochemically (in batteries) or by pumping water into elevated storage reservoirs and using the water to generate electricity during periods of peak demand. Significant improvements in battery technology seem unlikely, and current thinking is that hydrogen fuel — produced from water by passing an electric current through it — may provide the best medium for storing PV energy in the future.

This document describes several viable approaches to the manufacture of low-cost, high-efficiency photovoltaic modules. But commercial PV modules of the future could be based on technologies that don't yet exist outside the realm of ideas. As an example, researchers in Switzerland are developing a photovoltaic system that emulates the process of photosynthesis (by which plants harness the sun's energy). In this new cell, the process of light

Diffusion Model for Photovoltaic Applications



Following its success in space, photovoltaic power came down to Earth in the 1970s to find other niche markets in the armed forces and a small number of remote-power applications. As these markets continued to grow, the 1980s witnessed a proliferation of PV-powered consumer products. In the 1990s, PV systems began to be used for municipal applications in the U.S. and to power homes and communities in the developing world. The domestic utility market is now gradually opening up, with building-mounted PV systems and local grid support expected to be well-established by the year 2005. Soon after that, photovoltaic electricity is expected to be cost-competitive for utility bulk power applications.

absorption is separate from the transportation of the electrical charge. In conventional cells, the semiconductor material fulfills both functions simultaneously, creating very heavy demands on the purity of the material, which therefore carries a very high price tag. Novel approaches emulating biological systems could be the key to the future, or they could be an evolutionary dead end. Time will tell.

One thing, however, is clear: as humankind enters the new millennium with ever-increasing energy requirements, photovoltaic technology will make a significant contribution to the sustainability of global civilization.

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