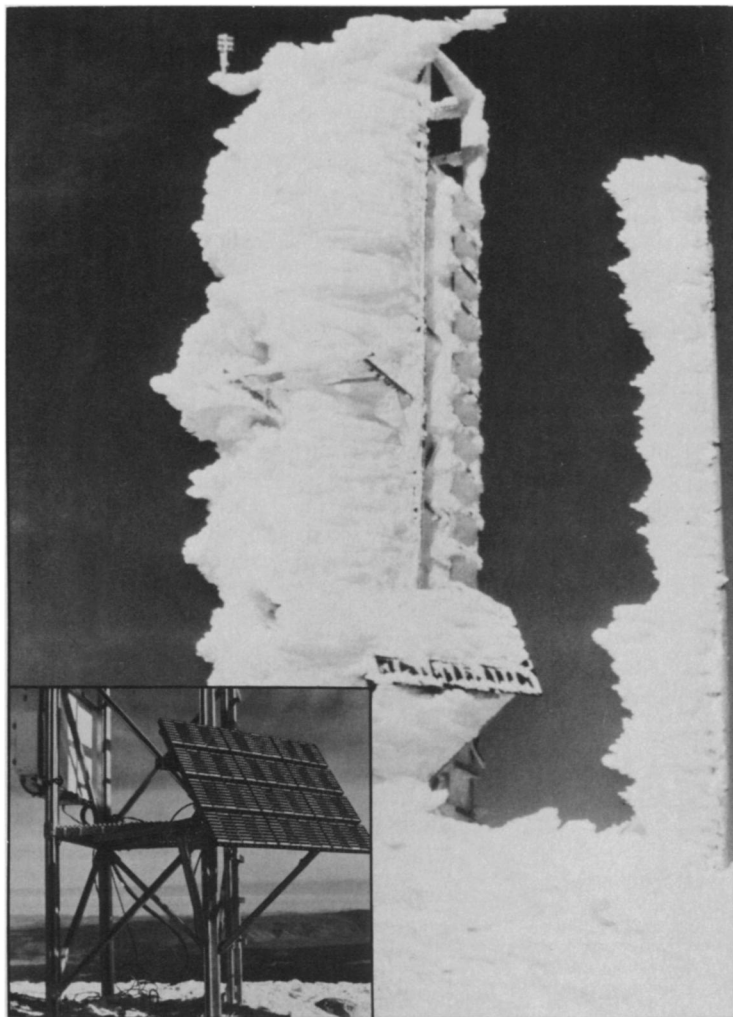


Solar Electricity: From Dream to Scheme

Devices to convert light directly to electric current are beginning to compete with traditional energy sources

BY JOHN H. DOUGLAS



Solar cells power remote automatic meteorological observation station at 11,000 feet on Mammoth Mountain, Calif. The solar cell array (inset) has operated satisfactorily since November 1973, despite heavy ice accumulations and winds exceeding 100 miles per hour.

Of all the dreams of solar energy enthusiasts, that of converting light directly to electricity has been the most enchanting—and the most elusive. So far, the applications and the costs have been equally astronomical: A communications satellite may be powered by more than 20,000 light-sensitive semiconductor cells, but the cost is several hundred times greater than that of generating electricity for home use. Direct conversion using light to stimulate electricity-producing chemical reactions is in an even less developed state. Recently increased funding, a new commitment to produce commercial devices and a fortunate series of technical

breakthroughs are rapidly bringing solar electricity down to earth.

The knowledge that light could knock electrons out of their bound states to form electric current has been around a surprisingly long time: Einstein won the 1921 Nobel Prize for explaining this "photoelectric effect." Light, he concluded, must consist of discrete units, called photons, and when one of these bits of light is absorbed by an electron, its energy is converted into the kinetic energy of the electron. This notion—which upset the traditional idea of light as a wave—revolutionized modern physics, but little practical use could be made of it for three

decades. Then, in the 1950s, semiconductors began to replace the clumsy, vacuum tube "electric eyes," which generated no power and could do little more than signal grocery store doors to open.

A semiconductor can be thought of as a ship on which the lower energy "valence band" electrons are confined to stowage while the higher energy "conduction band" electrons are free to run around on the upper decks. There is no intermediate stage, and a transition has to be made in one big jump. Photons of light provide the energy for the jump, but a crystal must be very pure or the liberated electrons quickly lose their energy, like falling through holes in a deck. By the mid-1950s, silicon photocells could be made pure enough to achieve about 10 percent conversion of the impinging light energy to electrical flow, and these cells made possible the powering of long-lived satellites in the next decade.

Now silicon cells are approaching what appear to be intrinsic limits to their cost and efficiency. Pure, cylindrical crystals several inches long can now be grown, but cutting these into wafers may waste more than half the material. Only recently have cells with as much as 13 percent conversion efficiency become commercially available, and an absolute upper limit of 18 to 19 percent seems likely. Less material might be wasted if lasers were used to cut the wafers, and various laboratories are making progress in growing flat silicon crystals—either as ribbons or sheets. But the search for alternate materials and inherently cheaper manufacturing techniques has grown rapidly.

One new technique involves using thin, polycrystalline films of different semiconductors instead of one large silicon crystal. Such thin films are cheaper not only because they use less material but also because they are easier to fabricate since layers can be applied simply by spraying or dipping. Silicon is not a very efficient converter of light, so a solar wafer made from this material may have to be some 100 microns thick. At the junction between two thin films, however, light can be absorbed in about one micron. Thus the total deposited material can be as thin as a sheet of paper.

The disadvantage of such devices is that electrons can more easily be reabsorbed into a bound state at the junction and at the boundaries between adjacent tiny crystals that make up the individual layers. To continue the boat analogy, it would be cheaper to let people run around the adjacent decks of several small boats joined in a flotilla than to construct one huge deck on a single ship—but the chances of falling through the cracks is also greater. Research has thus concentrated on improving the efficiency of polycrystalline photocells by reducing electron reabsorption.

A typical polycrystalline photoelectric device is made as follows: A layer of

cadmium sulfide (CdS) is deposited on a sheet of copper, which gives strength and an electrical contact. Exposing the top surface to a reactive solution changes the top micron or so into copper sulfide (CuS). Finally, a fine metal mesh is attached to serve as the other electrical contact and the whole device is encapsulated in plastic or glass to protect it from corrosion. Sheets of such material are now commercially available—a square 18 inches on a side produces about 1.4 watts of electricity when exposed to sunlight (about the power of a small flashlight).

To improve the performance of such devices—so that someday one watt of electricity can be produced from a piece of material only about three inches on a side—several variations of the basic fabrication technique are being tried. Heating the thin film surface tends to make the constituent crystals run together, reducing the number of boundaries electrons must cross. Allen Rothwarf of the University of Delaware's Institute of Energy Conversion reports progress in using zinc to improve the contact between semiconductor layers. Both power and voltage of the cells are being increased in this manner; their efficiencies now run around 6 percent, but Rothwarf hopes this can soon be increased to 10 percent.

Sigurd Wagner of Bell Laboratories says that modifying the composition of one layer has resulted in an "interesting candidate for inexpensive mass production." His lab uses one layer of indium phosphide (InP) or copper indium diselenide (CuInSe₂), instead of CuS, and concludes the devices are "in a stage ready for engineering." He says efficiencies of 7 or 8 percent should soon be demonstrated.

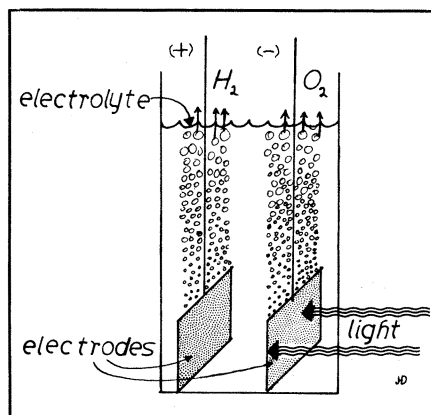
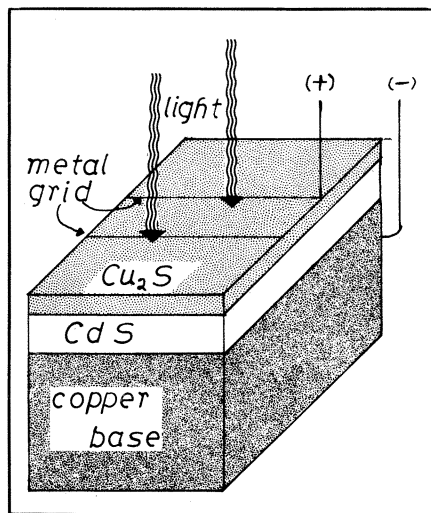
The alternative strategy to making large, cheap photovoltaic cells is to use small cells more efficiently, by concentrating light from a broader area on them. Materials scientists Roy Kaplow and Robert Frank are about to test a model of such a system at MIT, with funding from the National Patent Development Corp.

In their system, curved mirrors several feet on a side are used to track the sun across the sky while concentrating light on individual photovoltaic cells mounted near their focal points. In addition to making more efficient use of the expensive photovoltaic cells, the new system also produces usable heat, which would have to be drawn off in any case to keep from damaging the cells. Piped water will be used initially as the heat transfer medium. The system also has the advantage of modular construction—individual mirror units can be strung together to provide a tailor-made installation for heating and power generation.

Also under consideration are devices that can withstand high temperatures without either damage or too great a loss of efficiency. Called "III-V compound solar cells"—because they are made from

materials chosen from the third and fifth columns of the periodic table—these devices constitute what Harold J. Hovel of IBM terms "a long shot." The raw materials involved are relatively expensive, but higher efficiency and the ability to withstand heat may more than make up for this disadvantage. Gallium arsenide (GaAs) cells, for example, have operated at temperatures exceeding 350°C, with 5,000 solar intensities focused on them. In a hybrid system, where excess heat is drawn off and used, Hovel says total system efficiency may approach 25 percent.

There is also another whole approach



Cross section of thin film voltaic cell (upper) and diagram of electrochemical cell to produce electricity and hydrogen.

to direct conversion, which has received much less publicity than solar voltaic cells, but which may be equally promising—photoelectrochemistry. In a typical system, two electrodes are placed in a liquid electrolyte, with one electrode exposed to light and the other left in darkness. When light frees the electrons in one electrode, they are carried through the external load to the other electrode, where they combine with ions in the electrolyte. The operation is somewhat similar to that in an ordinary battery, except that the ultimate source of energy is sunlight rather than a chemical reactant. One major advantage of such devices is that they can be used in hybrid systems that produce

hydrogen fuel as well as electricity. A major problem has been degradation of the electrodes and the electrolyte.

One enthusiastic researcher in photoelectrochemistry is J.O.M. Bockris of Flinders University of South Australia, who says these devices look as if they may someday become much cheaper than photovoltaics. The efficiency is now much lower—only 2 to 3 percent—but because of the lower costs perhaps only 6 to 8 percent efficiencies will be needed to compete. In one version, titanium oxide (TiO₂) electrodes in a water solution produce oxygen gas bubbling off the electrode exposed to light and hydrogen gas off the dark electrode. Some 15 percent of the light energy converted goes into electricity and 85 percent into the gases—an interesting coincidence, Bockris says, because this is roughly the same proportion with which society now divides its energy use between electricity and petroleum fuels. Scientists have for some time discussed replacing fossil fuels with hydrogen (SN: 9/1/73, p. 135).

The problem of electrode degradation is being attacked by a team of chemists at MIT: Arthur B. Ellis, Steven W. Kaiser and Mark S. Wrighton. They recently reported that by using cadmium selenide (CdSe) electrodes in a polysulfide electrolyte, they were able to produce electricity with no measurable degradation of either. They measured an efficiency of nearly 9 percent for monochromatic light of the most desirable wavelength, but only about 2 percent efficiency for solar radiation. Since this system *cannot* be used to produce hydrogen, the device as it now stands will probably not find commercial use; but the researchers hope their discovery may increase understanding of the degradation process. (The theory of how such reactions take place is now, in Bockris's words, "Pretty weak and watery.")

To bring such processes out of the laboratory and into uses in both home and industry, the Energy Research and Development Administration (ERDA) has launched a National Photovoltaic Program, which its chief, Morton B. Prince, says has two specific goals. The short term goal is to reduce the cost of solar voltaic panels from the present cost of \$20,000 per peak kilowatt output to \$500 per kilowatt, by 1985. The longer term goal is to reduce the cost further to the neighborhood of \$100 to \$300, by the year 2000.

Such figures can be a bit confusing when one tries to compare the projected costs of complete solar power generating systems to those using coal or nuclear fuel. In an interview with SCIENCE NEWS, Prince explained that even when the price of solar panels has decreased to \$500 per peak kilowatt, a large-scale power station using them will still cost some \$1,700 to \$2,000 per kilowatt to construct—twice as much as conventional plants. Thus, by 1985, solar voltaics may be used to power fairly large installations in remote areas,

Illustrations: John H. Douglas

but they will still not be able to compete in the public utility market. By 1995, however, he says, complete solar conversion power stations may cost only \$1,100 per peak kilowatt to construct, a rather large figure by today's standards, but probably pretty close to the costs (in constant 1977 dollars) of other utility plants by that time.

While sponsoring research to reduce the costs, the program will also try to build potential markets, so that by 1985 some 500 megawatts of solar cell panels are being manufactured each year, and by the turn of the century, enough panels each year to produce 50 billions of watts.

Last year, slightly more than half of the program's \$22.4 million budget went to the Jet Propulsion Laboratory to support work on silicon cells, since this is the most advanced technology and will be the key to meeting the 1985 goals. This year, the administration has requested \$32.8 million and Congress may add another \$4

million. It is expected that as time progresses more funds will be channeled into polycrystalline cells and other options. The Sandia Corp. is now responsible for overall system and engineering analysis of the program and for work on systems using solar concentrators. The National Aeronautics and Space Administration (NASA) is in charge of setting up facilities for testing new devices and establishing standards of acceptance, through its Lewis Research Center. NASA is also in charge of setting up applications to demonstrate devices and establish markets.

The head of the Research and Technology Section of the Solar Energy Branch at NASA-Lewis, Henry W. Brandhorst Jr., emphasizes that the efforts of his group have already begun to bear fruit. Beginning three years ago, NASA provided solar cells to the National Oceanic and Atmospheric Administration (NOAA) to power remote meteorological stations in West Virginia and California. A measure of

success has been that the one on Mammoth Mountain, Calif., has continued to function satisfactorily even when covered with several inches of ice. The Forest Service has also begun to use solar voltaics—first to aid communications by powering radio repeater stations in the back country, and more recently, to extend the time rangers can remain in the wilderness. Walkie-talkie batteries can be recharged with solar cells carried on the ranger's backpack. The Coast Guard has begun using solar cells on buoys, a very large potential market. The Defense Department is looking at possible applications in battery charging, water pumping and even using solar electricity to provide 20 to 30 percent of the power of a wilderness military base.

Clearly the age of direct solar conversion has arrived, and with the progress promised for the next decades—based on recent research breakthroughs—the end is nowhere in sight. □

. . . Family Research

number of demographic variables. All factors were correlated with the 18 dimensions of child behavior and ranked in order of their reliability as predictors of those behaviors. (See table for listing of most important predictive family characteristics and behaviors they predict.)

Because most of the factors had immediate as well as long-lasting effects, they were examined from both perspectives during the longitudinal study. Punitive parenting, for instance, ranked fourth as a predictor of concurrent or present behavior, but when looked at for its effects five years later, it was by far the most powerful factor in terms of predicting long-term behavior. "It is important to know both of these relationships," says Langner, "since prevention and intervention may have both short- and long-term goals. Punitiveness has more unique contributions to behavior over time, and these were of larger size than any other familial predictor available." This was especially true in the area of aggression and antisocial behavior.

Even though child abuse is not something one would normally brag about, 7 percent of the cross-sectional group and 21 percent of the welfare mothers reported using a stick or strap to beat their children. And while only 25 of the parents studied had been reported as child abusers, Langner says several hundred of the children could easily be considered abused. "Stopping child abuse, using group methods for known abusers, and especially discussing punishment with potential parents in high school and during the first pregnancy with fathers present," says Langner, "is a high priority goal for preventing mental disorder in children for both the short and long term."

In addition to family characteristics, race and ethnic background were considered and found to be powerful predictors

of concurrent behaviors. Being Spanish-speaking was linked with five behavior dimensions: isolation, weak group membership, mentation problems, training difficulties and compulsiveness. Being black was linked with mentation problems, demandingness and impairment of school functioning. The five-year follow up showed that being Spanish-speaking had long-term predictive power for weak group membership, compulsiveness and dependence. It also predicted less regressive anxiety and less conflict with parents (when compared with being white). Long-term behaviors associated with being black were dependence and repetitive motor behavior as well as less conflict with parents. Being white predicted more conflict with parents.

Other factors were also found to be predictive but were associated with fewer behaviors. Moving a great deal, perhaps as a result of uprooting, was related to fighting and delinquency. High rent was linked to conflict with parents and siblings, perhaps, suggests Langner, "mostly a reflection of a middle class atmosphere permissive for intrafamilial expression of anger." Having a large number of children in the household was related to reduced competition and impairment of the children's school functioning. And the number of natural parents (mostly father missing) was related to delinquency.

For a final ranking, the factors were listed in order of predictive power by averaging both short-term and long-term forecasting ability. The highest ranking predictors are being Spanish-speaking, having punitive or cold parents, being black and having an excitable-rejecting mother. Langner asks: What can be done about this list of devils? How can they be cast out?

To Langner, some of the answers seem quite obvious. "Physical punishment

must be stopped or mitigated," he says. "Child-beating is almost unheard of in some cultures, so it must be amenable to social intervention by legal strictures and by the creation of an atmosphere condemning it." Coldness, he says, is perhaps more difficult to change, but going through the motions of hugging and kissing a child can sometimes stimulate a parent to develop more real warmth. Not only conditioning, but discussion of parental behavior and its origins is helpful and possibly not too expensive in group form through PTA's and pregnancy classes. Similarly, the excitable mother can be exposed to behavior therapy, and group reinforcement will help, especially if mother-child pairs with similar problems are brought into the group.

Birth control is already cutting down on family size, but bulldozing of neighborhoods, Langner says, should be minimized since it is the poorest who must move before the blade. Children lose friends, while facing new schools and unfamiliar surroundings. Loss of parents, particularly fathers, is due primarily to divorce, abandonment and separation. Support for marriage via employment, counseling and particularly changes in the welfare system, could reduce the major portion of broken homes.

What can be said of the high risks of black and Puerto Rican children? What is left of the race and ethnic variable, says Langner, "can be part diet, part parasitic infestation and many other things, but most of all it is likely to be discrimination and the low self-esteem that goes with it."

Depending on one's point of view, the Family Research Project may indeed be proving the obvious. But whether it proves or disproves anything, it at least provides an impressive body of data that should probably be considered before general statements are made about what is obvious in terms of child rearing. □