and in the near infrared, consists of three identical subunits, each containing seven chlorophylls enclosed within an envelope of protein. The cyanobacterium's LHC not only differed in the pigment used—phycobilins, which absorb in the 500- to 650-nanometer range (green, yellow, and orange light)—but in the LHC's shape, which consists of tiny rodlike assemblies.

The picture of LHC diversity has broadened over the past year and a half, as four new structures have come in, including the first of a membrane-bound LHC from a higher plant. As Werner Kühlbrandt of the European Molecular Biology Laboratory in Heidelberg, Germany, and his colleagues showed, this LHC, known as LHC II, consists of three identical proteins, each with three helices that are woven into the membrane of the chloroplast, the site of photosynthesis in higher plants. Associated with each protein are 12 chlorophylls and two carotenoids, which are also embedded in the membrane in close proximity to the helices and to each other.

Kühlbrandt notes that the arrangement of pigments and protein has apparently reached an optimal state because the LHC II proteins of higher plants have similar amino acid sequences, indicating that the structure has been conserved. "This structure is most successful at putting the maximum number of chlorophylls in the smallest space. It has the highest density of pigment per protein," Kühlbrandt says.

About 1 year ago, Cogdell's group at Glasgow and Simone Karrasch and her colleagues at the Medical Research Council (MRC) Laboratory in Cambridge, U.K., described both of the two sorts of membrane-bound LHC found in purple, nonsulfur, photosynthetic bacteria, which live almost everywhere. LH1 has one ring of chlorophylls plus protein, while LH2 contains two rings of chlorophyll molecules, one close to the membrane surface with the second set in the middle of the membrane bilayer. This arrangement, says Kühlbrandt, puts each ring of pigments in a different chemical environment, so "they absorb at different wavelengths, extending the spectral range of light harvested." That's a helpful adaptation for the bacteria, which often live in murky water, because it means they can use whatever light is available.

The latest LHC structure, from A. *carterae*, maintains the diversity trend. The Welte-Hiller team chose to study this LHC partly because it is rich in carotenoids, and none of the other LHCs whose structures are known use carotenoids as dominant pigments. The x-ray studies showed that this LHC consists of three identical proteins, whose structures are described by the researchers as resembling that of a ship in which the bow, sides, stern, and deck are formed by protein helices. Inside the hull of this ship is the cargo: two chlorophylls plus eight peridinin molecules plus two molecules of a lipid called digalactosyl diacyl glycerol. The lipid was a surprise because none have been documented in other LHCs. Welte and his Konstanz colleague Kay Diederichs speculate that the lipid might help keep the protein in its correct fold.

Johan Deisenhofer, of the University of Texas, Houston, adds that the elegant design of this LHC may also help to explain the superb success of PCP. He says that the shape of the hull puts the various pigments in extremely close proximity, only 3 or 4 angstroms apart, and oriented so that energy can easily be transferred from the peridinins to the chlorophylls. "It is interesting to see how nature solved the problem [of efficient light harvesting]," says Deisenhofer. "The geometry is key."

Researchers expect that they still haven't seen the full extent of the adaptations for light harvesting. "There will be an enormous array of these light-harvesting complexes," predicts structural biologist Richard Henderson of the MRC's Cambridge lab. "And each molecular structure will have its own knobs and whistles to improve the efficiency of light capture: It's a survival mechanism."

–Anne Simon Moffat

PHOTOVOLTAICS

New Solar Cells Seem to Have Power at the Right Price

Efficiency versus cost. It's a trade-off that bedevils makers of solar cells, frustrating their efforts to harness the sun. Cells made from wafers of crystalline silicon are rather good at absorbing photons and converting them to electricity. But they cost a lot to make. In contrast, noncrystalline cells made with an ultrathin film, amorphous silicon, are much cheaper. Their efficiency, however, is about half that of their crystalline counterparts. Now researchers think they can trade in this devilish trade-off.

New thin-film materials are showing signs that they can be both inexpensive and efficient, and have created "a sense of tremendous excitement in the technological side of the field," says Ken Zweibel, who heads thin-film solar cell research at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. At a photovoltaic (PV) conference last month in Arlington, Virginia,* he and other participants were energized by a report that one material—a mixture of copper, indium, gallium, and selenium (CIGS)—has been made into prototype cells that convert nearly 18% of incoming sunlight to electricity, a performance approaching that of the best crystalline silicon cells. Hans Schock, a thin-film solar cell expert at the University of Stuttgart in Germany, says this result and others on display at the meeting "really give us a chance to bring the cost down."

How far down? Current crystalline solar cells can be built for manufacturing costs of \$3.50 to \$4 per watt generated. Many researchers expect the new thin films—CIGS and one other, a blend of cadmium and tellurium (CdTe)—to do better. If researchers can overcome nagging manufacturing and marketing problems, new devices could produce power for less than \$0.50 per watt, low enough to make the cost of PV-generated electricity competitive with gas generators, says Zweibel. But those problems won't give way easily. CIGS, for instance, is difficult to deposit over large areas, and PV panels are window pane–sized; and anything made with cadmium, a toxic heavy metal, could face resistance from consumers.

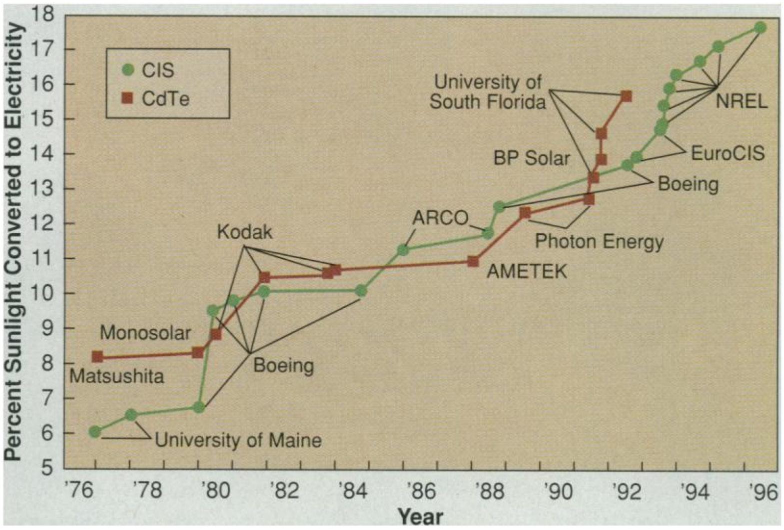
To convert sunlight to electricity, all PVs rely on layers of semiconducting materials at their core. Electrons in these materials exist at discrete energy levels known as bands. When the material absorbs photons, the extra energy boosts electrons up to a higher "conduction" band, leaving behind positively charged "holes." Additional semiconductor layers above and below the absorbing layer then channel the electrons and holes in opposite directions, creating an electric current.

Conventional crystalline silicon PVs are good at this charged-particle steering, hence their efficiency. They are not so good at kicking electrons up to the conduction band; the photons need an extra energy boost from vibrations in the crystalline lattice, or phonons, to get the electrons to move. So solar-cell makers use large crystalline wafers up to 200 micrometers thick to give photons more opportunity to encounter phonons in the material. And the thickness of the material drives up the cost of the PVs.

---

* 25th IEEE Photovoltaic Specialists Conference, Arlington, VA, 13–17 May 1996.

Amorphous silicon, in contrast, is a "direct bandgap" material, meaning its electrons don't need extra phonon help to jump bands. Manufacturers need to lay down layers only a few micrometers thick. And because the material, being amorphous, doesn't have a regular crystal structure, it can essentially be sprayed onto large panels at relatively low cost. But the amorphous nature of the material also comes with a drawback: defects. These defects—silicon atoms with an unfilled bond—trap the moving electrons and holes, preventing the charges from traveling to their destinations. This limits the efficiency of the best existing devices to about 11%.



SOURCE: NREL

Powering up. Two thin films—copper, indium, and selenium (CIS), with gallium added later, and cadmium and tellurium (CdTe)—have converted more sunlight to electricity year after year.

CdTe and CIS (without the gallium) were originally explored as possible thin films back in the 1970s, because they are direct bandgap materials well suited to absorbing photons from the sun. The materials—now being investigated by dozens of groups worldwide—also tend to have fewer charge-trapping defects than amorphous silicon does, in part because they're actually made up of thousands of tiny crystallites: The charged particles flow relatively unimpeded within each crystalline grain.

The charges do, however, run into trouble at the grain boundaries, which are harder to jump. In an effort to convert CIGS and its predecessor into efficient solar cells, scientists have reduced the number of boundaries in films of the material by slightly increasing the crystallite size, says John Tuttle, a physicist and solar-cell expert at NREL whose team holds the current CIGS efficiency record. They have done so by varying the concentration of copper as the film is deposited. Because copper and selenium trigger a temporary liquid phase in the material, making it easier for atoms to arrange themselves into larger, trap-free groups, a copper-rich layer at the bottom produces slightly larger crystalline grains when the film is complete.

But the biggest boost, says Tuttle, has come from gallium. The recent addition of gallium to the CIS mix, graded so that its greatest concentration is near the bottom of the film, has produced two benefits. First, it increases the bandgap of the alloy to a point that more closely matches the energy of most photons in sunlight, improving light-to-electricity conversion. Second, the graded gallium content causes the bandgap to vary throughout the CIGS layer, from a larger bandgap at the base to a smaller one on top, creating a kind of slope for electrons to flow along. Electron energies follow bandgap size, so those kicked into the conduction band at the bottom of the film can easily give up a little energy as heat to occupy lower bandgap sites closer to the front, while the lower energy electrons can't move the opposite way. "This gives extra force driving electrons to the top contact," says Alan Delahoy, who heads research at Energy Photovoltaics (EPV), a Princeton, New Jersey–based PV company.

Thanks to these and other improvements, Tuttle and his colleagues were able to unveil their latest record holder in April at the Materials Research Society meeting in San Francisco: a 17.7% efficient test cell 0.4 cm^2 in area. And at the Arlington meeting, Schock and his colleagues also showed that they could produce a CIGS cell more than 100 times that size that was 13.9% efficient.

But even Schock's cell measured just 10 centimeters on a side, a fraction of the size of real-world PVs. And larger CIGS cells are out of reach for the moment, says Vijay Kapur, president of International Solar Energy Technology (ISET) in Inglewood, California. The complicated evaporation techniques used to produce small CIGS cells "are not amenable to large-scale production," he says, for they cannot maintain constant film thickness over much larger surfaces. But companies are working on improvements. According to Delahoy, EPV has already developed a machine capable of depositing CIGS films on areas roughly 1 meter by 0.5 meter. And ISET has come up with a nonvacuum method capable of making large-area films, albeit with poorer efficiency.

CdTe films, by contrast, don't face the same scale-up problems. "CdTe can be manufactured by four or five technologies that all produce fairly high-efficiency devices" over large areas, says Chris Ferekides, a CdTe solar cell researcher at the University of South Florida in Tampa. Working with lab-scale machines, Ferekides and his group have produced small cells that achieve nearly 16% efficiency.

To get these record-breaking results, Ferekides and his colleagues needed a couple of tricks of their own to overcome a drawback that has limited the efficiency of CdTe solar cells in the past: their light-blocking outer layers. In order to operate, CdTe PVs require that a layer of photon-absorbing cadmium-sulfide (CdS) be grown atop the CdTe; the CdS draws electrons from the CdTe toward the top electrode. To minimize unwanted photon absorption by CdS, the group used a special liquid-based technique to grow a thinner than normal—and therefore more transparent—CdS layer in the device. The Florida group also topped off its device with a special ultratransparent glass.

Full-scale CdTe panels have yet to reproduce these results. Nevertheless, because CdTe is more easily produced than CIGS, at least two companies—Golden Photon in Golden, Colorado, and Solar Cells Inc. (SCI) in Toledo, Ohio—are already building pilot-scale facilities to manufacture CdTe panels. Early full-scale prototypes currently being tested by these and other companies have reached about 7% to 9% efficiency, and they hope to reach Ferekides's level. CdTe may lag slightly behind CIGS in the lab, "but it seems ready for the market," says David Carlson, a physicist at Solarex in Newtown, Pennsylvania, who invented the amorphous silicon solar cell.

The question is whether the market is ready for CdTe, or at least cadmium. Concern over consumer resistance to products containing the toxic metal has already prompted companies like EPV to bet on the competition. "We considered going into CdTe [production]," says Delahoy. "But we became convinced that public perception of cadmium would create tremendous difficulties in marketing." However, SCI's vice president of operations, Dan Sandwisch, maintains that the cadmium problem can easily be managed by setting up a recycling program to recover the solar panels at the end of their lives. Until such panels and programs are rolled out, though, solar-cell makers anticipating consumer reactions will be working in the dark.

–Robert F. Service