EDWIN CARTLIDGE

A Smart View of the Future

HIGH-TECH WINDOWS COULD SOON BE GENERATING ELECTRICITY, AS WELL AS SAVING ON HEATING AND COOLING.

The electrochromic windows in the Boston Science Museum's lobby, made by SageGlass, reduce glare and allow vistors to enjoy a scenic view of the Charles River while also improving the lobby's thermal efficiency.

Inside Out Studios

CN Tower's smart windows in Toronto, Canada.

Getty Images

When it comes to helping the environment, windows often leave a lot to be desired. By letting in heat during the summer and releasing it in winter, they can place huge demands on air conditioning and heating systems—thereby increasing energy consumption and raising greenhouse gas levels in the atmosphere. But so-called smart windows are designed to change all that, as the iconic CN Tower in Toronto demonstrates.

The tower's observation deck was outfitted last year with new windows containing a millimeter-thick layer of polymer-based material made by Michigan, USA, company Pleotint. That layer darkens as the sunlight hitting it intensifies, causing the windows on the building's east side to become more tinted as the sun rises in the morning, blocking some of the light. As the day progresses, those windows return to a nearly clear state while the ones on the south- and then west-facing sides progressively darken and lighten. This cuts air-conditioning use in the summer, while still allowing significant solar heating during the winter—all the while providing visitors with plenty of natural light to enjoy the view.

Smart windows are currently manufactured by just a handful of fairly small firms in the United States and Europe, but they have a potentially huge market. Buildings require vast amounts of power—in the U.S., they accounted for 41 percent of all energy consumed in 2010—so many countries are bringing in new rules to make buildings more efficient. For example, in Japan it will become obligatory by 2020 for newly constructed public buildings to be "zero energy"—meaning that they produce at least as much energy as they use up.

Indeed, some scientists and engineers see a dual role for smart windows. The idea is not only to make them more efficient but also to transform them into electricity generators. Fully or partially transparent "solar windows," currently being developed by a number of groups around the world, incorporate photovoltaic technology but are designed to exploit the vertical spaces of skyscrapers and other tall buildings rather than rooftops. "Zero-energy buildings in urban settings with large glass facades are nearly impossible right now," says Lance Wheeler, a staff scientist at the National Renewable Energy Laboratory (NREL) in Golden, Colo., USA. "They are energy hogs. But with the right windows, they could make as much energy as they consume."

Making windows "smart"

Improving windows' energy efficiency is nothing new. Double glazing—which relies on setting up an insulating air gap between two panes of glass—has been around since at least the 1930s, while dark-tinted and reflective glass followed a couple of decades later. And since the early 1990s, low-emissivity (low-e) coatings have been commercially available. These are layers of

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metal or metal oxide, generally just a few tens of nanometers thick, applied to one of the inner surfaces of a double- or triple-glazed window that reflect infrared radiation while allowing most of the visible light to pass through.

Some of that infrared radiation comes in the form of longer-wavelength emission from black bodies, both outside and inside the building. Blocking the former helps to keep the building cool during the summer, while trapping the latter reduces heating bills during the winter. In addition, some low-e coatings also block shorter-wavelength infrared radiation emitted by the sun.

However, because low-e coatings block very little visible light, they can't stop glare, which can be a particular nuisance when people are looking at computer screens. They also can't prevent the heating effect of visible radiation, which can be uncomfortable given that visible wavelengths carry 44 percent of solar energy (compared with infrared's 53 percent and ultraviolet's 3 percent).

Smart or "dynamic" windows are designed to block much of the visible light when the sun's rays are at their most intense. This allows a building's occupants to do away with blinds and save on electric lighting—potentially improving their wellbeing and boosting productivity—while reducing the need for air conditioning. Conversely, when the sun's rays are weaker, particularly in winter, the devices let in significant natural light and so save on heating compared with some windows with fixed tints.

Wired up

The most common type of smart window uses electrochromic technology, a usually battery-like arrangement that relies on an applied voltage to switch a material between light and dark states. This technology has been used for decades in cars' rear-view mirrors to reduce glare when a sensor detects headlights from a vehicle behind. But its exploitation in windows has taken longer to achieve (see sidebar, p. 42).

According to Michael McGehee, a materials scientist at the University of Colorado in Boulder, USA, the biggest hurdle for electrochromic windows is price. While double-glazed windows fitted with a low-e coating typically sell for around US$10/ft^2 (US$110/m^2), smart windows average about US$50/ft^2 (US$540/m^2). That gulf, he explains, is mainly due to the high cost of production, since electrochromic windows require each layer to be laid down using sputtering—a slow process that requires huge vacuum chambers. Further raising the price, he points out, is the need to wire up each window when it is installed.

Added to that is the problem of color. McGehee says that electrochromic windows tend to be "bluish," as a result of the coating, and consumers generally prefer more natural-looking lighting. McGehee says this may be less noticeable in recent models. More problematic, perhaps, is the question of speed. An electrochromic window, like a battery, takes time to transfer all of the charge needed to change its state—up to 20 minutes, or even more—which is clearly a problem when wanting to switch a window instantaneously.

To try and overcome these limitations, McGehee's group in Boulder is working on a technique that others have struggled with for decades: so-called reversible electroplating. This involves sandwiching an electrolytic gel containing copper and silver ions between two electrodes—one a copper ring and the other a layer of indium tin oxide on glass. By applying a voltage, the researchers are able to plate the indium electrode with a thin film of the metal ions, which blocks light passing through the device. Reversing the polarity and reapplying the voltage then restores transparency.

Because metals are extremely good at blocking light, a film just 10-nm thick is enough to render the device opaque. That means saving money on raw materials, which, together with a relatively inexpensive production process, could result in cheaper smart windows, says McGehee. But it also means that even the tiniest variations in thickness could cause patchy transparency. The researchers found that by using platinum nanoparticles to seed growth of the metal film, they could plate the metal very evenly and also quite quickly—switching between clear and dark states in around 30 seconds. Nevertheless, their biggest window to date is just 100 cm^2, and McGehee says that figuring out how to successfully plate much larger areas could take several years.

Cutting costs

Scientists are, in fact, investigating a range of materials and nanotechnologies to try and improve electrochromic devices. But electrochromics are far from the only game in town. The windows in the CN Tower use thermochromic technology, which requires no voltage to switch between light and dark states. Pleotint's windows rely on chemical reactions involving nickel and other transition-metal ions together with molecules known as ligands. Intense solar radiation heats up the windows, causing the metal to bind to different ligands and absorb more visible light—resulting in a progressive tinting of the windows. When the intensity drops off, the reaction reverses, and transparency is gradually restored. "We use the sun to block the sun," as Pleotint's CEO Harlan Byker puts it.

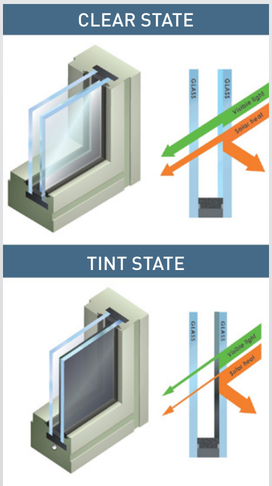
The automatic switching means that no wires need to be installed to operate the windows, which cuts costs. Byker acknowledges that some customers are put off by not being able to control the tinting of their windows when they need to. But he reckons that with lower costs for both installation and production—which involves extrusion rather than sputtering—he can undercut electrochromic producers by around 50 percent. Although the company currently sells a fairly modest 200,000 ft^2 (18,500 m^2) of windows annually, he foresees the relative affordability leading to a doubling of its output year on year.

One drawback with Pleotint's windows is that they need a low-e coating to block infrared wavelengths, which means that they can't let near-infrared radiation in to boost solar heating

Electrochromic windows in Tarrytown, N.Y., USA, manufactured by View. The windows darken or lighten depending on where exactly the sun is shining. View Inc.

Electrochromics: From darkness to light

An electrochromic window is typically made by placing a stack of different materials just a few microns thick between two glass panes. That stack resembles a battery, being made up of an anode and cathode that are separated by an electrolyte and sandwiched between transparent conductors. When a voltage is applied across the device—either by pressing a button or by using sensors and computer algorithms to respond to changes in solar radiation—ions stored in the anode cross the electrolyte, causing electrons to move into the cathode.



View Inc., 2018

A popular choice for the cathode is tungsten oxide, which usually contains one tungsten ion (charge: +6) for every three oxygen ions (charge: –2). Inflowing electrons are attracted to the tungsten ions, reducing the ions' charge to +5. But when exposed to light, those electrons get a kick, causing them to jump to another tungsten ion. That absorbs and therefore blocks the light. The device will generally remain tinted when the voltage is turned off, but becomes clear again when the voltage is reversed.

R&D on tungsten oxide has been ongoing since the 1970s, but the difficulties involved in making large panes cheap enough and durable when exposed to full sunlight mean that smart windows for buildings have been on the market for less than a decade. The biggest producers of electrochromic windows today—Sage in Faribault, Minn., USA, and View near San Jose, Calif., USA—are growing rapidly, with the latter "increasing revenues at a 100 percent-plus growth rate," says company spokesman Cameron Craig. However, the overall market remains very small—amounting to just 0.0006 percent of the (roughly US$200 billion) glazing market, according to Sage spokesman Ryan Park.

When it comes to generating electricity from windows, a number of products are either on or near the market.

The "reversible electroplating" technology developed by Michael McGehee, University of Colorado in Boulder, USA (formerly at Stanford University, California), and colleagues. By applying voltages of opposite polarities they are able to coat a transparent electrode with metal ions, making it opaque (panels 2 and 3), and then remove the ions, restoring transparency (panel 4).
Dan Slotcavage

during the winter. But research groups at Sandia National Laboratories in New Mexico, USA, and RMIT University in Melbourne, Australia, are developing thermochromic coatings made of vanadium dioxide that let visible light pass through while switching between transparent and opaque states in the near-infrared. Meanwhile, a company called Heliotrope, based in Berkeley, California, USA, has produced an electrochromic coating made up of indium tin oxide and niobium oxide that can switch separately at visible and infrared wavelengths.

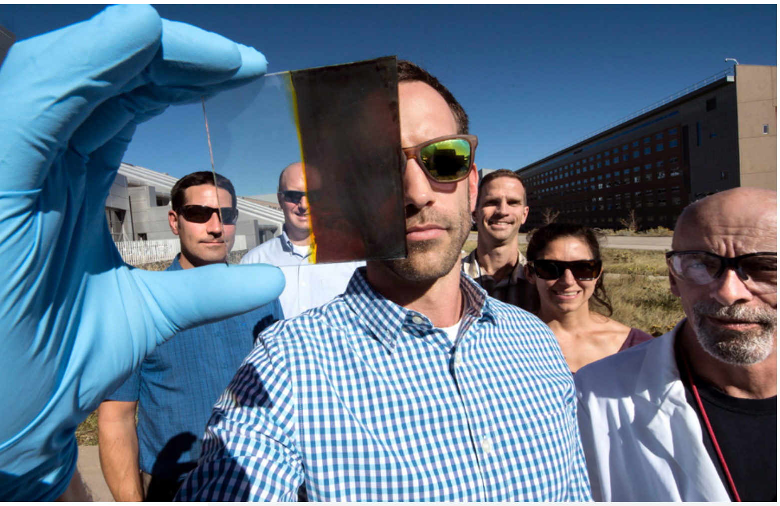
Among other approaches to smart windows, some devices switch from tinted to clear states by using an applied voltage to align otherwise randomly oriented particles suspended in a polymer matrix. This switching takes place in a matter of seconds but requires a high voltage and continuous power to maintain transparency. Likewise, devices consisting of liquid-crystal droplets dispersed in a polymer require a voltage to become, and stay, transparent. When switched "off," the liquid crystals scatter light, which makes the devices translucent and thus more suited to indoor privacy screens than external windows.

Electrical engineers at the University of Delaware, USA, meanwhile, are trying to slash the costs of smart windows by taking a more back-to-basics, macroscopic approach. Keith Goossen and Daniel Wolfe have fabricated a 30-$\mathrm{cm^2}$, 9-mm-thick piece of plastic comprising angled cubes that deflect incoming light through a process of total internal reflection, much like a bicycle reflector. However, when they fill their device with a fluid having a refractive index matching that of the plastic, the light no longer encounters an air–plastic interface and instead passes straight through—rendering the device transparent.

Given the absence of complex electro-optic components, Goossen reckons that the technology could be used to make smart windows for as little as $\mathrm{US\$10/ft^2}$ ($\mathrm{US\$110/m^2}$). But first they must solve a number of problems, including finding a fluid that not only has a refractive index very close to that of a suitable plastic, but that also doesn't freeze when temperatures drop. Possible nearer-term applications, says Goossen, include roofs that reflect sunlight in the summer while transmitting it in the winter—their original motivation for developing the technology—as well as sun roofs that direct bright sunlight away from cars.

Taking charge

When it comes to generating electricity from windows, a number of products are either on or near the market. However, these windows tend not to be dynamic. For example, Next Energy Technologies in Santa Barbara, Calif., USA, sells a fixed-tint window incorporating a fairly cheap organic photovoltaic cell that can turn 7 percent of solar energy into electricity as a result of blocking 50 percent of the incoming light. That absorption makes the window



Lance Wheeler and his team at the National Renewable Energy Laboratory in Colorado with their perovskite thermochromic window technology that switches at about 60°C from a transparent state to a dark state—when it works instead as a solar cell.
Dennis Schroeder/NREL

Having cake and eating it too?

Lance Wheeler and his colleagues at the National Renewable Energy Laboratory, Golden, Colo., USA have developed a lead-based perovskite device that switches between two states: dark, allowing it to function as a solar cell, and transparent, when it instead becomes a window. Their trick was to add molecules of a gas similar to ammonia, known as methylamine, which leave the perovskite when heated, turning the crystal structure into an absorber of light, and return when cooled, restoring transparency.

Wheeler's team found that the device, currently measuring just 1 cm^2, could convert as much as 11.3 percent of incoming solar energy into electricity when it was darkened. As for the variation in transparency, it admitted nearly 70 percent of incident light at low temperatures and just 3 percent above 60°C. "Pure smart windows save energy, while solar cells generate electricity," Wheeler says. "Our device does both."

However, the group did encounter a major problem: after just a few cycles of switching between light and dark, the crystal structure no longer returned to its original state and the efficiency dropped. A group at the Berkeley lab, led by materials scientist Peidong Yang, has in the meantime developed a similar device containing a cesium-based perovskite that can switch states without having to absorb and release a gas. This has proved much more durable than the lead-based cell but suffers from a lower efficiency—about 7 percent—and only switches once the temperature tops 100°C, which is too high for solar heating.

darker than it would otherwise be, but because light is blocked across the spectrum, it takes on a fairly neutral (gray) color.

Meanwhile, Sergio Brovelli, a materials scientist and physicist at the University of Milano-Bicocca in Italy, and colleagues have developed what is known as a luminescent solar concentrator. This uses tiny specks of silicon and semiconductor nanoparticles, or quantum dots, embedded in a transparent polymer, to absorb radiation across the visible spectrum and re-emit it at infrared wavelengths. The emitted radiation undergoes total internal reflection, which guides it to small photovoltaic cells housed in the window frame. This approach eliminates the need for the mosquito-net-like grid of wires visible on the surface of some solar windows.

Brovelli says that the group has so far managed to convert up to 3.3 percent of solar energy into electricity, but he reckons that by boosting the nanoparticles' efficiency so that they emit nearly as many photons as they absorb, and by making the polymer more transparent, they should get up to around 5 percent per square meter. The researchers have set up a company called Glass to Power that Brovelli expects to have its first window on the market "in the first half of 2019." He adds that although they plan eventually to vary the transparency of their device, for the moment they are focusing exclusively on producing windows that generate power.

Some groups, in contrast, are simultaneously pushing ahead on both fronts, including scientists at NREL and the Lawrence Berkeley National Laboratory, California, USA, as well as others at Michigan State University, USA. They're all exploiting what many see as the next big thing in solar energy technology: perovskites, crystalline materials that are nearly as efficient as silicon, but potentially much cheaper.

In June, chemical engineer Richard Lunt and colleagues at Michigan State reported having made a transparent photovoltaic cell from a perovskite compound tuned precisely to harvest ultraviolet photons with wavelengths below 440 nm—to maximize both its electrical output and its transparency. Although the device had an efficiency of only 0.5 percent, Lunt is confident—given progress with perovskite solar cells more generally—that it can reach efficiencies "in the 4 to 5 percent range within a couple of years."

That itself would be enough to operate a smart window and have energy to spare to power other

Smart windows and solar windows, Lunt argues, "absolutely can mix," leading to devices that "eventually send electricity back to the grid."

applications. But Lunt reckons that by combining an ultraviolet-only solar cell with one made from organic semiconductors to capture infrared photons, it should be possible to reach efficiencies of at least 10 percent within several years. Smart windows and solar windows, he argues, "absolutely can mix," leading to devices that "eventually send electricity back to the grid."

One step at a time

But not everyone is convinced. Claes-Göran Granqvist, a physicist at Uppsala University, Sweden, and founder of Swedish electrochromic-window producer ChromoGenics, reckons there is a fundamental clash between windows and solar cells. "You can't both absorb the sunlight's energy and let it through," he says, maintaining that infrared-only solar cells will probably be too inefficient for practical purposes.

Granqvist argues that non-transparent areas of buildings, such as rooftops or the glass between windows, are much better suited to electricity generation. Another possibility, he says, is to integrate solar cells into electrochromic windows simply to power the latter, so doing away with the cumbersome and expensive wiring.

Indeed, Yueh-Lin Loo and colleagues at Princeton University have built a smart window containing a solar cell made from an organic semiconductor that absorbs a narrow range of near-ultraviolet wavelengths. Although the cell has an efficiency of no more than 1.5 percent, the researchers showed that it nevertheless generates enough power to switch the window, changing it from a light state to a dark-blue color. They also argue that the cell's reliance on purely ultraviolet radiation is an important plus point, since it does not interfere with the smart window's regulation of the visible and infrared parts of the solar spectrum.

Harlan Byker of Pleotint admits that he still gets "tempted to talk to the guys" working on solar windows.

Richard Lunt, Michigan State University, USA, with a solar cell made from organic molecules that absorb light at infrared wavelengths.

Kurt Stepnitz/Michigan State University

But he remains unconvinced that smart and solar windows really can be combined in the same device. For the moment at least, he is putting all his effort into making his thermochromic technology a success. "We don't really know how the market will grow," he says. "But when I see these things working every day, darkening down and absorbing heat, then I think smart windows have a future." OPN

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