# Paint-on power, the saviour of solar

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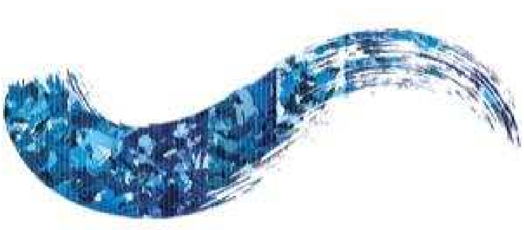

Solar power without the panels *(Image: Don Farrall/Photodisc/Getty)*

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SO YOU want to offset your electricity bill by tapping the most widely available, free source of energy in the world, the sun? Right now, you'd need to shell out a lot of money for a specialist to come to your home and install inefficient solar panels on your roof. Now imagine taming the sun minus the specialist, the empty wallet and the panels. What if taking your home off the grid required only a trip to the shops, a bucket of paint, an afternoon on the roof with a brush and a couple of beers, and an electrician to hook your new roof up to your power supply?

That's the promise of a spate of research into harnessing the sun's energy with materials called thermoelectrics, which can generate a current simply by exploiting a temperature difference between one side of the material and the other. Once written off as unusable, they might now find redemption by rescuing solar panels, which have hit a formidable pothole in their efficiency. Thermoelectric materials could help push them out of their trough and into the big league. But ironically the panels' saviours could also be the architects of their downfall.

We've chased the dream of marrying thermoelectric materials and solar power for half a century. In 1954, solar energy pioneer Maria Telkes used a sheet of thermoelectric material to soak up the sun's heat and from that, generate electricity. The heat on one side springs electrons from the atoms they are normally part of, and they flow to the cooler side, leaving the hot side positively charged and making the cold side negative. Telkes did manage to produce a current this way, but only just. Her best efforts maxed out at well below 1 per cent efficiency.

At the time, this wasn't too far from the performance of light-capturing silicon solar cells, which were able to convert about 3 or 4 per cent of the sun's photons into electricity. By the end of the 1950s, however, those numbers had tripled, whereas Telkes's result remained the increasingly pitiful benchmark for solar thermoelectrics. Understandably, the nascent solar power industry quickly abandoned them for the silicon solar panels that began to populate roofs during the 1970s and 80s.

After that, thermoelectric materials went largely neglected for decades. Alongside their pathetic efficiencies, the materials themselves - usually exotic semiconductors such as bismuth telluride - were too expensive to justify the trickle of energy they produced. They're cost-effective only in applications of last resort, such as the Voyager space probes, where they exploit the temperature difference between a small chunk of radioactive material and the frigid chill of outer space, and a few other niche applications.

But then solar panels stalled. Despite all efforts to improve them, the best photovoltaic (PV) solar panels for sale today only reach an efficiency of between 15 and 20 per cent.

This is down to the way they convert sunlight into electricity. When a photon strikes a solar panel with enough energy, it gives an electron in a silicon atom the kick it needs to break free and begin to flow through the material - otherwise known as an electric current. But the trick is that the photon has to have just the right amount of energy. Venture too far outside the small sweet spot at which photons are able to kick-start the electricity generation, and problems arise. If photons have too much energy -

such as those in the high-energy ultraviolet end of the light spectrum - their heat creates chaos in the material. On the other hand, if photons have too little energy - for example, photons in the microwave or infrared range, also known as heat - they simply pass right through the solar cell without interacting with any electrons. Unfortunately, these lower-energy photons make up nearly half of the sun's spectrum, so solar panels can't even hope to hit efficiencies over 50 per cent.

Worse yet, the heat from the high-energy photons puts the squeeze on the photovoltaic material's finely tuned electronic structure: in the hot cell, electrons start sloshing about in the material chaotically, countering the orderly flow across the material that leads to good electrical current.

So about half of the sun's photons are useless and a highly energetic handful are actively harmful to the panel's efficiency. You can mitigate the destructive heat with so-called active cooling, which involves pumping air or water around the panels. That adds cost and bulk, however, and requires extra energy, the three enemies of the efficient solar panel.

Could thermoelectric materials help? In 2007, Gang Chen at the Massachusetts Institute of Technology began to wonder if it was worth unearthing these long-neglected materials to help solar cells make the most of the light spectrum.

The idea was enticing. And the physics seemed to bear out. Combining thermoelectric materials and photovoltaics into a hybrid solar cell would cool the cell by diverting the damaging high-energy photons, and a layer of thermoelectric material would allow us to harvest the entire solar spectrum by capturing the low-energy photons to make electricity.

So Chen set out to make it happen (*Applied Physics Letters*, vol 92, p 243503).

### Splitting the light

Theoretically, the best way to combine the materials would be in something called a spectrum-splitting solar cell. It would act a bit like a traffic cop, segregating the incoming sunlight according to wavelength. In Chen's calculations, such a hybrid would be almost 1.5 times as efficient as a standard silicon solar cell, the kind of jump that could finally see solar energy rival fossil fuel-based energy systems. But there was a problem: "To do spectrum splitting you need solar concentrators and beam splitters," Chen explains, and those added more cost than the extra efficiency subtracted.

Perhaps a better option would be something simpler, thought Huiming Yin and Dajiang Yang at Columbia University in New York. Instead of building complicated structures to divert the low-energy photons, why not just let them pass right through the solar cell and onto a thermoelectric layer beneath? Cooling water pipes under that would draw chaotic heat out of the photovoltaic layer, and the hot solar cell and cool water would also make an ideal sandwich for the thermoelectric layer in between (*IEEE Transactions on Energy Conversion*, vol 26, p 662). The electricity generated by that layer would make up for the cost of the extra material.

But even that didn't cut the mustard. The trickle of extra energy the thermoelectric layer captured just wasn't enough to make up for the expense of the material. It was time to get to the root of the problem: the thermoelectric material itself.

The way it generates energy is also the culprit in its inefficiency. When one side of the material gets hot, the electrons get knocked off their atoms and drift to the cold side of the material (see diagram). The difficulty is maintaining the difference in temperature between the hot and cold sides. Electrons aren't the only things travelling through the material: heat travels in the form of phonons, vibrations that, because they are passed along from atom to atom, act for all the world like particles.

It doesn't take long for this heat to warm up the cold side, and once this happens electrons no longer feel the need to move in one particular direction, instead bouncing around chaotically. Now the very property that is crucial for generating the current has been lost.

For five decades, this was a problem without a solution. But then came nanotechnology. Now materials researchers find themselves with the ability to control a material's structure at the finest scales.

In an orderly, crystalline material like silicon, all the atoms are very regularly aligned. That allows both electrons and phonons to travel smoothly through it. By contrast, a jumbled-up material, such as glass, blocks the flow of both electrons and phonons.

Nanotechnology lets you create hybrid materials that allow electrons - but not phonons - to flow. Yin and Yang used a material based on quantum dots, tiny semiconducting crystals just a few tens of nanometres across, which are engineered with minute defects that preferentially scatter phonons while allowing electrons through unimpeded (*Science*, vol 297, p 2229). The researchers calculated that the material will have nearly double the efficiency of an ordinary thermoelectric material. Sandwiched into a water-cooled photovoltaic system that also uses the heated water for energy, they think this material will help push solar panel systems to over 50 per cent overall efficiency, a massive improvement.

## A new hope

Charles Stafford at the University of Arizona in Tucson was out to create a similar device when he realised that there was another possibility, one that could reinvent solar power. What if you could just forget all about finicky photovoltaic cells? What if you could make a material so good at capturing solar heat that it could replace solar panels completely? If it was cheap enough, it wouldn't matter if its peak efficiency was less than 50 per cent.

For that, he would need to abandon semiconductors for a new material. He found that polymers called polyphenol ethers might be up to the task. "They're very cheap," he says. "You could imagine buying the stuff in 100-litre jugs and just painting it onto any surface that you wanted to use for thermoelectric conversion." Stafford thinks he can engineer these molecules to disrupt the flow of the phonons. By building molecular chains with carefully chosen side groups, or chemical "offshoots", attached, Stafford thinks he can preferentially block the flow of phonons while letting the electrons through. The material tricks electrons into seeing an ordered material through which they can easily flow, while the phonons hit a messy roadblock.

Stafford's calculations predict an efficiency of 20 to 25 per cent for such a material, six times as high as today's best thermoelectric materials (*ACS Nano*, vol 4, p 5314). If he can pull it off, the outcome will be astounding. Photovoltaic panels may find their days are numbered.

In fact, that might be true already. In May, Chen published results that suggest panel-free solar systems could soon be a reality: that's because thermoelectrics offer a new way to concentrate solar energy. Until now, that approach hasn't worked for small rooftop panels because concentrating sunlight requires a complex system of lenses to track the sun's path across the sky, prohibitively expensive in all but commercial-scale systems.

Yet concentrating heat is as easy as placing a slab of copper in a sunny spot. Placing the copper inside a cheap glass vacuum enclosure traps the heat inside, and all you need to turn it into power are small pieces of thermoelectric material attached to the back of the copper sheet (*Nature Materials*, vol 10, p 532).

Even with an ordinary thermoelectric material, Chen's prototype managed to achieve an unprecedented efficiency of almost 5 per cent. If there are no significant material costs, even a system with efficiency as low as that could be worth making. And then, if thermoelectric materials get even marginally better, photovoltaics could certainly find themselves out of a job.

Whether the future is Chen's solar concentrators or Stafford's paint-on molecules, either way, thermoelectric materials look set to yield far cheaper, far more practical ways to harness the sun's energy. Maria Telkes's 50-year-old dream is close to reality.

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# Some like it hot



When one side of a thermoelectric material gets hot, the electrons get knocked off their atoms. Hot electrons drift to the cold side of the material faster than cold electrons can flow the other way, and so a negative charge accumulates at the cold side, creating a current