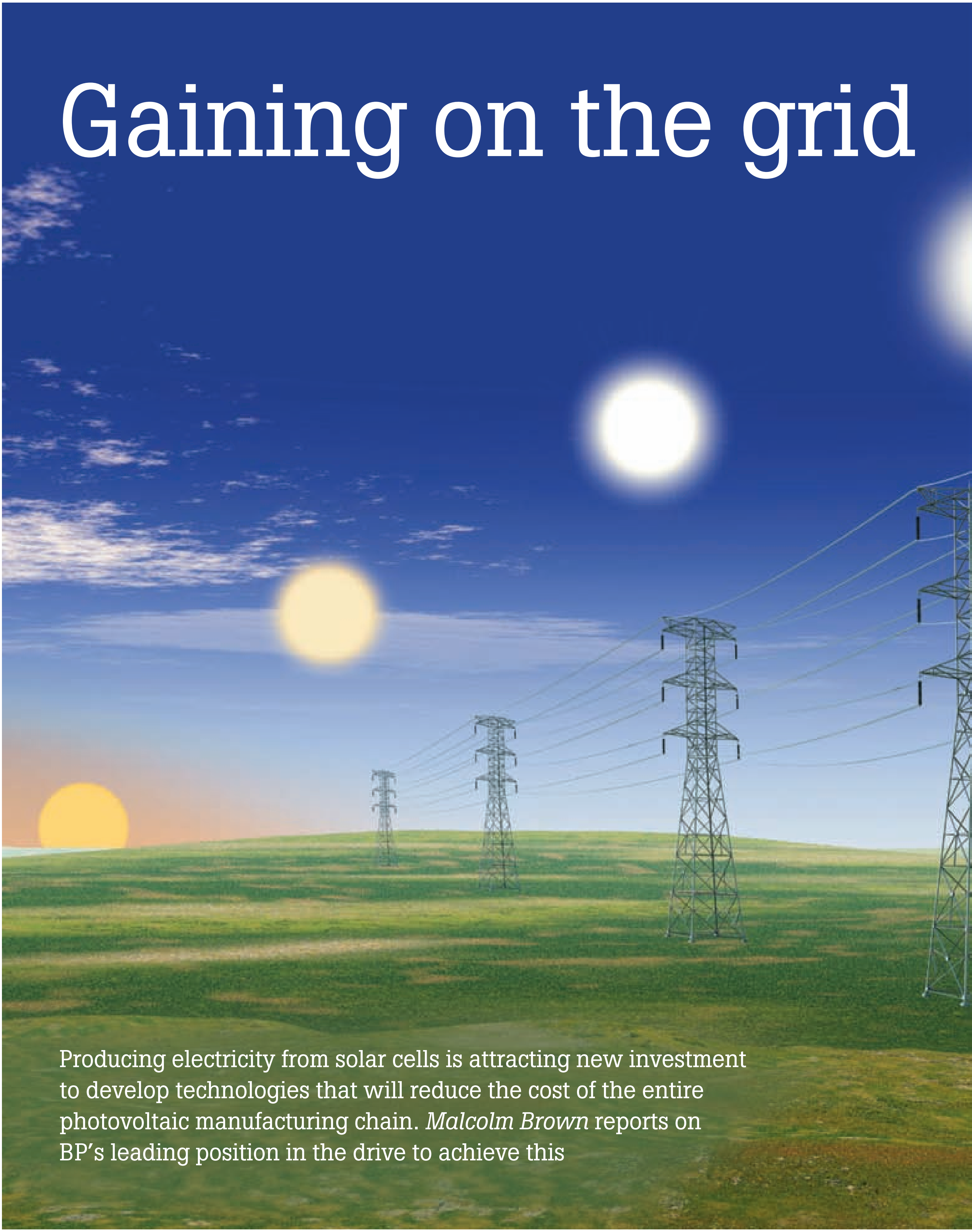
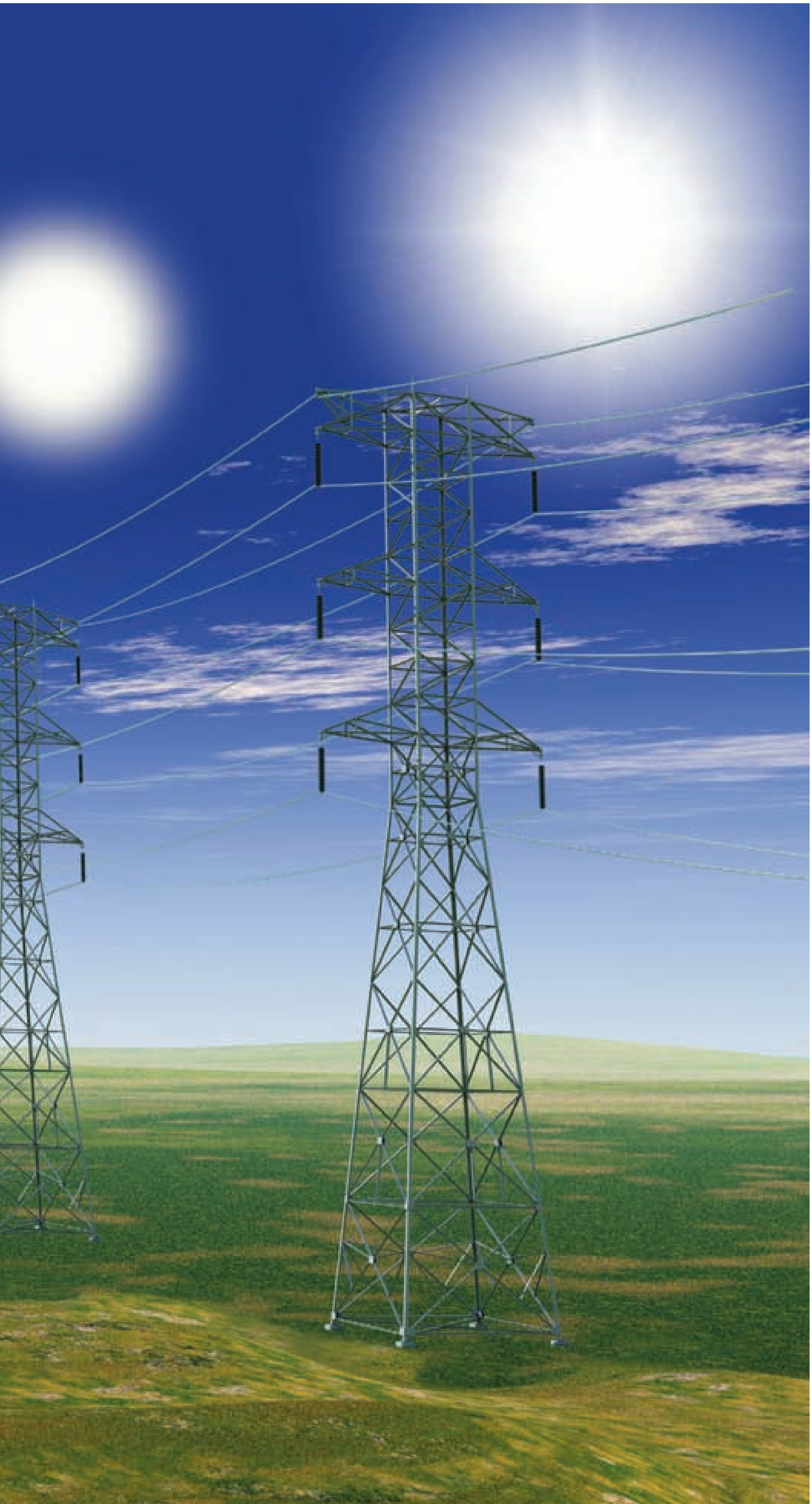
Gaining on the grid



Producing electricity from solar cells is attracting new investment to develop technologies that will reduce the cost of the entire photovoltaic manufacturing chain. *Malcolm Brown* reports on BP's leading position in the drive to achieve this

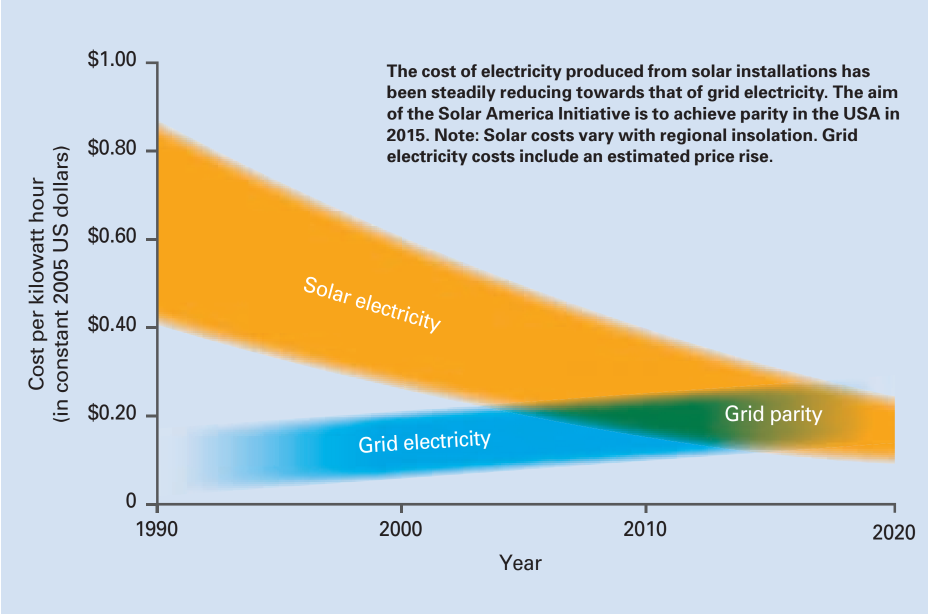


In 1931, just months before he died, the great inventor Thomas Edison told car maker Henry Ford what the next big thing for visionaries like them should be: 'I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that.'

Three quarters of a century later, solar electrical energy – in which photovoltaic cells made of semiconducting materials, usually silicon, convert sunlight directly into electricity – is beginning to emerge as a viable and potentially very profitable business. But the change in its fortunes has been a long time coming. It hasn't come about because of what Edison feared most – coal and oil running out – but because of worries about global warming and energy security. Burning fossil fuels pumps carbon dioxide (CO_2), the principal gas associated with global warming, into the atmosphere. Solar energy generation doesn't. It is clean. It is also close at hand. Wherever the sun is strong enough, solar energy is available. You do not have to rely on producers in other countries.

But, despite steady reduction in the costs of producing and installing solar cells, solar energy is still comparatively expensive – leading to two questions. Can the costs of solar be cut further, to make it competitive with conventional grid-supplied electricity? And if so, when will solar achieve what energy economists call 'grid parity'?

THE PATH TO GRID PARITY



The cost of electricity produced from solar installations has been steadily reducing towards that of grid electricity. The aim of the Solar America Initiative is to achieve parity in the USA in 2015. Note: Solar costs vary with regional insolation. Grid electricity costs include an estimated price rise.

› President George W Bush, a late but nonetheless welcome convert to solar energy, has set 2015 as the date for grid parity in the USA. He has pledged nearly $170 million of public money for the first three-year phase of a programme which his advisors think will make meeting that target feasible. The vehicle for change is the Solar America Initiative (SAI), a collaborative effort between industry and American universities to accelerate the development of advanced solar electric technologies. The US Department of Energy estimates that if the 2015 goal is met it should involve between five and ten gigawatts of new electricity generating capacity (enough to power one to two million homes), and avoid ten million tonnes of CO_2 emissions. It should also create 30,000 new jobs in the solar industry.

BP Solar has been one of the first beneficiaries of the SAI. In March a development team led by BP Solar was named as one of 13 teams to win funding for the first three-year phase of the programme. The BP team comprises 12 other US-based companies and three universities. The partner companies range from silicon manufacturers to makers of the inverters that convert the direct current (DC) produced by solar energy systems to the alternating current (AC) that is used to power electrical equipment like lights and computers. Other winning teams are led by companies like General Electric, Dow Chemical and Boeing. The arrangement is a 50/50 cost share and requires that the activities are largely US based. The government will match every dollar invested by the BP-led team up to a level of $7.5 million in the first year and more than $19 million over three years. The US government and the BP team will between them invest just short of $40 million during phase one.

BP hopes to cut the cost of residential solar systems by nearly 65 per cent by 2015

Silicon downgrade

BP is taking a holistic approach to reducing the installed cost of solar. Every aspect of the photovoltaic value chain, from the supply of the silicon used to make cells to the way systems are installed on customers' properties, is being examined in detail by BP and its team, and augments the existing technology roadmap being pursued by BP for achieving grid parity.

One of the crucial aspects of BP's winning proposal, says BP's John Wohlgemuth, the SAI team leader, is the close coordination between the partners. BP has already worked with several of them on a one-to-one basis, he says, but for the SAI project they are all working in parallel. 'We went through all of our really key process components and sought partners who can contribute, and can then grow with us so that the whole business will expand,' he explains.

The company hopes to cut the 2006 installed cost of residential solar systems by almost 40 per cent by 2010 and by nearly 65 per cent by 2015. A key step towards that goal will be to establish a potentially lower-cost solar-grade silicon. Until now the solar industry has vied with the semiconductor industry for supplies of silicon. This competition for a scarce resource has kept prices up. Furthermore, the electronics-grade silicon used in semiconductors is actually purer than the solar industry requires to make efficient cells.

'Today's silicon supply may be an overkill as far as purity is concerned,' says Jean Posbic, BP Solar's technology project director. 'It's *too* good. We could live with one or two orders of magnitude less in percentage purity terms and still make decent solar cells. But this only has relevance if we can substantially reduce the cost of manufacturing that solar-grade silicon too.'

The super-purity of electronics-grade silicon is achieved by an expensive capital-intensive process that involves producing a gas from the silicon, purifying the gas, then redepositing the gas as a solid. Solar grade will bypass or at least simplify the gasification stage. For the SAI, BP is collaborating with Dow Corning Corporation of Michigan to develop a solar grade manufacturing process, with the aim of establishing a new lower-cost form of silicon specific to solar needs.

Wafer thin

Making the silicon feedstock is only the starting point in manufacturing solar systems. BP believes it now has the know-how to radically change the next stage – the way that the silicon is made into the wafers at the heart of solar cells – and to do so much more cheaply and with higher quality. This involves a new technology, launched by BP Solar last year, known as Mono^2.

Mono^2 combines the best elements of two existing wafer making processes, the Czochralski process and the multicrystalline process (see diagram on page 18). Wafer makers have traditionally used the Czochralski process (named after a Polish chemist), to make a large cylindrical monocrystal of silicon, a metre or more in length, called a 'boule'. The boule is made by melting silicon in a crucible then dipping into it a seed of single-crystal silicon mounted on a rod. The rod is pulled upwards and rotated at the same time – rather like making candy floss or cotton candy. By controlling the temperature gradients, the rate of pulling, and the speed at which the rod is rotated, it is possible to draw a single large cylindrical crystal from the melted silicon. Each boule is sliced into circular wafers, measuring 125–156mm across and about 200–220 microns thick.

The solar cells made from boules typically have very good cell efficiency – efficiency is a measure of the percentage of sunlight energy striking the cell that is ultimately transformed into electricity. But they are wasteful: to make the cells, solar modules and arrays, the round wafers have first to be trimmed into a square shape, creating offcuts.

About 30 years ago one of the companies that eventually became part of BP developed an alternative, the so-called multicrystalline process. This, again, starts with a crucible of molten silicon, but the silicon is usually of a lower grade than the semiconductor-grade used for the monocrystal. The bath of silicon, which is square this time rather than circular, is cooled in a very precise way. Since this time there is no seed crystal involved the result is a square ingot made up of many different crystals, much like water when it freezes into ice. The multicrystalline process is faster and less energy-intensive than the

Czochralski process. The result is a cheaper, if slightly lower efficiency, solar wafer and solar cell.

Mono² combines these two ideas, says Eric Daniels, BP Solar's chief technology officer: 'Mono² allows us to make silicon wafers that have "mono" characteristics while having the cost and capital efficiency benefits of the traditional "multi" casting process. In addition, Mono² maintains mono Czochralski characteristics in that the single crystal is effective in separating out impurities as it grows, resulting in longer-life material. BP's cell efficiency improvement projects will further leverage the benefits offered by Mono².'

Wohlgemuth describes the result as having 'the quality of single crystals at the cost of multicrystals. You do a casting process, but you do it in such a way that you grow a single crystal which has no grain boundaries and a lot fewer dislocations and other structural defects in it.'

Whichever way it is made the silicon ingot is eventually cut into wafers using a thin steel wire in a wire-saw. A wasteful by-product of the sawing is kerf, or silicon sawdust. As part of the SAI, BP is working to reduce the thickness of wafers used for the cell production. One option is to reduce the thickness of the steel wire. Thinner wire will mean less waste and thinner wafers, which means lower costs. The target is to cut the present thickness of around 220 microns to 150 microns by 2010, and to 100 microns by 2015.

Posbic believes that there is enormous scope for improving the solar efficiency of cells and reducing costs by using innovative fabrication techniques. In the operation of solar cells, photons of sunlight with high enough energy that strike the silicon can release one electron each from a silicon atom (see panel 'How solar cells work', right). The trick then is to carry the electrons off through a metal contact into an electrical circuit where they can perform work. Posbic suggests that the efficiency of solar cells could be increased by as much as 40 per cent from 2006 levels by some simple innovations.

'The way we capture the electrons is one such innovation. The trick is to maximise the capture and we're going to be doing that with better ways of printing the conductors. Today we print silver conductors on the front of the wafer, and aluminium on the back. It's done using a screenprinting proces, similar to the technique used for printing designs on T-shirts. We are probably going to move away from that simple technique to advanced printing concepts that will minimise contact with the thinner wafers.'

The primary goal here is to reduce the amount of metal on the face of the cell: the silver on the face of the cell may be a good conductor but it stops a proportion of the sunlight actually reaching the silicon atoms, because they are in a shadow thrown by the metal.

Accelerating parity

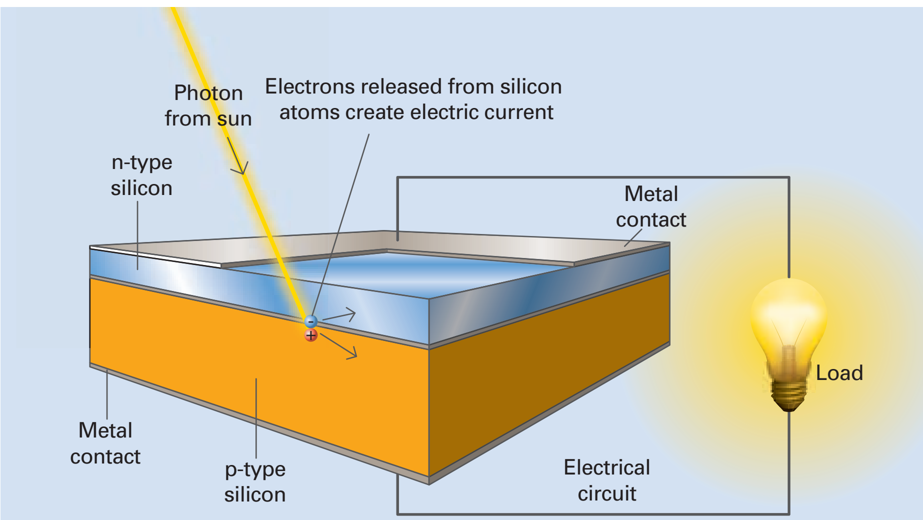
Today most solar installations are retrofits, that is, they are installed on existing buildings. Further big cost savings will be possible, says Posbic, when solar systems are incorporated as part of new buildings. To make that option attractive to house buyers, BP Solar is working to produce more aesthetically pleasing solar modules and arrays. In one project it is working with Arizona State University to produce modules that look like roof tiles.

In the USA, parity with the electricity grid at peak charging rates has already been achieved in northern California and Hawaii.

'Hawaii imports all of its energy, which means that it costs around 18–20 cents per kilowatt hour for electricity for home owners. Because of the ample sunshine in Hawaii, the cost of electricity from the sun is also around 20 cents per kilowatt hour,' says Posbic.

BP Solar is, of course, not confined to the USA. It works with many partners around the globe. The technology roadmap for the SAI is consistent with that for BP Solar's activities worldwide, and is complementary to efforts under way with global partners. The SAI may ›

HOW SOLAR CELLS WORK



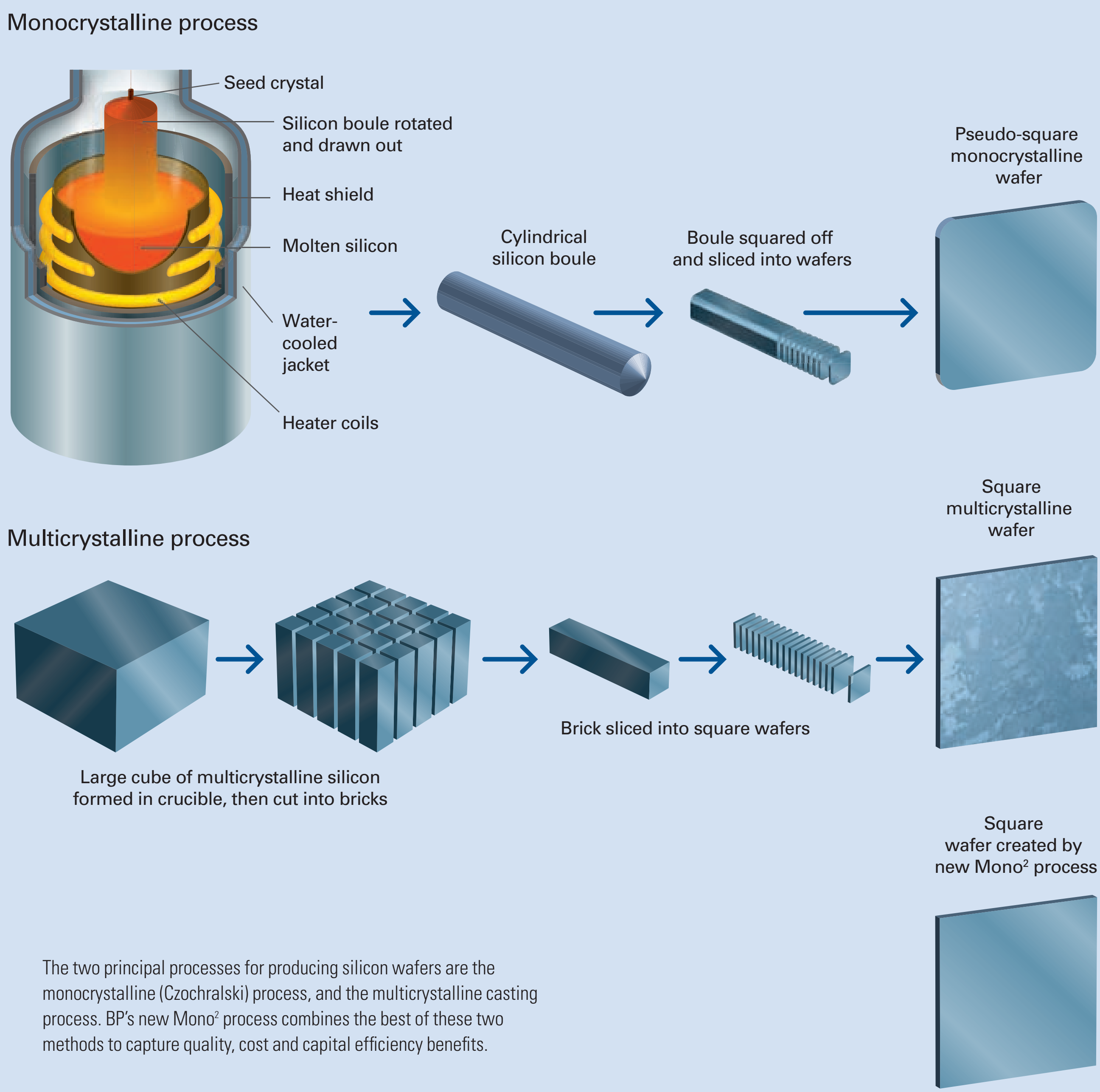
At the heart of photovoltaic solar cells are semiconductors – materials that can be chemically altered in order to vary their electrical conductivity. Several materials are suitable for this purpose. The most widely used is silicon, mainly shaped in the form of monocrystalline or multicrystalline wafers. Layers of these materials are treated with chemicals and heat to slightly alter their composition, creating either an excess of positive (p-type) or negative (n-type) electrical charges in the molecular structure.

A junction is formed by layering the two oppositely charged materials to form what is known as a p-n (or n-p) junction. To complete the cell, metallic contacts are located on each side of the cell to collect electrons, one on top and one as a back contact. BP Solar's cells are then encapsulated between plastic polymers and laminated onto a transparent cover, normally strengthened glass, which seals them against weather.

When the cell is exposed to sunlight, photons carrying energy from the sun are absorbed into the cell. Some of the photons have enough energy to free an electron from a silicon atom, separating it from that atom. After a short time, the electron would normally recombine with its atom or another nearby atom, but the purpose of the cell configuration is to allow liberated electrons to exit the cell through the front electric contacts, perform useful work outside the cell as electricity, and return through the back contact of the cell. The key to obtaining good performance from the cell lies in maximising the number of photons converted to electricity.

Typically, crystalline silicon cells generate high currents but at low voltages. Cells are connected in series to generate higher voltages for practical power applications in residential and commercial properties. By banking solar panels together and passing the output through an inverter to produce alternating current, large scale solar energy may be fed into national electricity grids.

MANUFACTURING SILICON WAFERS



The two principal processes for producing silicon wafers are the monocrystalline (Czochralski) process, and the multicrystalline casting process. BP's new Mono² process combines the best of these two methods to capture quality, cost and capital efficiency benefits.

help BP accelerate grid parity in the USA, but the company could probably use the same or similar technologies elsewhere.

Achieving grid parity elsewhere will depend on a range of factors, from the availability of sunshine to government incentives, and technological innovation.

In Europe, Italy, Germany and Spain are regarded as strong candidates, not least because of the government subsidies available for residential systems.

BP is pressing ahead on all fronts in what has become a fast growing industry. 'The industry has been growing at 30–40 per cent a year and we want to remain a top player,' says Daniels. 'We're going from roughly 200 megawatts (MW) of manufacturing capacity at the end of 2006 to 300MW by the end of 2007. We've just announced a $97 million expansion of the Frederick, Maryland, facility and we're expanding our factories in Madrid in Spain and Bangalore in India.'

There are plans to take BP's manufacturing capacity to 1000MW in the next few years. So it seems that the company is within reach of a goal which was regarded as utopian just a few years ago. Thomas Edison would be delighted. ■

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