



A NEW DAY DAWNING?

Sunlight is a ubiquitous form of energy, but not as yet an economic one. In the first of two features, **Oliver Morton** looks at how interest in photovoltaic research is heating up in California's Silicon Valley. In the second, **Carina Dennis** talks to Australian researchers hoping to harness the dawn Sun's heat.

Silicon Valley sunrise

The Sun provides Earth with as much energy every hour as human civilization uses every year. If you are a solar-energy enthusiast, that says it all. No other energy supply could conceivably be as plentiful as the 120,000 terawatts the Sun provides ceaselessly and unbidden. If the tiniest fraction of that sunlight were to be captured by photovoltaic cells that turn it straight into electricity, there would be no need to emit any greenhouse gases from any power plant.

Thanks to green thoughts like that, and to generous subsidies from governments in Japan and Germany, the solar-cell market has been growing on average by a heady 31% a year for the past decade (see chart, overleaf). One of the most bullish industry analysts, Michael Rogol, sees the industry increasing from about US\$12 billion in 2005 to as much as \$70 billion in 2010. Although not everyone predicts such impressive growth, a 20–25% annual rise is widely expected. The market for shares in solar-energy companies is correspondingly buoyant.

And yet in the projections of energy supply made by policy analysts and climate wonks, solar remains so marginal as to be barely on the map at all. At the moment, the world's total

installed solar cells have a capacity of about five gigawatts. That looks small compared with almost 400 gigawatts for nuclear power and much more than 1,000 gigawatts for coal. And that's before taking into account the fact that solar cells do not produce electricity at their peak rating all the time. Even within the world of renewables, solar is dwarfed by wind power and hydroelectricity, simply because the technology is much more expensive. And expert opinion does not expect growth in the field to change the picture very much: a 25% annual growth in installed capacity for the next 15 years would still see solar photovoltaics producing just 1% of the world's energy.

Points of view

Reconciling the solar-cell industry's optimism with global indifference is basically a matter of perspective. Seen from the viewpoint of a small industry, solar's recent decade of expansion is indeed extraordinary. But even heady growth is not enough to spur a radical overhaul of energy infrastructure when you start such a long way behind your competitors. So, although no one doubts that solar electricity will become cheaper in the future,

D. SANGER PHOTOGRAPHY/ALAMY



Lighting the way: Chris Eberspacher has developed a relatively low-cost way to manufacture solar cells.

few expect it to do so fast enough to force radical change.

Few worldwide, that is. In California's Silicon Valley, the corridor of land along the southwest side of San Francisco Bay, the outlook is more optimistic. Home first to the semiconductor boom and then to the Internet boom, the valley is perhaps the most fertile environment for new technologies in the world. As well as an extraordinary density of successful technology-based companies, it boasts world-class research universities, abundant capital, and a cultural fixation on getting to the future first and making money from it. The dot.com bust of 2000 did relatively little to dent the valley's fundamental strengths and attitudes; instead, it left the area's entrepreneurs and venture capitalists looking for somewhere else to put their millions.

'Cleantech' of all sorts, from water purification to biofuels, is currently the place they want to be. In 2005, \$1.6 billion in venture capital went into cleantech, a growth of 35% year on year according to the Cleantech Venture Network, an umbrella group. The high-profile venture-capital firm Kleiner Perkins Caulfield and Byers is putting \$100 million of its latest \$600-million investment fund into cleantech start-ups. Bill Joy, a partner at Kleiner Perkins who used to be chief scientist at Sun Microsystems, says that the firm will look at perhaps 1,000 different cleantech ideas in the next year. And amid all these opportunities, photovoltaics seem to resonate most with Silicon Valley's history and culture.

One attraction is technological familiarity. Solar power has grown up in the shadow of the chip industry, using its cast-off materials and technologies. The silicon in traditional solar cells comes from the same suppliers who feed the chip market; new techniques to make solar cells often use processing technology, such as chemical vapour deposition, that is already widely used in the production of integrated circuits. Miasolé, a Silicon Valley solar start-up in which Kleiner Perkins has invested, uses expertise derived from the manufacture of computer hard drives.

But there is a broader cultural attraction, too. The potential of solar power to decentralize energy generation — a potential shared, to a lesser extent, by wind power — appeals to a culture that places huge societal significance on the empowering spread of the Internet. And a business community that saw personal

computers go from hobbyists' workshops to almost a billion of the world's desks in 30 years is not fazed by the small size of the solar market today, but energized by the possibilities of tomorrow.

It's also a help that Silicon Valley is sunny not just in its outlook; a solar cell in California can produce almost twice as much electricity a year as one in the Ruhr.

Catching the rays

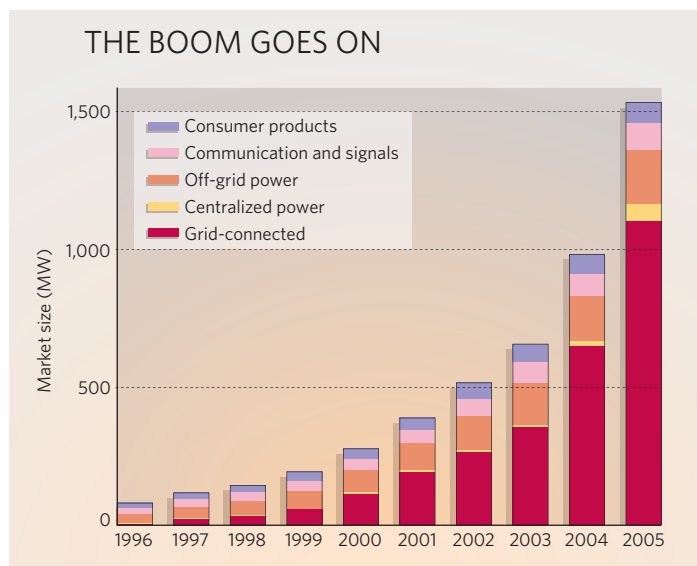
The poster child for Silicon Valley's interest in solar power is a company called Nanosolar, based in a distinctly unimposing one-storey building next to Palo Alto's municipal airfield. Disappointingly, it has no solar panels on its roof, although there is a smattering of Prius hybrids in its parking lot.

Nanosolar was founded in 2001 by Brian Sager, a biotech veteran with expertise in intellectual property, and Martin Roscheisen, an Austrian entrepreneur who mixes grandiloquence, enthusiasm and edginess. Like many Silicon Valley entrepreneurs, Roscheisen had a good track record: companies he had had a founding role in had sold for more than a billion dollars. And Nanosolar quickly attracted 'angel' investors with powerful reputations, including the founders of Google. In 2002, it became the first solar company to raise money on Sand Hill Road, Palo Alto's superconcentration of venture-capital firms.

Nanosolar was not founded with one specific solar technology in mind, says Roscheisen. That's just as well, because the range of technologies it spent its first years investigating have not as yet panned out. The 'nano' in the company's name reflected an early belief that the use of very small structures would allow novel photovoltaics made of organic molecules to overcome certain difficulties, such as being able to transfer charge only over very short distances. But the founders soon concluded that "the organic part was going to require a number of years to mature", says Chris Eberspacher, the company's vice-president of engineering. "And even when mature it would not be very efficient, and not be very durable."

That was where Eberspacher came in. He had been a solar aficionado since a school trip to the University of Texas, Austin; instead of being awestruck by the Texas Turbulent Tokamak fusion experiment being shown to potential students, he found himself drawn to the ramshackle alternative-technologies centre across the street. Eberspacher went on to become head of research and development at Arco, once the largest maker of solar cells in the world, before starting a company of his own.

When Nanosolar had trouble getting its organic technologies



W. BREUER
to work, the company leaders looked around for something less risky that they could get to work in the medium term. They had capital; Eberspacher had technologies that, while still innovative, were considerably more tried and tested than those Nanosolar had been working on. He licensed the technologies to them and joined up in 2005.

That technology is now being scaled up for production at Nanosolar's first factory, which aims to produce more than 200 megawatts of solar cells in its first year and 430 megawatts a year later. That would make it among the largest solar-cell fabrication facilities in the world, and by far the largest devoted to this sort of 'thin-film' solar cell.

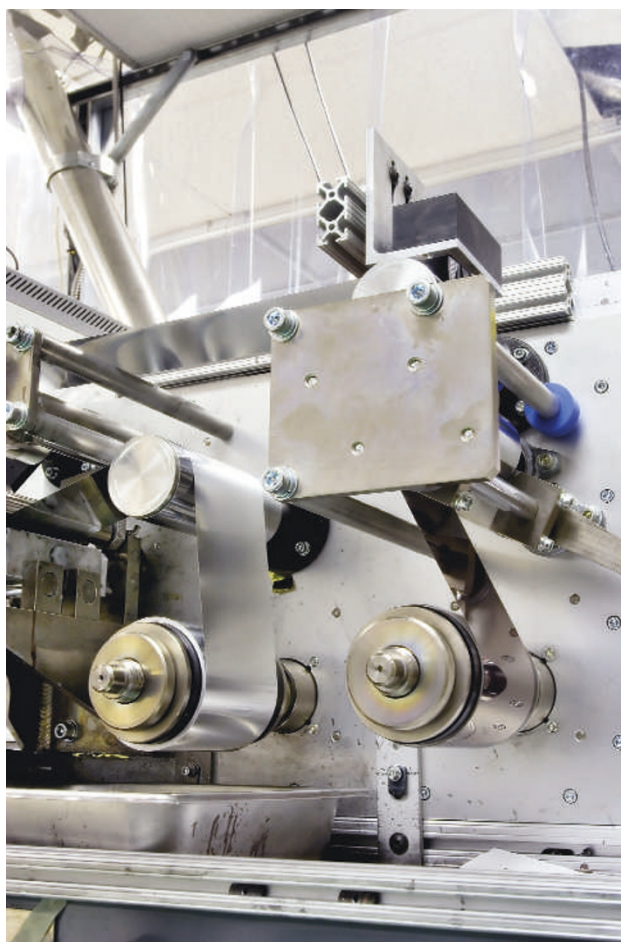
Traditional silicon solar cells are made out of chunks of silicon 200 micrometres thick or more, but slivers a single micrometre across can suffice for a 'CIGS' thin film. CIGS cells are made up of copper, indium, gallium and selenium. Even though some of those elements are increasingly expensive — the price of copper has more than tripled in the past four years and the price of indium has shot up by a factor of ten — they are used in such sparing amounts that this is not too great a problem.

What is a problem is that making very thin layers of CIGS has often been a complicated and expensive business, typically involving carefully controlled vapours being laid on to surfaces kept in vacuums. "The silicon [photovoltaic] industry got founded on a wafer technology we inherited from the integrated-circuit industry," says Eberspacher, "and the thin-film photovoltaic industry got founded on deposition techniques inherited from them in the same way." But expenses that are reasonable for materials that process information are too high for materials that process energy.

On a roll

Decades of development have made CIGS cells as efficient as mass-market silicon cells; they can convert about 15% of incoming solar radiation into outgoing electrical current. They are also durable — the National Renewable Energy Laboratory in Golden, Colorado, has been running some since 1988 without any significant degradation. But they are not yet cheap to produce.

The leaders of Nanosolar think that Eberspacher's techniques offer a way around that. They make tiny CIGS particles and mix them into a sort of ink, printing them on to a substrate of metal foil and curing that foil in such a way that the particles condense into a continuous semiconductor. The cells should hit the market in 2007, and the fact that the particles



Thin-film solar cells can be made continuously using a roll printer.

are nanometres across means that the company is still accurately named — although more by luck than judgement.

Perhaps the most attractive aspect of the Nanosolar process is that it can be carried out on foil being continuously pulled off one roll on to another, allowing very high throughput. Such 'roll-to-roll' technologies make it possible to build a large factory with a relatively small investment and make cells cheaply. Roscheisen boasts that the production costs for Nanosolar's cells are so low that even if you subtracted the costs of materials, manpower and energy from a traditional silicon factory, its cells would still be more expensive than those of Nanosolar.

Whether Nanosolar can live up to that boast remains to be seen. The fact that it has just raised a further \$75 million in private capital suggests that some fairly serious investors believe it will. Whether or not it succeeds, many other companies are trying the same thing. Miasolé in Santa Clara is starting to produce CIGS films made with its hard-drive technology. Earlier this year, Applied Materials — a far larger Santa Clara company that sells the machinery used to make chips and flat-

panel displays — acquired the rights to ways of making thin-film silicon-based photovoltaics developed in Germany. And Nanosys, a Palo Alto firm, is working on nanostructures that could minimize current difficulties with the sort of organic polymer-based solar cells that Nanosolar was looking at in its early days.

The valley does not have a monopoly on innovation. DayStar, based in Halfmoon, New York, is also pursuing CIGS thin films, as is Wurth Solar in Germany. In Austin, Texas, B. J. Stanbery has founded a company called Heliovolta. Stanbery, who has been working with CIGS thin films since the early 1980s, when they were first under development at Boeing, has developed techniques for printing such films on a variety of substrates, speeding up their manufacture. In Lowell, Massachusetts, a company called Konarka is working on a novel system for using dyes to produce solar power from flexible plastics. The interaction of sunlight with these organic dyes produces solar power in a way that is perhaps more similar to photosynthesis than to the semiconductor processes in normal solar cells.

Measuring up

But even if one or more of these companies manages to make solar cells a great deal cheaper, it will be only the beginning. Manufacturing the cells accounts for just half of the roughly \$6 per watt it costs to get a solar-cell system up and running. The remaining cost is needed to put them into a protective, mountable module, tune their output from direct current to alternating current, and install them.

This has various implications. One is that cells below about 10% efficiency have a hard time making economic sense, because the costs of mounting and installing cells in traditional models get bigger the larger the area involved, and low-efficiency cells require larger areas. Another is that even if you gave away 15%-efficient cells for free, systems using modules such as today's would still be too expensive for many applications. This is why Nanosolar and almost all

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the other recent solar start-ups take a strong interest in new ways of mounting their cells — ways that take advantage of their light weight or flexibility. Eberspacher hopes, for example, that such light-weight systems could be used on Nanosolar's own roof, which is too flimsy to take the load from a traditional array.

The ultimate aim, says Stanbery, is to integrate the cells straight into building materials

of all sorts. New houses, he points out, need roofs anyway. Photovoltaic tiles could be wired into the house from the start. "Integrating the photovoltaics as a coating," he says, "is frankly the only practical and cost-effective way to do it." Heliovolt's printing process is meant to help make that integration possible. And Konarka talks of adding its dye-based 'Power Plastic' to more or less anything, from windows (where it would just cream off a bit of the light) to wind sheeters.

None of these technologies, however cleverly mounted, will get the costs of generating electricity low enough for solar power to compete directly with coal, gas, wind or nuclear. But because solar panels are inherently easily decentralized, they do not have to compete with the cost of generating electricity; they just have to compete with the price consumers pay for it. This is four or five times more than the cost of generation, because the power companies need to pay for transmission networks, build new plants and please shareholders.

So the industry's aim is to get significantly below 'grid parity'. This is the point at which the cost of borrowing the money to buy and install a solar-power system is more than covered by savings on your electricity bill. At the moment, grid parity is not quite within reach; in most places with a lot of solar cells there is or has been a great deal of government subsidy. In Germany, a particularly powerful subsidy is a government requirement that electric utilities be willing to buy electricity generated by small photovoltaic installations, such as those in homes and small businesses, at more than 50 cents a kilowatt-hour. Although this rate decreases over

time, it is still a costly subsidy, and some wonder how long it can last in its present form. In its favour is popularity with the electorate — and, of course, with Germany's producers of solar cells.

Reaching grid parity is not in itself enough. But if a mixture of much cheaper cells and adaptable, easily installed modules could bring the total cost of installation down by a factor of three, solar energy would start to look prudent, analysts say.

Spending to save

There is a lively research agenda in basic materials science that a thriving solar industry could use to drive costs down further still. Michael McGehee of Stanford University, the young investigator whose work on organic photovoltaics was part of the original inspiration for Nanosolar, is developing a proposal for a major initiative in solar energy research. "We are going to apply for a large centre here, funded by the Department of Energy," he says. "We have a team of people who will work on using sunlight to excite a semiconductor, or to split water to make hydrogen." If fully funded, it would have 16–20 principal investigators and be one of the biggest research groups with a specific target at Stanford.

Steve Chu, the Nobel prizewinning Stanford physicist who now runs the Lawrence Berkeley National Laboratory on the other side of San Francisco Bay, has ambitious plans for an initiative called Helios. This would integrate new photovoltaic research with studies into other ways of capturing and storing sunlight, such

as biofuels; the idea is currently under review at the Department of Energy.

Also testimony to the research interest in this area is the way that it is being presented at meetings. Organizing a session on solar applications at last November's meeting of the Materials Research Society, McGehee found himself swamped with hundreds of abstracts; it

was the third most popular of the meeting's 40 sessions.

One potential source of funding for all this research is Proposition 87, which will be on the California ballot this November. The proposition, which is strongly opposed by oil producers, would increase the cost of drilling fees in order

to raise \$4 billion for clean-energy initiatives, including research. Vinod Khosla, a former partner at Kleiner Perkins, is a main backer of the initiative, and other venture capitalists are also on board.

But the fact that Silicon Valley is abuzz with solar enthusiasm doesn't necessarily mean that all the activity there will trigger a revolution. Someone elsewhere might come up with the key breakthrough technology. And just because venture capitalists are successful in making money doesn't mean they will effect major economic changes. As Stephen Levy of the Center for the Continuing Study of the California Economy points out, venture capitalists have been saying that biotech would be the big new growth sector for years, "and it is still 'just about to explode', with an emphasis on the 'just about'."

Solar enthusiasts can respond that solar cells have no Food and Drug Administration to face, and that they don't need to invest hundreds of millions to get a product to market, as drug developers do. Yet a decade's growth, however buoyant, doesn't by itself mean that much. That growth needs to last for several decades to change an economy, and needs to accelerate to an even higher level to change the world.

The difference between growing at a more than respectable 25% a year and at 44% a year — the rate at which volume grew in 2005 — is the difference between doubling in size in just over three years and in just over two. That may not sound a great deal, but over 15 years it means something growing at 44% would outdo something growing at 25% by a factor of eight. Between now and 2050, the difference is a factor of 500. And that could be the difference between providing just 2% of Earth's energy needs — and 10 times those needs.

The remarkable thing is that the products of the semiconductor industry have grown at a yet faster rate for a similar length of time. If Silicon Valley can apply Moore's law to the capture of sunshine, it could change the world again. ■

Oliver Morton is *Nature's* chief news and features editor.

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— B. J. Stanbery



High flyers: the bright sparks of Silicon Valley can see a future in solar cells.