The future of energy

A fundamental change is coming sooner than you might think

SINCE the industrial revolution 200 years ago, mankind has depended on fossil fuel. The notion that this might change is hard to contemplate. Greens may hector. Consciences may nag. The central heating's thermostat may turn down a notch or two. A less thirsty car may sit in the drive. But actually stop using the stuff? Impossible to imagine: surely there isn't a serious alternative?

Such a failure of imagination has been at the heart of the debate about climate change. The green message—use less energy—is not going to solve the problem unless economic growth stops at the same time. If it does not (and it won't), any efficiency saving will soon be eaten up by higher consumption per head. Even the hair-shirt option, then, will bring only short-term relief. And when a dire prophecy from environmentalism's jeremiad looks as if it is coming true, as the price of petroleum rises through the roof and the idea that oil might run out is no longer whispered in corners but openly discussed, there is a temptation to believe that the end of the world is, indeed, nigh.

Not everyone, however, is so pessimistic. For, in the imaginations of a coterie of physicists, biologists and engineers, an alternative world is taking shape. As the special report in this issue describes, plans for the end of the fossil-fuel economy are now being laid and they do not involve much self-flagellation. Instead of bullying and scaring people, the prophets of energy technology are attempting to seduce them. They promise a world where, at one level, things will have changed beyond recognition, but at another will have stayed comfortably the same, and may even have got better.

This time it's serious

Alternative energy sounds like a cop-out. Windmills and solar cells hardly seem like ways of producing enough electricity to power a busy, self-interested world, as furnaces and steam-turbines now do. Battery-powered cars, meanwhile, are slightly comic: more like milk-floats than Maseratis. But the proponents of the new alternatives are serious. Though many are interested in environmental benefits, their main motive is money. They are investing their cash in ideas that they think will make them large amounts more. And for the alternatives to do that, they need to be both as cheap as (or cheaper than) and as easy to use as (or easier than) what they are replacing.

For oil replacements, cheap suddenly looks less of a problem. The biofuels or batteries that will power cars in the alternative future should beat petrol at today's prices. Of course, today's prices are not tomorrow's. The price of oil may fall; but so will the price of biofuels, as innovation improves crops, manufacturing processes and fuels.

Electrical energy, meanwhile, will remain cheaper than petrol energy in almost any foreseeable future, and tomorrow's electric cars will be as easy to fill with juice from a socket as today's are with petrol from a pump. Unlike cars powered by hydrogen fuel cells, of the sort launched by Honda this week, battery cars do not need new pipes to deliver their energy. The existing grid, tweaked and smartened to make better use of its power stations, should be infrastructure enough. What matters is the nature of those power stations.

The price is right

They, too, are more and more likely to be alternative. Wind power is taking on natural gas, which has risen in price in sympathy with oil. Wind is closing in on the price of coal, as well. Solar energy is a few years behind, but the most modern systems already promise wind-like prices. Indeed, both industries are so successful that manufacturers cannot keep up, and supply bottlenecks are forcing prices higher than they otherwise would be. It would help if coal—the cheapest fuel for making electricity—were taxed to pay for the climate-changing effects of the carbon dioxide produced when it burns, but even without such a tax, some ambitious entrepreneurs are already talking of alternatives that are cheaper than coal.

Older, more cynical hands may find this disturbingly familiar. The last time such alternatives were widely discussed was during the early 1970s. Then, too, a spike in the price of oil coincided with a fear that natural limits to supply were close. The newspapers were full of articles on solar power, fusion and converting the economy to run on fuel cells and hydrogen.

Of course, there was no geological shortage of oil, just a politically manipulated one. Nor is there a geological shortage this time round. But that does not matter, for there are two differences between then and now. The first is that this price rise is driven by demand. More energy is needed all round. That gives alternatives a real opening. The second is that 35 years have winnowed the technological wheat from the chaff. Few believe in fusion now, though uranium-powered fission reactors may be coming back into fashion. And, despite Honda's launch, the idea of a hydrogen economy is also fading fast. Thirty-five years of improvements have, however, made wind, solar power and high-tech batteries attractive.

As these alternatives start to roll out in earnest, their rise, optimists hope, will become inexorable. Economies of scale will develop and armies of engineers will tweak them to make them better and cheaper still. Some, indeed, think alternative energy will be the basis of a boom bigger than information technology.

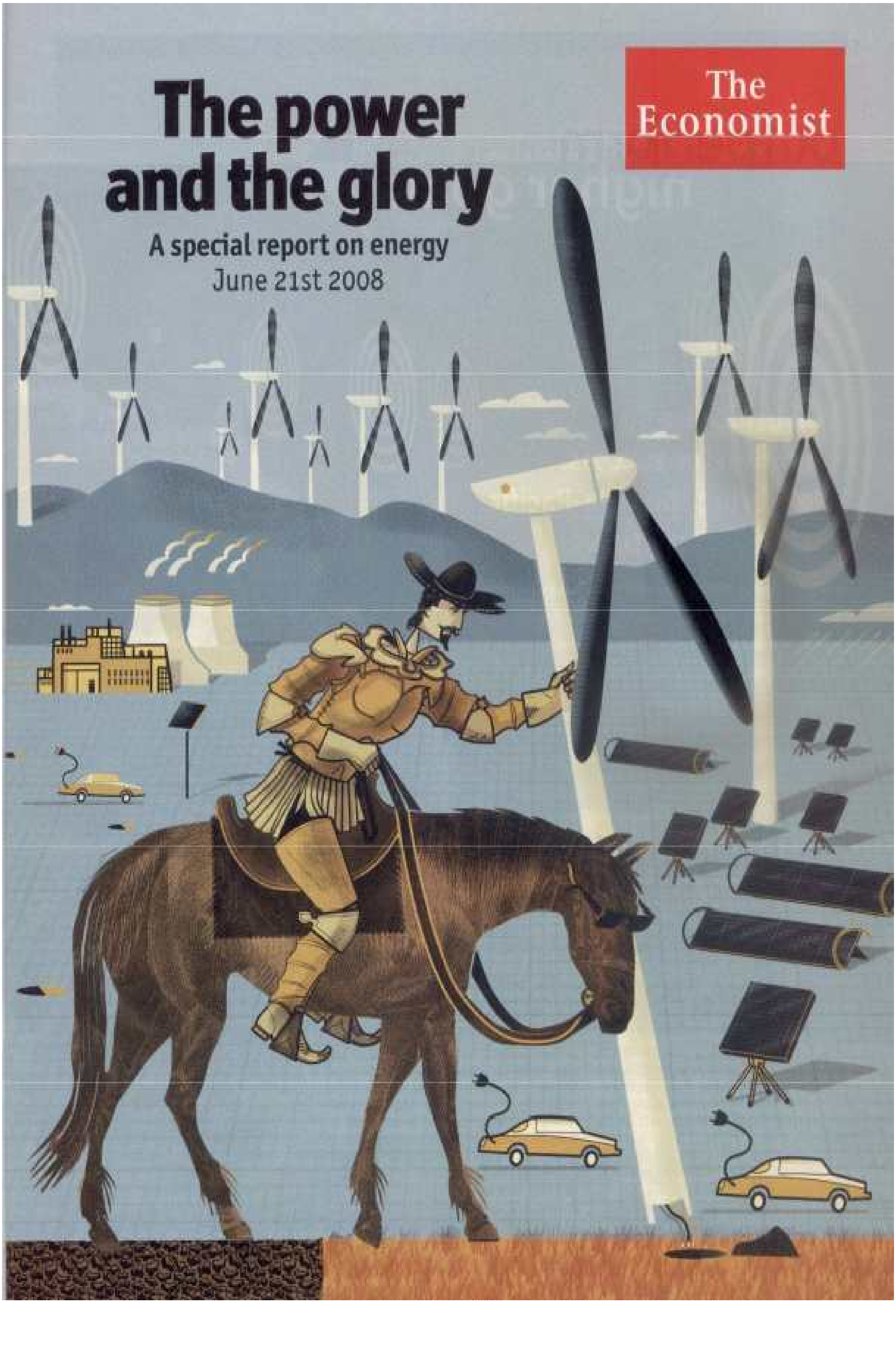
Whether that boom will happen quickly enough to stop the concentration of carbon dioxide in the atmosphere reaching dangerous levels is moot. But without alternative energy sources such a rise is certain. The best thing that rich-world governments can do is to encourage the alternatives by taxing carbon (even knowing that places like China and India will not) and removing subsidies that favour fossil fuels. Competition should do the rest—for the fledgling firms of the alternative-energy industry are in competition with each other as much as they are with the incumbent fossil-fuel companies. Let a hundred flowers bloom. When they have, China, too, may find some it likes the look of. Therein lies the best hope for the energy business, and the planet. ■

The power and the glory

A special report on energy

June 21st 2008

The Economist



The power and the glory

Also in this section

Acknowledgments
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A list of sources is at
www.economist.com/specialreports

An audio interview with the author is at
www.economist.com/audiovideo

More coverage of alternative energy and other green issues is at
www.economist.com/greenview

The next technology boom may well be based on alternative energy, says Geoffrey Carr. But which sort to back?

EVERYONE loves a booming market, and most booms happen on the back of technological change. The world's venture capitalists, having fed on the computing boom of the 1980s, the internet boom of the 1990s and the biotech and nanotech boomlets of the early 2000s, are now looking around for the next one. They think they have found it: energy.

Many past booms have been energy-fed: coal-fired steam power, oil-fired internal-combustion engines, the rise of electricity, even the mass tourism of the jet era. But the past few decades have been quiet on that front. Coal has been cheap. Natural gas has been cheap. The 1970s aside, oil has been cheap. The one real novelty, nuclear power, went spectacularly off the rails. The pressure to innovate has been minimal.

In the space of a couple of years, all that has changed. Oil is no longer cheap; indeed, it has never been more expensive. Moreover, there is growing concern that the supply of oil may soon peak as consumption continues to grow, known supplies run out and new reserves become harder to find.

The idea of growing what you put in the tank of your car, rather than sucking it out of a hole in the ground, no longer looks like economic madness. Nor does the idea of throwing away the tank and plugging your car into an electric socket instead. Much of the world's oil is in the hands of governments who have little sympathy with the rich West. When a former head of America's Central Intelligence Agency allies himself with tree-hugging greens that his outfit would once have suspected of subversion, you know something is up. Yet that is one tack James Woolsey is trying in order to reduce his country's dependence on imported oil.

The price of natural gas, too, has risen in sympathy with oil. That is putting up the cost of electricity. Wind- and solar-powered alternatives no longer look so costly by comparison. It is true that coal remains cheap, and is the favoured fuel for power stations in industrialising Asia. But the rich world sees things differently.

In theory, there is a long queue of coal-fired power stations waiting to be built in America. But few have been completed in the past 15 years and many in that queue have been put on hold or withdrawn, for two reasons. First, Americans have become intolerant of large, polluting industrial plants on their doorsteps. Second, American power companies are fearful that they will soon have to pay for one particular pollutant, carbon dioxide, as is starting to happen in other parts of the rich world. Having invested heavily in gas-fired stations, only to find themselves locked into an increasingly expensive fuel, they do not want to make another mistake.

That has opened up a capacity gap and an opportunity for wind and sunlight. The future price of these resources—zero—is known. That certainty has economic value as a hedge, even if the capital cost of wind ▸▸

and solar power stations is, at the moment, higher than that of coal-fired ones.

The reasons for the boom, then, are tangled, and the way they are perceived may change. Global warming, a long-range phenomenon, may not be uppermost in people's minds during an economic downturn. High fuel prices may fall as new sources of supply are exploited to fill rising demand from Asia. Security of supply may improve if hostile governments are replaced by friendly ones and sources become more diversified. But none of the reasons is likely to go away entirely.

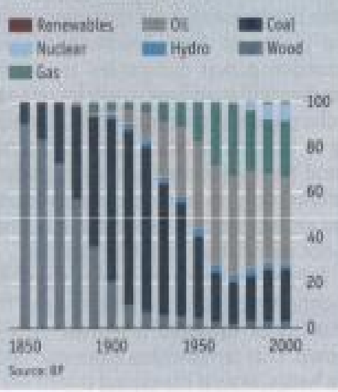
Global warming certainly will not. "Peak oil", if oil means the traditional sort that comes cheaply out of holes in the ground, probably will arrive soon. There is oil aplenty of other sorts (tar sands, liquefied coal and so on), so the stuff is unlikely to run out for a long time yet. But it will get more expensive to produce, putting a floor on the price that is way above today's. And political risk will always be there—particularly for oil, which is so often associated with bad government for the simple reason that its very presence causes bad government in states that do not have strong institutions to curb their politicians.

A prize beyond the dreams of avarice

The market for energy is huge. At present, the world's population consumes about 15 terawatts of power. (A terawatt is 1,000 gigawatts, and a gigawatt is the capacity of the largest sort of coal-fired power station.) That translates into a business worth $6 trillion a year—about a tenth of the world's economic output—according to John Doerr, a venture capitalist who is heavily involved in the industry. And by 2050, power consumption is likely to have risen to 30 terawatts.

A dance to the music of time 1

Sources of US energy supply, %



Scale is one of the important differences between the coming energy boom, if it materialises, and its recent predecessors—particularly those that relied on information technology, a market measured in mere hundreds of billions. Another difference is that new information technologies tend to be disruptive, forcing the replacement of existing equipment, whereas, say, building wind farms does not force the closure of coal-fired power stations.

For both of these reasons, any transition from an economy based on fossil fuels to one based on renewable, alternative, green energy—call it what you will—is likely to be slow, as similar changes have been in the past (see chart 1). On the other hand, the scale of the market provides opportunities for alternatives to prove themselves at the margin and then move into the mainstream, as is happening with wind power at the moment. And some energy technologies do have the potential to be disruptive. Plug-in cars, for example, could be fuelled with electricity at a price equivalent to 25 cents a litre of petrol. That could shake up the oil, carmaking and electricity industries all in one go.

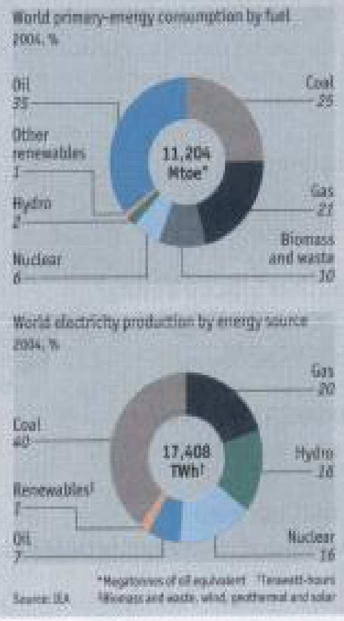
The innovation lull of the past few decades also provides opportunities for technological leapfrogging. Indeed, it may be that the field of energy gives the not-quite-booms in biotechnology and nanotechnology the industrial applications they need to grow really big, and that the three aspiring booms will thus merge into one.

The possibility of thus recapturing the good times of their youth has brought many well-known members of the "technorati" out of their homes in places like Woodside, California. Energy has become supercool. Elon Musk, who co-founded PayPal, has developed a battery-powered sports car. Larry Page and Sergey Brin, the founders of Google, have started an outfit called Google.org that is searching for a way to make renewable energy truly cheaper than coal (or RE<C, as they describe it to their fellow geeks).

Vinod Khosla, one of the founders of Sun Microsystems, is turning his considerable skills as a venture capitalist towards renewable energy, as are Robert Metcalfe, who invented the ethernet system used to connect computers together in local networks, and Mr Doerr, who works at Kleiner Perkins Caufield & Byers, one of Silicon Valley's best-known venture-capital firms. Sir Richard Branson, too, is getting in on the act with his Virgin Green Fund.

This renewed interest in energy is bringing forth a raft of ideas, some bright, some batty, that is indeed reminiscent of the dotcom boom. As happened in that boom, most of these ideas will come to naught. But there could just be a PayPal or a Google or a Sun among them.

The way we live now 2



More traditional companies are also taking an interest. General Electric (GE), a large American engineering firm, already has a thriving wind-turbine business and is gearing up its solar-energy business. The energy researchers at its laboratories in Schenectady, New York, enjoy much of the intellectual freedom associated with start-up firms, combined with a secure supply of money.

Meanwhile, BP and Shell, two of the world's biggest oil companies, are sponsoring both academic researchers and new, small firms with bright ideas, as is DuPont, one of the biggest chemical companies. Not everyone has joined in. Exxon Mobil, the world's largest oil company not in government hands, is conspicuously absent. But in many boardrooms renewables are no longer seen as just a way of keeping environmentalists off companies' backs.

Some people complain that many existing forms of renewable energy rely on subsidies or other forms of special treatment for their viability. On the surface, that is true. Look beneath, though, and the whole energy sector is riddled with subsidies, both explicit and hidden, and costs that are not properly accounted for. Drawing on the work of people like Boyden Gray, a ▸▸

former White House counsel, Mr Woolsey estimates that American oil companies receive preferential treatment from their government worth more than $250 billion a year. And the Intergovernmental Panel on Climate Change (IPCC), a United Nations-appointed group of scientific experts, reckons that fossil fuels should carry a tax of $20-50 for every tonne of carbon dioxide they generate in order to pay for the environmental effects of burning them (hence the fears of the power-generators).

So the subsidies and mandates offered to renewable sources of power such as wind turbines often just level the playing field. It is true that some subsidies amount to unwarranted market-rigging: examples include those handed by cloudy Germany to its solar-power industry and by America to its maize-based ethanol farmers when Brazilian sugar-based ethanol is far cheaper. Others, though, such as a requirement that a certain proportion of electricity be derived from non-fossil-fuel sources, make no attempt to pick particular technological winners. They merely act to stimulate innovation by guaranteeing a market to things that actually work.

If the world were rational, all of these measures would be swept away and replaced by a proper tax on carbon—as is starting to happen in Europe, where the price arrived at by the cap-and-trade system being introduced is close to the IPCC's recommendation. If that occurred, wind-based electricity would already be competitive with fossil fuels and others would be coming close. Failing that, special treatment for alternatives is probably the least bad option—though such measures need to be crafted in ways that favour neither incumbents nor particular ways of doing things, and need to be withdrawn when they are no longer necessary.

The poor world turns greener too

That, at least, is the view from the rich world. But poorer, rapidly developing countries are also taking more of an interest in renewable energy sources, despite assertions to the contrary by some Western politicians and businessmen. It is true that China is building coal-fired power stations at a blazing rate. But it also has a large wind-generation capacity, which is expected to grow by two-thirds this year, and is the world's second-largest manufacturer of solar panels—not to mention having the largest number of solar-heated rooftop hot-water systems in its buildings.

Brazil, meanwhile, has the world's second-largest (just behind America) and most economically honest biofuel industry, which already provides 40% of the fuel consumed by its cars and should soon supply 15% of its electricity, too (through the burning of sugarcane waste). South Africa is leading the effort to develop a new class of safe and simple nuclear reactor—not renewable energy in the strict sense, but carbon-free and thus increasingly welcome. These countries, and others like them, are prepared to look beyond fossil fuels. They will get their energy where they can. So if renewables and other alternatives can compete on cost, the poor and the rich world alike will adopt them.

That, however, requires innovation. Such innovation is most likely to come out of the laboratories of rich countries. At a recent debate at Columbia University, which *The Economist* helped to organise, Mr Khosla defended the proposition, "The United States will solve the climate-change problem". The Californian venture capitalist argued that if cheaper alternatives to fossil fuels are developed, simple economics will ensure their adoption throughout the world. He also insisted that the innovation which will create those alternatives will come almost entirely out of America.

As it happens, he lost. But that does not mean he is wrong. There are lots of terawatts to play for and lots of money to be made. And if the planet happens to be saved on the way, that is all to the good. ■

Trade winds

Wind power has come of age. But to make the most of it, electrical grids will have to be overhauled

ON A ridge near Toledo in Castile-La Mancha stands a row of white windmills. Literary buffs, even if they have never been to Spain, will recognise them as the ferocious giants attacked by Don Quixote, Miguel de Cervantes's fictional 17th-century hero. These days, however, they are dwarfed by legions of modern wind turbines that grind out not flour but power, helping to make Spain one of the leading producers of wind-based electricity in Europe.

Does this amount to tilting at windmills? There is no doubt that Spain's wind turbines would not have been built without assistance from the highly visible hand of a government that wanted to prove its green credentials. But wind power is no illusion. World capacity is growing at 30% a year and will exceed 100 gigawatts this year. Victor Abate, General Electric's vice-president of renewables, is so convinced that by 2012 half of the new generating capacity built in America will be wind-powered that he is basing his business plan on that assumption.

Wind currently provides only about 1% of America's electricity, but by 2020 that figure may have risen to 15%. The one part of the United States that has something approximating a proper free market in electricity, Texas, is also keener than any other state on deploying the turbines. In May, T. Boone Pickens, one of the state's most famous oil tycoons, announced a deal with GE to build a one-gigawatt wind farm—the world's largest—at a cost of $2 billion.

What was once a greener-than-thou toy has thus become a real business (GE alone expects to sell $6 billion-worth of turbines this year)—and one with many advantages. For example, as Lester Brown, the president of the Earth Policy Institute, a think-tank in Washington, DC, points out, a farmer in Iowa who gives up a tenth of a hectare (a quarter of an acre) of land to a turbine might earn $10,000 a year from it (about 3% of the value of the electricity it produces). Planted with maize, the same land would yield a mere $300-worth of bioethanol.

Moreover, wind farms can be built piecemeal, unlike most power stations. A half-finished coal-fired or nuclear power plant is a useless waste of money, but a half-finished wind farm is simply a wind farm half the size originally intended—and one that has been providing revenue since the first turbine was completed.

One consequence of this rapidly growing market is a virtuous circle of technological improvement that is pushing wind-generated electricity closer and closer to ▸▸

solving Google's cheaper-than-coal equation. The first turbines were cobbled together from components intended for ships. Now the engineers are borrowing from aircraft design, using sophisticated composite materials and equally sophisticated variable-geometry blades to make those blades as long as possible (bigger is better with turbine technology) and as smart as possible (a blade that can flex when the wind blows too strongly, and thus "spill" part of that wind, is able to turn when other, lesser turbines would have to be shut down for their own safety). The theoretical maximum efficiency of a turbine, worked out in the early 20th century by Albert Betz, is 59.3%. Modern turbines get surprisingly close to that, being about 50% efficient.

They are also more reliable than their predecessors. According to Mr Abate, when GE entered the turbine business in 2002 the average turbine was out of commission 15% of the time. Now its downtime is less than 3%. As a result, the cost of the energy cranked out by these turbines has come down to about 8 cents a kilowatt-hour (kWh) and is still falling.

That makes wind power competitive with electricity generated by burning natural gas. Coal power is still cheaper, at about 5 cents a kWh. But according to a study by the Massachusetts Institute of Technology (MIT), that would rise to 8 cents if the CO_2 from coal-fired power stations had to be captured and stored underground (see box on the next page)—or, for that matter, if a carbon tax of $30 a tonne were imposed.

The power companies that buy the turbines are also getting smarter. They employ teams of meteorologists to scour the world for the best places to put turbines. It is not just a question of when the wind blows, but also of how powerfully. A difference of as little as one or two kilometres (one mile) an hour in average wind speed can have a significant effect on electrical output. And another lot of meteorologists sit in the control centres, making detailed forecasts a day or two ahead to help a company manage its power load. For one problem with wind is that if it stops blowing, the turbines stop turning. After cutting costs, that is the second great challenge of the spread of wind power.

The third is that people do not necessarily live where the wind blows. Indeed, they often avoid living in such places. Solving these problems, though, is a task not for the mechanical engineers who build the turbines but for the electrical engineers who link them to places where power is wanted. That means electricity grids are about to become bigger and smarter.

Bigger means transcontinental, at least for people like Vinod Khosla. His analogy is America's interstate highway system, built after the second world war. The new grids would use direct, rather than alternating, current. AC was adopted as standard over a century ago, when the electrical world was rather different. But DC is better suited to transporting power over long distances. Less power is lost, even on land. And DC cables can also be laid on the seabed (the presence of all that water would dissipate an AC current very quickly). In the right geographical circumstances that eliminates both the difficulty of obtaining wayleaves to cross private land and the not-in-my-backyard objections that power lines are ugly. Indeed, there is already a plan to use underwater cables to ship windpower from Maine to Boston in this way.

Rewiring the planet

As it happens, Europe already has the embryo of a DC grid. It links Scandinavia, northern Germany and the Netherlands, and there is talk of extending it across the North Sea to the British Isles, another notoriously windy part of Europe. By connecting distant points, this grid not only delivers power to market, it also allows the system some slack. It matters less that the wind does not blow all the time because it blows at different times in different places. The grid also permits surplus power to be used to pump water uphill in Norwegian hydroelectric plants (a system known as pumped storage), ready for use when demand spikes.

Smarter grids, however, would help to smooth out such spikes in the first place. The ability to accommodate inherently intermittent sources such as wind is only one of several reasons for wanting to do this, but it is an important one.

A smart grid will constantly monitor its load and (this is the smart bit) take particular consumers offline, with their prior agreement and in exchange for a lower price, if that load surges beyond a preset level. For this purpose, a consumer may not necessarily be the same as a customer. The grid's software would be able to identify particular circuits, or even particular appliances, in a home, office or factory. Their owners would decide in what circumstances they should shut down or boost up, and the smart grid's software would then do the job. Water heaters and air-con- ▶▶

ditioners might stock up on heat or cold in anticipation of such shutdowns. Fridges would know how long they could manage without power before they had to switch on again.

Reducing spikes in demand that way will cut the need for what are known in the industry as "peakers"—small power plants such as pumped-storage systems that exist solely to deal with such spikes. Parts of America's existing dumb and fragmentary electricity grid are so vulnerable to load variations that their owners think they may be able to cope with no more than about 2% of intermittent wind power. Clearly peaks will never be eliminated entirely. However, Mr Abate reckons that a combination of smart grids and gas-fired peakers should push the potential for wind power up a long way.

To prove the point, GE is collaborating with the government of Hawaii, a state which is served by a series of small, isolated grids highly vulnerable to disruption. The firm's engineers reckon that clever grid management will allow up to 30% of local power to come from wind without any blackouts. If that improvement can be translated to the grids on the mainland, wind's future looks assured. ■

Dig deep

Carbon storage will be expensive at best. At worst, it may not work

EVEN in the most alternative-friendly future imaginable, coal is unlikely to go away. It is cheap, abundant and often local. So what can be done to make coal's use more acceptable?

One much-discussed possibility is carbon capture and storage, or CCS, which involves burying the carbon dioxide deep underground. The generating companies have high hopes of it (see chart 3). There are just two problems. No one knows if it will work (in other words, if the CO_2 will stay buried). And everyone knows that, whether it works or not, it will be expensive—so much so that the alternatives start to look rather attractive. The one serious attempt to investigate its use in an actual power station, the FutureGen project, based in Illinois, was cancelled in January because the expected cost had risen from $830m to $1.8 billion.

The "capture" part is not that hard. Carbon dioxide reacts with a group of chemicals called amines. At low temperatures CO_2 and amines combine. At higher temperatures they separate. Power-station exhaust can thus be purged of its CO_2 by running it through an amine bath before it is vented, and the amine can be warmed to release the gas where it will do no harm. Better still, the coal can be reacted with water to produce a mixture of CO_2 and hydrogen in which the carbon dioxide is much more concentrated than in normal flue gas, so it is easier to scrub out. What is then burned is pure hydrogen.

All this processing is expensive, but there is no reason why it should not work. An experimental plant in Denmark that uses monoethanolamine as the captor has been running for two years. Alstom, a French firm, has almost finished building one in Wisconsin that uses ammonia.

It is what comes next that is the problem. The disposal of carbon dioxide needs to be permanent, so a lot of conditions have to be met. To be a successful burial site, a body of rock needs to be more than 1km underground. That depth provides enough pressure to turn CO_2 into what is known as a supercritical fluid, a form in which the stuff is more likely to stay put. The rock in question also has to have enough pores and cracks in it to accommodate the CO_2. Lastly, it needs to be covered with a layer of non-porous, non-cracked rock to provide a leakproof cap.

So far, only three successful CCS projects are under way. The Weyburn-Midale CO_2 project is burying carbon dioxide from a coal gasification plant in North Dakota in a depleted oil field in Saskatchewan. The Salah gasfield project in Algeria, run by BP, strips CO_2 from local natural gas and injects it back into the ground. And Statoil, a large Norwegian oil and gas company, performs a similar trick at two places in the North Sea. None of these projects is actually linked to generating electricity. Still, a few years ago they were touted proudly. But the touting has become more nervous, and no new projects have come on stream.

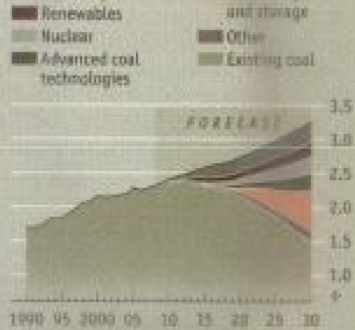
The scale of the problem is awesome. The three showcase projects each dump about a million tonnes of CO_2 a year. But America's electricity industry alone produces 1.5 billion tonnes, which would mean finding 1,500 appropriate sites, and nobody knows whether the country's geology can oblige. Even transporting that amount of gas would be a huge task.

As to the cost, a report published last year by MIT reckons on $25 a tonne to capture CO_2 and pressurise it into a superfluid, and $5 a tonne to transport it to its burial site. It therefore suggests that power stations which dump CO_2 into the atmosphere should be charged $30 a tonne, a figure conveniently near both the middle of the IPCC's suggested carbon price and the actual price in Europe. Another report, by a consultancy called Synapse Energy Economics, notes that American power companies are already starting to employ carbon prices in their internal accounting, using a range of $3-61 a tonne. Again, the middle of that range is about $30.

Such a charge, whether a tax or a system of tradable permits to pollute, would change energy economics radically. But even the most optimistic proponents of carbon capture and storage doubt it will be a serious alternative much before 2020. And by then both the physical and the political climate may look rather different.

Change or die 3

US electricity sector: possible ways of substituting CO_2 emissions, tonnes bn



Another silicon valley?

The rise of solar energy, in one form or another

WIND power works, and will work better in the future. But wind is only an interim stop on the way to a world where electricity no longer relies on fossil fuels. The ultimate goal is to harvest the sun's energy directly by intercepting sunlight, rather than by waiting for that sunlight to stir up the atmosphere and sticking turbines in the resulting airstreams.

Fortunately, inventors love that sort of problem. Ideas they have come up with range from using the sun to run simple heating systems for buildings, deploying "reverse radiators" painted black, to the sharpest cutting edge of that trendiest of fields, nanotechnology, to ensure that every last photon is captured and converted into electricity. The most iconic form of solar power, the photovoltaic cell, is currently the fastest-growing type of alternative energy, increasing by 50% a year. The price of the electricity it produces is falling, too. According to Cambridge Energy Research Associates (CERA), an American consultancy run by Daniel Yergin, a kWh of photovoltaic electricity cost 50 cents in 1995. That had fallen to 20 cents in 2005 and is still dropping. Not RE<C, but heading in the right direction.

Photovoltaic cells (or solar cells, as they are known colloquially) convert sunlight directly into electricity. But that is not the only way to use the sun to make electrical power. It is also possible to concentrate the sun's rays, use them to boil water and employ the resulting steam to drive a turbine. These two very different approaches illustrate an unresolved question about the future of energy: whether it will be generated centrally and transported over long distances to the consumer, as it has been in recent decades, or generated and consumed in more or less the same place, as it was a century ago.

A hot tin roof

The idea of solar cells is to keep things local. They are like wind turbines, only more so, in that even a single solar panel can produce power immediately. Put a few on your roof and, if you live in a reasonably sunny place, you can cut your electricity bill. Indeed, you may be able to sell electricity back to your own power company. The problem is that at the moment you may need to take out an overdraft to pay for the solar panels, and you will not get your money back for a long time.

Many engineers, however, are working to change that. One of them is Emanuel Sachs of MIT. Some engineers look for big, exciting technological improvements in the way solar cells work, but Dr Sachs prefers incremental change. As he sees it, it is such change that drives Moore's law, that well-established description of the rapid improvement in the power of computer processors.

Moreover, the analogy is appropriate. Traditional solar cells are made of silicon, like computer chips, and for the same reason. They rely on that element's properties as a semiconductor, in which negatively charged electrons and positively charged "holes" move around and carry a current as they do so. In the case of a solar cell, the current is created by sunlight knocking electrons out of place and thus creating holes. Dr Sachs's first contribution to the incremental improvement was a technique called the string ribbon, which halved the amount of silicon needed to make a solar cell by drawing the element (in liquid form) out of a vat between two strings. That invention was marketed by a firm called Evergreen Solar.

His latest venture, a firm called 1366 Technologies (after the number of watts of solar power that strike an average square metre of the Earth's surface), aims to follow this up with three new ideas that should, in combination, bring about a 27% improvement in efficiency. He and his colleagues have redesigned the surfaces of the silicon crystals on a nanoscale in order to keep reflected light bouncing around inside a cell until it is eventually absorbed. They have also managed to do something similar to the silver wires that collect the current. And they have made the wires themselves thinner as well so that they do not block so much light in the first place.

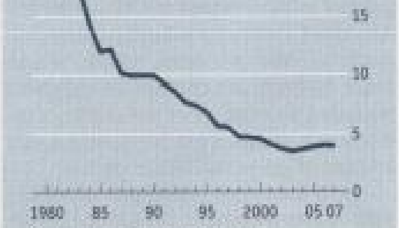
Dr Sachs says that these innovations will bring the capital cost of solar cells below $2 a watt. That is closing in on the cost of a coal-fired power station: a gigawatt (one billion watt) plant costs about $1 billion to build. The price, of course, is a different matter. As Paula Mints of Navigant Consulting, a firm based in Palo Alto, California, points out, price is set by market conditions. These—particularly the generous subsidies given to solar power in some European countries—have kept prices well above costs in recent years. Nevertheless, as chart 4 shows, the price of solar cells has fallen significantly, too.

Other researchers back a newer technology known as thin-film photovoltaics. Thin-film cells can be made with silicon, but most progress is being made with ones that use mixtures of metals, sometimes exotic ones, as the semiconductor. These mixtures are not as efficient as traditional bulk-silicon cells (meaning that they do not convert as much sunlight to electricity per square metre of cell). But they use far less material, which makes them cheaper, and they can be laid down on flexible surfaces such as sheets of steel the thickness of a human hair, which gives them wider applications.

At the moment, the commercial leader in this area is a firm called First Solar, which uses cadmium telluride as the film. But First Solar is about to be given a run for its money by companies such as Miasolé, a small Californian firm, that have gone for a mixture of copper, indium, gallium and selenium, known as CIGS. This mixture is reckoned to be more efficient than cadmium telluride, though still not as good as traditional silicon. And it has the public-relations advantage of not containing cadmium, a notorious poison—though First ▸▸

Selling cells 4

Photovoltaic modules, price per watt, $



Sources: Navigant Consulting; Paula Mints

Solar's films carefully lock the cadmium up in a way that renders it harmless.

At the moment thin-film solar cells are being packaged and sold as standard solar panels, but that could easily change. First Solar applies its films to glass, but Miasolé's boss, Joseph Laia, points out that his steel-based products are flexible and lightweight enough to be used as building materials in their own right. Greener-than-thou Californians who wish to fall in with their governor's plan for a million solar roofs, announced in 2006, currently have to bolt panels onto their houses—an ugly, if visible, show of their credentials. If Mr Laia has his way, they will soon be able to use sheets of his company's CIGS-covered steel as the roofing material itself.

Supporters of solar-thermal energy tend to look askance at solar panels. Cadmium telluride and CIGS may be cheaper than silicon, but glass and steel, on which solar-thermal relies, are cheaper still. The technology's proponents think big: square-kilometres big. They want to fill the deserts with steel and glass mirrors and use the reflected sunlight to boil water and generate electricity, then plug into the long-distance DC networks developed for wind power to carry the juice to the cities.

Desert song

Those who worry about the political side of the world's dependence on oil will be less than delighted to find that one country thinking seriously about such systems is Algeria. With the power-hungry markets of Europe to its north, across the Mediterranean, and a lot of sunshine going to waste in the Sahara desert to its south, Algeria's government is looking for ways to connect the two. It is now building an experimental solar-thermal power station at Hassi R'mel, about 400km south of Algiers, which if all goes well will open next year. In April work started on a similar project at Aïn Béni Mathar, in Morocco, and others are in the pipeline elsewhere in north Africa. Fortunately for people like Mr Woolsey, the ex-CIA man, America has deserts of it own which are about to bloom with mirror-farms too.

There are four competing designs: parabolic-trough mirrors, parabolic-dish mirrors, "power towers" which use an array of mirrors to focus the sun's rays on to an elevated platform, and Fresnel systems, which mimic a parabolic trough using (cheaper) flat mirrors. All either heat up water to make steam, which drives a generator, or heat and liquefy a salt with a low melting point such as sodium nitrate that is used to make steam.

Beneath your feet

Geothermal could be hot

THE Philippines are not generally associated with the cutting edge of technological change. In one respect, though, the country is ahead of its time: around a quarter of its electricity is generated from underground heat. Such heat is free, inexhaustible and available day and night.

It is also part of a geology that sees parts of the country devastated by volcanic eruptions from time to time. The geysers that turn the generators are merely the gentlest manifestations of this volcanism. The question that exercises Jefferson Tester, a researcher at MIT, is whether it is possible to have the one without the other. The Earth's depths are, after all, hot everywhere. So if there is no natural volcanism around to bring this heat to the surface, his answer is to create controlled, artificial volcanism—what is known as an engineered geothermal system (EGS). Instead of relying on natural hot springs, you make your own.

In principle, this is easy. Drill two parallel holes in the ground, a few hundred metres apart, and carry on drilling until the rock is hot enough (say 200°C). Then pump cold water down one hole and wait for it to come back up the other at a suitably elevated temperature. The superheated water turns to steam which you use to power a generator. In Dr Tester's view, the reason this source of power is neglected is that it is invisible. Everybody feels the wind and the sun, but only miners notice that the Earth's interior is hot, so no one thinks of drilling for that heat.

Dr Tester reckons that spending about $1 billion on demonstration projects over the next 15 years would change that. It would provide enough information to allow 100 gigawatts-worth of EGSs to be created in America by 2050, at a commercially acceptable price.

In principle, much more could be done. The recoverable heat in rock under the United States is the equivalent of 2,000 years-worth of the country's current energy consumption, according to a report he and his colleagues published two years ago. A similar assessment of Europe's heat resources from the Earth suggests that they could be used to generate as much electricity as all of the continent's nuclear power stations produce now.

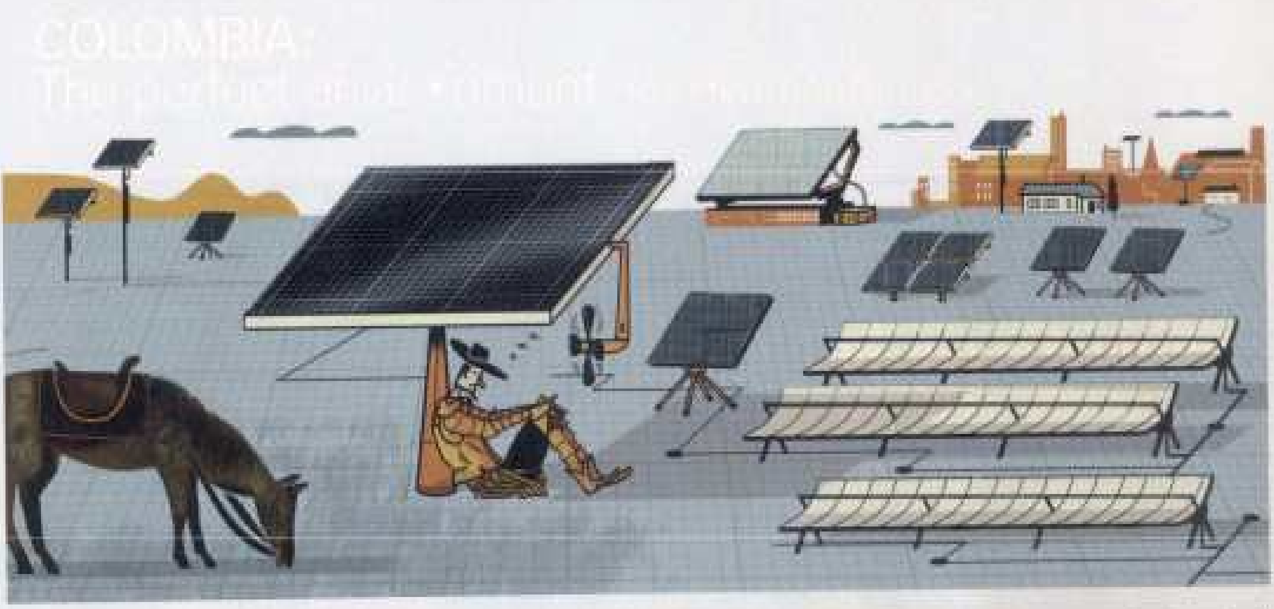
Rock-hard

Extracting this subterranean energy is not as easy as it sounds. Until the term EGS was coined, the field was known as hot-dry-rock geothermal energy, a name that encapsulates the problem precisely. A century of data collected by oil companies suggest it is impermeable rocks such as granite that are the most effective reservoirs of heat. Their very dryness increases their heat capacity. But to get the heat out you have to make them permeable. Hence the "engineered" in the new name.

Some of Dr Tester's $1 billion would be spent working out how to drill cheaply and effectively through this sort of rock—something that oil companies tend to avoid because impermeable rocks do not contain petroleum. A lot of the money would go on finding ways to force open fissures in the granite to let the water flow from the injection hole to the exit.

The Cooper Basin in South Australia has the hottest non-volcanic rocks of any known place in the world, and Australia leads the field in exploiting subterranean heat, with seven firms snooping around the area. One of them, Geodynamics, recently completed what it claims is a commercial-scale well. And the turbines will also turn soon at an experimental non-commercial project at Soultz, in France.

If it can be made to work, EGS has got the lot. No unsightly turbines. No need to cover square kilometres of land with vast mirrors. And it is always on. Anybody got a billion dollars handy?



All four of these designs are now either operating commercially in the deserts of south-west America or are undergoing pre-commercial trials. Although the total capacity at the moment, according to CERA, is a mere 400 megawatts, this will grow tenfold over the next four years if all projects now scheduled come to fruition, and probably a lot more after that. Moreover, those plants that melt a salt are able to divert part of the heat they collect into a thermal reservoir that can keep the generators turning at night. The main objection to solar power—that it goes off after sunset—is thus overcome.

From little acorns

The engineers clearly think they can deliver the technology. But can the technology deliver the power? A back-of-the-envelope calculation suggests that it can. Two years ago a task force put together by the governors of America's western states identified 200 gigawatts-worth of prime sites for solar-thermal power within their territory (meaning places that had enough reliable sunshine, were close to transmission lines and were not environmentally or politically sensitive). That is equivalent to 20% of America's existing electricity-generation capacity: not a bad start.

Robert Fishman, the boss of Ausra, an Australian-American company based in Palo Alto, California, reckons that his firm's Fresnel arrays combined with its proprietary heat-storage system can produce electricity for 8 cents a kWh. That matches GE's wind turbines, and mass production should bring it down further. It is not cheaper than "naked" coal (Ausra will benefit from various state governments' requirements that their power utilities buy renewable power)—but if there were a carbon tax of $30 a tonne, or a requirement to capture and bury CO_2, Ausra would be able to match the coal-fired stations' prices.

The most intriguing technology of all, though, belongs to SUNGRI, a firm based in Los Angeles. This uses mirrors to concentrate sunlight, but focuses it on a solar cell rather than a boiler. The system is said to turn 37% of the light into electricity. In April the firm claimed it would be able to produce electricity for the magic figure of 5 cents a kWh.

That claim has yet to be put to the test, and should be viewed with some scepticism until it has been. But it is a good indication of the way the field is going. Solar power now seems to be roughly where wind was a decade ago. At the moment it contributes a mere 0.01% to the world's output of electricity, but just over a decade of 50% annual growth would bring that to 1%, which is where wind is at the moment. If SUNGRI is to be believed, and the point where RE is indeed <C is close, the rise to 1% might happen even faster. After that, the sky is the limit. ■

Grow your own

The biofuels of the future will be tailor-made

BURIED in the news a few weeks ago was an announcement by a small Californian firm called Amyris. It was, perhaps, a parable for the future of biotechnology. Amyris is famous in the world of tropical medicine for applying the latest biotechnological tools to the manufacture of artemisinin, an antimalarial drug that is normally extracted from a Chinese vine. The vines cannot produce enough of the stuff, though, so Amyris's researchers have taken a few genes here and there, tweaked them and stitched them together into a biochemical pathway enabling bacteria to make a chemical precursor that can easily be converted into the drug.

But that is not what the announcement was about. Instead, it was that Amyris was going into partnership with Crystalsev, a Brazilian firm, to make car fuel out of cane sugar. Not ethanol (though Brazil already has a thriving market for ethanol-powered cars), but a hydrocarbon that has the characteristics of diesel fuel. Technically, it is not ordinary diesel, either: in chemist-speak, it is an isoprenoid rather than a mixture of alkanes and aromatics. But the driver will not notice the difference.

The point of the parable is this: biotechnology may have cut its teeth on medicines, but the big bucks are likely to be in bulk chemicals. And few chemicals are bulkier than fuels. Where Amyris is leading, many are following. Some small firms with new and interesting technologies are trying to go it alone. Others are teaming up with big energy firms, in much the same way that biotech companies with a promising drug are often taken under the ▸▸

wing of a large pharmaceutical company. The big firms themselves are involved, too, both through in-house laboratories and by giving money to universities. Biofuels, once seen as a cross between eccentric greenwash and a politically acceptable way of subsidising farmers, are now poised to become big business.

Grassed up

The list of things that need to be done to create a proper biofuel industry is a long one. New crops, tailored to fuel rather than food production, have to be created. Ways of converting those crops into feedstock have to be developed. That feedstock has then to be turned into something that people want to buy, at a price they can afford.

All parts of this chain are currently the subjects of avid research and development. Some biofuels were already competitive with oil products even at 2006 oil prices (see table 5). The R&D effort will bring more of them into line, as will any long-term rise in the price of crude oil.

As far as the crops themselves are concerned, there are three runners at the starting gate: grasses, trees and algae. Grasses and trees are grown on dry land, but need a lot of processing. The idea is to take the whole biomass of the plant (particularly the cellulose of which a plant-cell's walls are made) and turn it into fuel. At the moment, that fuel is often ethanol. Hence the term "cellulosic ethanol" that has gained recent currency. Algae, being aquatic, are more fiddly to grow, but promise a high-quality product, oil, that will not need much treatment to become biodiesel.

One of the leading proponents of better grasses is Ceres, a firm based in Thousand Oaks, California. The species it has chosen to examine—switchgrass, miscanthus, sugarcane and sorghum—are so-called C4 grasses. These are favourites with the biofuel industry because they share a particularly efficient form of photosynthesis that enables them to grow fast. Ceres proposes to make them grow faster still, using a mixture of "smart" breeding techniques (in which desirable genes are identified scientifically but assembled into plants by traditional hybridisation) and straightforward genetic engineering.

The chosen grasses also thrive in a range of climates. Switchgrass and miscanthus are temperate. Sugarcane and sorghum are tropical. Ceres proposes to extend their ranges still further by creating strains that will tolerate heat or cold or drought or salt, allowing them to be grown on land that cannot be used for food crops.

Out of thin air 5

Biofuel costs compared with prices for oil and oil products, cents per litre

Fuel	2006
Price of oil $/barrel	50-80
Petroleum products pre-tax price	35-60
Petroleum products retail price*	150-200 in Europe, 80 in US

Biofuel	2006	Long-term about 2030
Ethanol from sugarcane	25-50	25-35
Ethanol from maize	60-80	35-55
Ethanol from beet	60-80	40-60
Ethanol from wheat	70-95	45-65
Ethanol from lignocellulose	80-110	25-65
Biodiesel from vegetable oils	70-100	40-75
Fuels made from "syngas"	90-110	70-85

Source: The Royal Society

*Taxes included

That will make them cheaper, as well as reducing the competition between foods and biofuels.

Trees, meanwhile, are the province of firms such as ArborGen, of Summerville, South Carolina. Like Ceres, ArborGen is working on four species: eucalyptus, poplar, and the loblolly and radiata pines. It is applying similar techniques to those used by Ceres to speed up the growth of these trees and to increase their tolerance of cold. Although creating raw materials for biofuels is not this company's only objective (paper pulp and timber are others), it sees such fuels as a big market.

Algae, too, are up for modification. One problem with them is harvesting the oil they produce. That means extracting them from their ponds, drying them out and breaking open their cells. This process is so tedious that some companies are considering the idea of burning the dried algae in power stations instead.

One firm that is not is Synthetic Genomics, the latest venture of Craig Venter (the man who led the privately funded version of the Human Genome Project). Dr Venter hopes to overcome the oil-collection problem by genetic engineering. Synthetic Genomics's algae have been fitted with genes that create new secretion pathways through their outer membranes. These cause the algal cells to expel the oil almost as soon as they have manufactured it. It then floats to the surface of the pond, allowing it to be skimmed off like cream and turned into biodiesel. The algae are also engineered to make more oil than their wild counterparts.

Harvesting useful fuels from vascular plants, as grasses, trees and their kind are known collectively, is a trickier business. These plants are composed mainly of three types of large molecule. Besides cellulose, there are hemicellulose and lignin. Each is made of chains of smaller molecules, and all three are often bound together in a complex called lignocellulose, particularly in wood. There are many ways these long-chain molecules might be turned into fuel, but all of these processes are more complex than for algae.

As chart 6 shows, turning sunlight into biofuel involves three steps, though different methods may miss out some of these steps. Algae can make the leap from start to finish directly, whereas vascular plants cannot. One way of dealing with them is to dry them and then heat them with little or no oxygen present. This is called pyrolysis and, if done correctly, results in a mixture of carbon monoxide and hydrogen called "syngas" (short for synthesis gas). With suitable catalysts, syngas can be turned into fuel.

This is the approach taken by Choren ▸▸

The chain of being 6

Potential pathways for biofuel production

Source: InterAcademy Council

Industries in Freiburg, Germany, and Range Fuels in Treutlen County, Georgia. In both cases the feedstock is chippings and other leftovers from forestry and timbermills. Choren is making hydrocarbon diesel and Range ethanol. Both factories, therefore, are steps on the road to making fuel from trees. Syngas can also be turned into ethanol by bacteria of the genus *Clostridium* (a group better known for the chemical used in botox treatment). That is being done by Coskata, a firm based in Warrenville, Illinois. General Motors (GM) likes this idea so much it has bought a share of the company.

An alternative to the syngas method is to break the cellulose and hemicellulose up into their component "monomer" molecules. That is easier said than done, particularly if lignin is involved, since lignin is resistant to such conversion. The amount of coal in the world is proof of its resilience. Coal is composed mainly of lignin from plants that failed to decompose completely and were fossilised as a result.

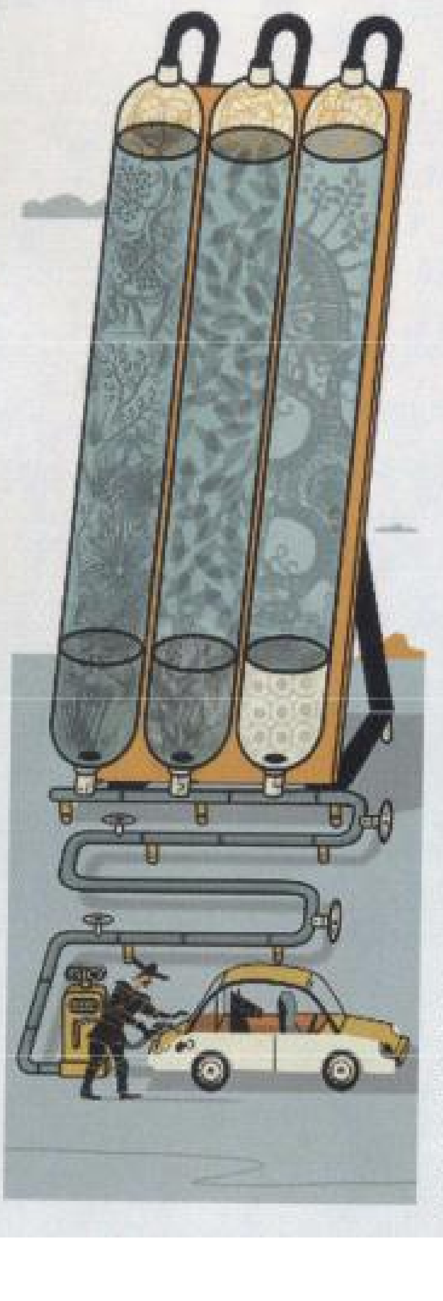
Many firms, however, have developed enzymes that break down biomass in this way. Iogen, of Ottawa, Canada, was one of the first. Its enzymes decompose cellulose and hemicellulose into sugar monomers. (The lignin is burned to generate heat for the process.) Abengoa, a Spanish firm that is also involved in solar energy, uses this approach as well.

Sugar and spice

Once you have your sugar, you can ferment it. These days that need not mean using yeast to make ethanol. A whole range of bugs, some natural, some engineered, can now be deployed to make a whole range of products. Amyris's souped-up micro-organisms (some are bacteria, some yeasts) turn sugar not into ethanol but into isoprenoids, at a cost competitive with petroleum-based diesel. LS9, based near San Francisco, uses a similar method but is turning out alkanes (for petrol) and fatty acids (for biodiesel). It, too, is starting to scale up production. Synthetic Genomics is doing something similar, though the firm is cagey about which fuel is being produced. In each case, however, what is made is a chemical precisely tailored to its purpose, rather than the *ad hoc* mixture that comes out of a refinery. The rival companies thus argue that their products are actually better than oil-based ones.

At least one firm, Mascoma, of Cambridge, Massachusetts, employs a single species of bug, *Thermoanaerobacterium saccharolyticum*, both to break down the biomass and to digest the resulting sugar. Mascoma will use both grass and wood as feedstocks. In May it signed deals with GM and Marathon Oil.

It is also possible to use purified enzymes to do the conversion from sugar to fuel, as well as from biomass to sugar, and at least two firms are working on applying them to the whole process. Codexis, based in Redwood City, California, has created a range of enzymes by a method akin to sexual reproduction and natural selection. Last year it signed a deal with Shell to use this technique to produce biofuels of various types. And a Danish firm, Danisco, has teamed up with DuPont to do the same thing with its own proprietary enzymes.



Shell is also involved in a project to turn sugar into hydrocarbons, this time by straight chemical processing. It is putting up the money. The technology (the most important part of which is a set of proprietary non-biological catalysts) is provided by Virent Energy systems, of Madison, Wisconsin.

Which of these approaches will work best is anybody's guess. But their sheer number is proof that the most radical thinking in the field of renewable energy is going on in biofuels. It is in this area that the most unexpected breakthroughs are likely to come, says Steven Koonin, BP's chief scientist. BP is backing one of the biggest academic projects intended to look into biofuels, the Energy Biosciences Institute (EBI), to the tune of \$500m, which suggests that the company's board agrees with him. The EBI is a partnership of the University of California, Berkeley, the Lawrence Berkeley National Laboratory and the University of Illinois.

One of the people involved, Steven Chu, the head of the Lawrence Berkeley laboratory, is a man with a grand vision. This vision is of a "glucose economy" that will replace the existing oil economy. Glucose, the most common monomer sugar, would be turned into fuels and maybe even the bio-equivalents of petrochemicals—bioplastics, for example—in local factories and then shipped around the world. That would be a boon to tropical countries, where photosynthesis is at its most rampant, though it might not play so well to James Woolsey's security fears, since it risks replacing one set of unreliable suppliers with another.

However, there is plenty of biomass to go around. A study by America's Departments of Energy and Agriculture suggests that even with only small changes to existing practice, 1.3 billion tonnes of plant matter could be collected from American soil without affecting food production. If this were converted into ethanol using the best technology available today, it would add up to the equivalent of 350 billion litres of petrol, or 65% of the country's current petrol consumption. And that is before specially bred energy crops and other technological advances are taken into account. If America wants it, biofuel autarky looks more achievable than the oil-based sort. And if it does not, then the world's hitherto impoverished tropics may find themselves in the middle of an unexpected and welcome industrial revolution. ■

The end of the petrolhead

Tomorrow's cars may just plug in

NOTHING ages faster than the future. A few years ago there was general agreement that if the internal-combustion engine ever was replaced by something clean, that something would be the fuel cell. A fuel cell is a way of reacting hydrogen and oxygen together in a controlled way and extracting electricity from the process. It was to be the precursor of what was known as the hydrogen economy, in which that gas would replace fossil fuels and power almost everything.

Leaving aside the problems of transporting and storing a light and leaky gas, what no one was very clear about was where the hydrogen itself would come from. You would have to make it from something else. That something would either be a mixture of fossil fuel and water (fuels can be reacted with steam to make hydrogen and carbon dioxide, but you still have to get rid of the carbon dioxide), or just water itself, via electrolysis.

But why bother? Why not cut out the middleman and plug your car directly into the electricity mains instead? And that, it seems, is what may happen. You don't hear much about the hydrogen economy these days. Nor fuel cells. The buzz-phrase now is "plug-in hybrid".

Plug-ins should not be confused with existing hybrid vehicles, such as Toyota's Prius, which contains an internal-combustion engine as well as two electric ones. Either sort may drive the wheels. The electric motors kick in when they can do a more efficient job than the petrol engine, but even then the electricity comes ultimately, via batteries, from burning petrol.

In a plug-in, the electricity comes from the mains, via an ordinary electrical socket. Some intermediate designs retain the idea of two sorts of engine, but the goal is that the car should be powered by electric motors alone. If the batteries run down, a petrol-powered generator will take over. (Existing batteries are too expensive to give such a car the range of a standard petrol-driven machine.) But most cars, most of the time, are used for short journeys. Gerbrand Ceder, a battery scientist at MIT, reckons that if the first 50km of an average car's daily range were provided by batteries rather than petrol, annual petrol consumption would be halved. Given that the electrical equivalent of a litre of petrol costs about 25 cents, that is an attractive reduction.

The widespread adoption of plug-ins might also reduce carbon-dioxide emissions, depending on what sort of power station made the electricity in the first place. Even energy from a coal-fired station is less polluting than the serial explosions that drive an internal-combustion engine. If the energy comes from a source such as wind or nuclear, the gain is enormous.

Beyond that, the rise of plug-ins has implications for the electricity industry itself. If they succeed, they will put an unanticipated load on the system. In fact, they may remake electricity as well as transport.

Don't all recharge at once

That is certainly the view of Peter Corsell of Gridpoint, a company based in Arlington, Virginia. His firm hopes to make its living selling the load-management technology required for "smart grids". As mentioned earlier in this special report, there are several reasons why such technology is desirable. Mr Corsell goes one further: he reckons it will become essential if plug-ins arrive in force. At the moment, the grid would be unable to cope if a large number of commuters arriving home plugged in their cars more or less simultaneously to recharge them. Yet if those same cars were recharged at three o'clock in the morning, when demand is low, it would benefit both consumer (who would get cheap power) and producer (who would be able to sell otherwise wasted electricity). Such cars might even act as micro-peakers—reservoirs of electrical energy that a power company could draw on if a car were not on the road. Managing plug-ins, Mr Corsell thinks, will be the smart grid's killer application.

In sunny climes, plug-ins might also provide another use for solar cells. Google is already experimenting with photovoltaic car parks. These have awnings covered in solar cells which will shade its employees' cars and simultaneously recharge them. That is an idea which could spread. Supermarkets, for example, might find that car parks with plugs would attract customers who wanted to top up their cars. And the more opportunities there are for stationary cars to be recharged, the more likely they are to be bought.

Plug-ins are moving from idea to reality with amazing speed. General production of the Tesla, Elon Musk's new sports car, began in March (the firm is Californian, but the cars are built in Britain). The Tesla is not even a hybrid. It draws all of its power from lithium-ion batteries (the sort that power laptop computers), and it has a range of 350km. It can manage that because its price of $109,000 buys a lot of batteries; Tesla owners are not the sort who count their pennies. »

Nor is the Tesla the only sports car to go down this road. Electric motors may lack a throaty roar, but they actually do a better job than petrol engines in high-performance vehicles. They have higher torque at low revs which makes them accelerate faster. In Britain a new firm called the Lightning Car Company plans to revive the country's sports-car tradition with the Lightning GT. Mr Musk also faces competition in California, from Fisker Automotive, whose eponymous founder Henrik Fisker helped design the Tesla. (Tesla Motors is now suing Fisker for infringing its intellectual property.)

Mass-production plug-ins are not far away either, and the rising price of petrol makes them look more attractive by the day. General Motors intends to launch a plug-in hybrid called the Volt by 2010, and Toyota plans a plug-in version of the Prius. Most of the other big car firms are making me-too noises. Only Honda and Mercedes seem to be sticking enthusiastically to fuel cells. It is all very encouraging. But what would really make a difference would be a breakthrough in battery technology.

At the moment, lithium-ion batteries are the favoured variety. This kind of battery uses lithium in its ionic form (ie, with the atoms stripped of an electron to make them positive). When the battery is fully charged, these ions hang around one of its electrodes, the anode, which is usually made of graphite. During operation, the ions migrate within the battery from this electrode to the other one, the cathode, and electrons (which are negatively charged) pass between the electrodes through an external circuit. It is that current of electrons which drives the motor. The cathode may be made of a variety of materials. Cobalt oxide is traditional but expensive. Manganese oxide is becoming popular. But the future probably lies with iron phosphate, which has less of a tendency to overheat, a problem that has resulted in battery recalls in the past.

Iron phosphate certainly will be the future if General Motors has anything to do with it. GM is collaborating with A123Systems, a firm started by Dr Ceder's colleague Yet-Ming Chiang, to develop batteries with iron-phosphate cathodes for the Volt. A123's particular trick is that the iron phosphate in its cathodes comes in the form of precisely engineered nanoparticles. This increases the surface area available for the lithium ions to react with when the current is flowing, so such batteries can be charged and discharged rapidly.

The Lightning, too, is making use of nanotechnology. Its batteries, developed by Altairnano of Reno, Nevada, replace the graphite anode with one made of lithium titanate nanoparticles. The firm claims that its batteries are not only safer (graphite can burn; lithium titanate cannot), but can also be recharged more rapidly. Using a 480-volt outlet, such as might be found in a roadside service station, the job should be done in ten minutes.

Dr Ceder reckons he may be able to do even better than this. His version of an iron-phosphate battery can charge or discharge in ten seconds. It, too, could be recharged rapidly at a roadside filling station. He reckons the process would have to be controlled to stop overheating, but a safe refill would take only five minutes. And he thinks batteries might get better still.

The 30,000-compound question

At the moment the process of finding better electrode materials is haphazard, but Dr Ceder proposes to make it systematic. Over the centuries, chemists have discovered about 30,000 inorganic chemical compounds (those that are not based around carbon skeletons), almost any of which might theoretically be suitable material for an electrode. Examining the relevant properties of all of them in the laboratory is out of the question, but Dr Ceder thinks he has found a short cut. He is involved in something called the materials genome project, which takes the known properties of inorganic compounds and turns them into extremely sophisticated computer models. These models are able to calculate the quantum-mechanical properties of the chemicals they are mimicking—and they seem to get it right. When Dr Ceder has checked the predictions for hitherto untested materials by conducting real experiments, he has found that the results coincide.

The materials genome project obviously has much wider applications than battery electrodes, but that is where Dr Ceder has started. His computer is now chewing its way through the chemical encyclopedia, looking for the likeliest candidates. Watch this space. ■

Life after death

Nuclear power is clean, but can it overcome its image problem?

IF YOU want to make an environmentalist squirm, mention nuclear power. Atomic energy was the green movement's darkest nightmare: the child of mass destruction, the spawner of waste that will remain dangerous for millennia, the ultimate victory of pitiless technology over frail humanity. And not even cheap. Well, times change. The followers of Rachel Carson and the Club of Rome in the 1960s and 1970s had not heard of the greenhouse effect, but today's greens have. And they know that nuclear reactors are the one proven way to make carbon-dioxide-free electricity in large and reliable quantities that does not depend (as hydroelectric and geothermal energy do) on the luck of the geographical draw. What a dilemma for a thoughtful tree-hugger.

Patrick Moore, one of the founders of Greenpeace, faces no such dilemma, though. He is such a convert to the nuclear cause that he now chooses to consult for it. Cynics take him to task for that, but he makes no apology. His view of the world, shared by James Lovelock, the inventor of Gaia (the idea that the Earth itself has some of the characteristics of a living organism), is that nuclear power—which already provides 15% of the world's electricity—is the only possible way out of climate change. Mr Lovelock thinks it is probably too late anyway, and that Gaia will shake herself and be rid of the plague of humans that now infest her skin. Mr Moore thinks she can be persuaded not to, if nuclear power is applied in even larger doses.

Given the widespread concern about nuclear energy, how can that be done? Partly, the answer comes, by shifting priorities (for today's youth, climate change is what global nuclear warfare was for the baby-boomers). Partly by the fading of memories: the accident at Three Mile Island, which ended America's nuclear dreams, ▸▸

took place nearly three decades ago, and even the Soviet disaster at Chernobyl is more than two decades past. And partly by redefining "cheap". The Electric Power Research Institute, an American industry body, puts the cost of nuclear electricity at 6.5 cents a kWh. Not cheaper than coal's 5 cents, but cheaper than coal that has had a price put on its carbon emissions. The time, then, is ripe for a rethink.

Ernest Moniz, MIT's leading energy guru and himself a nuclear physicist, agrees. He thinks that, on the technical side at least, the key to a nuclear revival is to go from a craft-based approach, in which each reactor is a bespoke thing of beauty, to a manufacturing approach, in which modules of components are made in factories and simply bolted together on site.

The other modern desideratum, he believes, is "passive safety". This seems to be the same as what engineers used to call "fail-safe", but perhaps the marketing department no longer approves of the word "fail" getting anywhere near a reactor. What it means is that safety measures kick in automatically in an emergency rather than having to be activated. That can be something as simple as configuring the control rods that regulate the speed of a reaction so that they drop by gravity rather than having to be inserted.

Both Dr Moniz's preconditions are beginning to be met. The world's three largest nuclear-reactor firms are hoping for sales of reactors whose designs have been upgraded to be more "bolt-together" and passively safe than their predecessors. According to CERA there are plans in America alone to build 14 AP1000 Westinghouse reactors, six General Electric economic simplified boiling-water reactors, two or more GE advanced boiling-water reactors and seven of the French firm Areva's latest design, the European pressurised reactor.

New generation

Indeed, the idea of modularity can be taken even further. Toshiba, a large Japanese engineering firm, is planning something known as nuclear batteries: factory-made sealed units with an output of 10 megawatts and a lifetime of 15-30 years. When they stop working, you simply send them back to the factory for disposal.

The acme of modular, factory-built, passively safe reactor design, however, is found in South Africa. People there have been experimenting with so-called pebble-bed reactors for decades. They hope to start building one for real in 2010. A pebble-bed reactor is fuelled by small spheres that are, in essence, tiny reactors in their own right. They are made of uranium oxide (the fuel) and graphite (a substance that slows down the flying neutrons that cause nuclear fission). Pile enough pebbles together and a chain reaction will start. Nor is any complicated pipework required to extract the heat. All you need do is run an inert gas such as helium through the pebbles and it will collect the heat for you.

The design also looks like the ultimate in passive safety because a phenomenon called Doppler broadening, which changes the speeds of the neutrons and makes them less likely to cause fission, shuts it down automatically if it overheats—though critics argue that the graphite in the pebbles is a fire hazard, and that helium is so leaky that there is a risk of air getting into the system and starting a fire.

None of these ideas deals with the question of nuclear waste. But that is largely a political problem, not a technical one. Though it sounds like a cop-out, the best answer really is to bury the stuff for the time being. That should be done in places where it can easily be recovered for reprocessing one day when technology has caught up. But it is also worth noting that buried, unprocessed waste cannot be used to make bombs. ■

Flights of fancy

The world of energy must change if things are to continue as before

As SAMUEL GOLDWYN wisely observed, you should never make predictions, especially about the future. As far as predicting the technological future is concerned, people almost always either overshoot or undershoot. Holidays on the moon by 2000, as forecast in the 1960s? Not exactly. A quick hop out of the atmosphere, courtesy of Virgin Galactic, is the limit of that vision for the moment. On the other hand, a seemingly boring way of linking computer files full of data on subatomic physics can turn into a world wide web of information in half a decade.

In retrospect, this special report will no doubt be proved to have been guilty of both over- and undershooting. It has begun from the premise that big changes are afoot in the energy field, and has tried to pick the technologies most likely to be important. Some outcomes are mutually exclusive. A truly electric car would eliminate the need for biofuels, except, perhaps, in aircraft. Truly cheap biofuels might price electric cars out of the market. A breakthrough in the capture and storage of carbon dioxide would bring coal back into play with a vengeance. Geothermal may be better than solar. Solar may be better than wind.

The report has ignored some technologies because they will not get anywhere. Fusion, that favourite of fantasists, is 30 years away, as it always has been and probably always will be. Giant satellites collecting sunlight and beaming the energy to Earth as microwaves are an idea of heroic proportions, but enough sunlight gets through the atmosphere to make them irrelevant. Other technologies may make a contribution, but only on a small scale. The idea of floating platforms that capture wave energy is technically feasible, but it seems more trouble than building wind turbines. Tidal power works but, even ▸▸

more than hydro, it depends on geography. And the idea of liberating hydro from geography with small, free-standing turbines may have local applications, but maintaining such turbines is far more trouble than taking a spanner to a windmill.

All sorts of wacky but intriguing ideas are being looked into, such as flying turbines that would exploit the high winds of the jetstream. And so are perfectly sensible ones, such as ultracapacitors for storing electricity, that are now niche products but might suddenly blossom, to the embarrassment of prophets. Maybe, too, the hydrogen economy will rear its head again—but only if a way can be found of storing the gas easily and at high density. That would require a material that can absorb large volumes of it. One for Dr Gerber's materials genome project, perhaps.

This report has also ignored the question of efficiency, except in the special context of smart grids. The idea of "negawatts", as improvements in efficiency are sometimes known, has always been a favourite of greens. But there is too often a gleeful hairshirtedness to their pronouncements, which helps to explain why high-profile changes such as the introduction of energy-efficient light bulbs are viewed cynically by so many people.

In any case, a lot of efficiency improvements just happen in the background, as part of most businesses' continuous search for cost savings. Car engines, for example, are much more efficient than they used to be, and are likely to become still more so. The reason that American cars are such gas-guzzlers is not that their engines have got worse but that the cars themselves have got heavier.

Besides, as Robert Metcalfe, the networking guru, said at a recent conference: "You are not going to conserve your way out of the problem." The need to keep doing the same thing—consuming energy in ever larger quantities—is a force for change. Price, political security and environmental pressures are all pushing in the same direction. How quickly that change will happen is hard to tell, but it is wise to remember the power of compound interest.

Sunlit uplands

In some fields, such as information technology, change happens suddenly or not at all. In others, such as energy, it can happen gradually to start with, but as the curve accelerates upward there comes a point where things move very fast. Ten years ago wind turbines were marginal. Now they are taken seriously, and in another decade they may contribute as much as a fifth of the world's electricity.

The same could happen to solar energy, which is ten years behind wind, and geothermal, with a 20-year lag. Whether it would happen faster if carbon emissions were charged for at an honest price is a moot point. Certainly, that is the only way to bring about the widespread adoption of carbon-dioxide capture and storage. But for the rest, the best way might, paradoxically, be what exists now: a threat that is real enough for electricity generators to price it into their future calculations without affecting their existing plants.

The lack of new coal-fired capacity creates a real opportunity for alternatives, among them renewables. But the lack of an actual carbon price still keeps the cost of existing electricity down, and thus the necessary incentives in place to make Google's cheaper-than-coal equation a reality.

If and when such cheaper alternatives arrive, the markets of Asia will open and Mr Khosla, an Indian-born American, will see the fruits of his adopted homeland roll out into his native country. It will be a long time before King Coal and Queen Oil are dethroned completely, but their reigns as absolute monarchs of all they survey are coming slowly to an end. ■