Electricity generation provides 18,000 terawatt-hours of energy a year, around 40% of humanity's total energy use. In doing so it produces more than 10 gigatonnes of carbon dioxide every year, the largest sectoral contribution of humanity's fossil-fuel derived emissions. Yet there is a wide range of technologies — from solar and wind to nuclear and geothermal — that can generate electricity without net carbon emissions from fuel.

The easiest way to cut the carbon released by electricity generation is to increase efficiency. But there are limits to such gains, and there is the familiar paradox that greater efficiency can lead to greater consumption. So a global response to climate change must involve a move to carbon-free sources of electricity. This requires fresh thinking about the price of carbon, and in some cases new technologies; it also means new transmission systems and smarter grids. But above all, the various sources of carbon-free generation need to be scaled up to power an increasingly demanding world. In this special feature, *Nature*'s News team looks at how much carbon-free energy might ultimately be available — and which sources make most sense.

ELECTRICITY WITHOUT CARBON

Hydropower

The world has a lot of dams — 45,000 large ones, according to the World Energy Council, and many more at small scales. Its hydroelectric power plants have a generating capacity of 800 gigawatts, and they currently supply almost one-fifth of the electricity consumed worldwide. As a source of electricity, dams are second only to fossil fuels, and generate 10 times more power than geothermal, solar and wind power combined. With a claimed full capacity of 18 gigawatts, the Three Gorges dam in China can generate more or less twice as much power as all the world's solar cells. An additional 120 gigawatts of capacity is under development.

One reason for hydropower's success is that it is a widespread resource — 160 countries use hydropower to some extent. In several countries hydropower is the largest contributor to grid electricity — it is not uncommon in developing countries for a large dam to be the main generating source. Nevertheless, it is in large industrialized nations that have big rivers that hydroelectricity is shown in its most dramatic aspect. Brazil, Canada, China, Russia and the United States currently produce more than half of the world's hydropower.

Cost: According to the International Hydropower Association (IHA), installation costs are usually in the range of US$1 million to more than $5 million per megawatt of capacity, depending on the site and size of the plant. Dams in lowlands and those with only a short drop between the water level and the turbine tend to be more expensive; large dams are cheaper per watt of capacity than small dams in similar settings. Annual operating costs are low — 0.8–2% of capital costs; electricity costs $0.03–0.10 per kilowatt-hour, which makes dams competitive with coal and gas.

ARTWORK BY J. TAYLOR

Capacity: The absolute limit on hydropower is the rate at which water flows downhill through the world's rivers, turning potential energy into kinetic energy as it goes. The amount of power that could theoretically be generated if all the world's run-off were 'turbined' down to sea level is more than 10 terawatts. However, it is rare for 50% of a river's power to be exploitable, and in many cases the figure is below 30%.

Those figures still offer considerable opportunity for new capacity, according to the IHA. Europe currently sets a benchmark for hydropower use, with 75% of what is deemed feasible already exploited. For Africa to reach the same level, it would need to increase its hydropower capacity by a factor of 10 to more than 100 gigawatts. Asia, which already has the greatest installed capacity, also has the greatest growth potential. If it were to triple its generating capacity, thus harnessing a near-European fraction of its potential, it would double the world's overall hydroelectric capacity. The IHA says that capacity could triple worldwide with enough investment.

Advantages: The fact that hydroelectric systems require no fuel means that they also require no fuel-extracting infrastructure and no fuel transport. This means that a gigawatt of hydropower saves the world not just a gigawatt's worth of coal burned at a fossil-fuel plant, but also the carbon costs of mining and transporting that coal. As turning on a tap is easy, dams can respond almost instantaneously to changing electricity demand independent of the time of day or the weather. This ease of turn-on makes them a useful back-up to less reliable renewable sources. That said, variations in use according to need and season mean that dams produce about half of their rated power capacity.

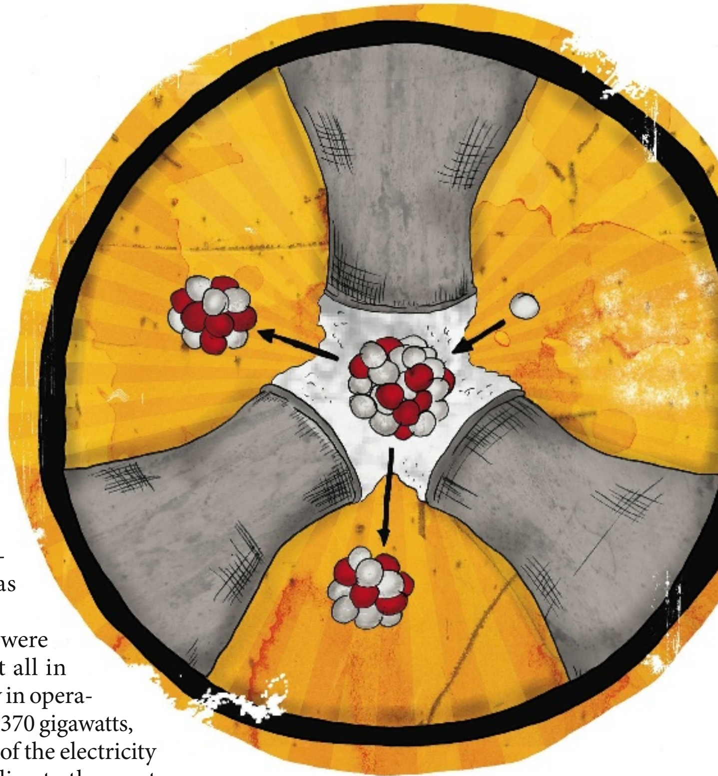
Hydroelectric systems are unique among generating systems in that they can, if correctly engineered, store the energy generated elsewhere, pumping water uphill when energy is abundant. The reservoirs they create can also provide water for irrigation, a way to control floods and create amenities for recreational use.

Disadvantages: Not all regions have large hydropower resources — the Middle East, for example, is relatively deficient. And reservoirs take up a lot of space; today the area under man-made lakes is as large as two Italys. The large dams and reservoirs that account for most of that area and for more than 90% of hydro-generated electricity worldwide require lengthy and costly planning and construction, as well as the relocation of people from the reservoir area. In the past few decades, millions of people have been relocated in India and China. Dams have ecological effects on the ecosystems upstream and downstream, and present a barrier to migrating fish. Sediment build-up can shorten their operating life, and sediment trapped by the dam is denied to those downstream. Biomass that decomposes in reservoirs releases methane and carbon dioxide, and in some cases these emissions can be of a similar order of magnitude to those avoided by not burning fossil fuels. Climate change could itself limit the capacity of dams in some areas by altering the amount and pattern of annual run-off from sources such as the glaciers of Tibet.

Because hydro is a mature technology, there is little room for improvement in the efficiency of generation. Also, the more obvious and easy locations have been used, and so the remaining potential can be expected to be harder to exploit. Small (less than 10 megawatts) 'run-of-river' schemes that produce power from the natural flow of water — as millers have been doing for four millennia — are appealing, as they have naturally lower impacts. However, they are about five times more expensive and harder to scale than larger schemes.

Verdict: A cheap and mature technology, but with substantial environmental costs; roughly a terawatt of capacity could be added.

Nuclear fission



When reactor 4 at the Chernobyl nuclear power plant in Ukraine melted down on 26 April 1986, the fallout contaminated large parts of Europe. That disaster, and the earlier incident at Three Mile Island in Pennsylvania, blighted the nuclear industry in the West for a generation. Worldwide, though, the picture did not change quite as dramatically.

In 2007, 35 nuclear plants were under construction, almost all in Asia. The 439 reactors already in operation had an overall capacity of 370 gigawatts, and contributed around 15% of the electricity generated worldwide, according to the most recent figures from the International Atomic Energy Agency (IAEA), which serves as the world's nuclear inspectorate.

Costs: Depending on the design of the reactor, the site requirements and the rate of capital depreciation, the light-water reactors that make up most of the world's nuclear capacity produce electricity at costs of between US$0.025 and $0.07 per kilowatt-hour. The technology that makes this possible has benefited from decades of expensive research, development and purchases subsidized by governments; without that boost it is hard to imagine that nuclear power would currently be in use.

Capacity: Because nuclear power requires fuel, it is constrained by fuel stocks. There are some 5.5 million tonnes of uranium in known reserves that could profitably be extracted at a cost of US$130 per kilogram or less, according to the latest edition of the 'Red Book', in which the IAEA and the Organisation for Economic Co-operation and Development (OECD) assess uranium resources. At the current use of 66,500 tonnes per year, that is about 80 years' worth of fuel. The current price of uranium is over that $130 threshold.

Geologically similar ore deposits that are as yet unproven — 'undiscovered reserves' — are thought to amount to roughly double the proven reserves, and lower-grade ores offer considerably more. Uranium is not a particularly rare element — it is about as common a constituent of Earth's crust as zinc. Estimates of the ultimate recoverable resource vary greatly, but 35 million tonnes might be considered available. Nor is uranium the only naturally occurring element that can be made into nuclear fuel. Although they have not yet been developed, thorium-fuelled reactors are a possibility; bringing thorium into play

By the numbers

In 2005, 18,000 terawatt-hours of electricity were generated. With almost 9,000 hours in a year, that averages out at a constant 2 TW or so. Generating capacity is a lot higher than that, because there are peaks and troughs and no plants operate at their full output all of the time.

No analogy makes it easy to picture a terawatt. A thousandth of a terawatt, a gigawatt, is more comprehensible. It is the output of a fairly large power station: Sizewell B, one of Britain's largest nuclear power stations, has an output of about 1.2 GW; the Hoover Dam on the Colorado River can produce about 1.8 GW.

A megawatt is a thousandth of a gigawatt. It takes 3–5 MW to power most modern trains (or, if you feel flash, you can think of one as the power of two Formula One cars). A kilowatt is easily thought of as an electric fan heater.

Domestic energy consumption is measured in kilowatt-hours. In 2004, the highest per capita use of electricity was in Iceland, where it reached 28,200 kWh per year. In the United States it is about 13,300 kWh a year; 300 million Americans thus use about 400 GW of power. In Chile the per capita level is 3,100 kWh, in China 1,600 kWh, in India 460 kWh. The lowest level, in Haiti, is 30 kWh.

would double the available fuel reserves.

Furthermore, although current reactor designs use their fuel only once, this could be changed. Breeder reactors, which make plutonium from uranium isotopes that are not themselves useful for power production, can effectively create more fuel than they use. A system built on such reactors might get 60 times more energy out for every kilogram of natural uranium put in, although lower multiples might be more realistic.

With breeder reactors, which have yet to be proven on a commercial basis, the world could in principle go 100% nuclear. Without them, it is still plausible for the amount of nuclear capacity to grow by a factor of two or three, and to operate at that level for a century or more.

Advantages: Nuclear power has relatively low fuel costs and can run at full blast almost constantly — US plants deliver 90% of their rated capacity. This makes them well suited to providing always-on 'baseload' power to national grids. Uranium is sufficiently widespread that the world's nuclear-fuel supply is unlikely to be threatened by political factors.

Disadvantages: There is no agreed solution to the problem of how to deal with the nuclear waste that has been generated in nuclear plants over the past 50 years. Without long-term solutions, which are more demanding politically than technically, growth in nuclear power is an understandably hard sell. A further problem is that the spread of nuclear power is difficult to disentangle from the proliferation of nuclear weapons capabilities. Fuel cycles that involve recycling, and which thus necessarily produce plutonium, are particularly worrying. Even without proliferation worries, nuclear power stations may make tempting targets for terrorists or enemy forces (although in the latter case the same is true of hydroelectric plants).

A long-term commitment to greatly increased use of nuclear power would require public acceptance not just of existing technologies but of new ones, too — thorium and breeder reactors, for instance. These technologies would also have to win over investors and regulators.

Nuclear power is also extremely capital intensive; power costs over the life of the plant are comparatively low only because the plants are long lived. Nuclear power is thus an expensive option in the short term. Another constraint may be a lack of skilled workers. Building and operating nuclear plants requires a great many highly trained professionals, and enlarging this pool of talent enough to double the rate at which new plants are brought online might prove very challenging. The engineering capacity for making key components would also need enlarging.

In light of these obstacles, predictions of the future role of nuclear power vary considerably. The European Commission's *World Energy Technology Outlook — 2050* contains a bullish scenario that assumes that, with public acceptance and the development of new reactor technologies, nuclear power could provide about 1.7 terawatts by 2050. The IAEA's analysts are more cautious. Hans-Holger Rogner, head of the agency's planning and economic study section, sees capacity rising to not more than 1,200 gigawatts by 2050. An interdisciplinary study carried out in 2003 by the Massachusetts Institute of Technology described a concrete scenario for tripling capacity to 1,000 gigawatts by 2050, a scenario predicated on US leadership, continued commitment by Japan and renewed activity by Europe. This scenario relied only on improved versions of today's reactors rather than on any radically different or improved design.

Verdict: Reaching a capacity in the terawatt range is technically possible over the next few decades, but it may be difficult politically. A climate of opinion that came to accept nuclear power might well be highly vulnerable to adverse events such as another Chernobyl-scale accident or a terrorist attack.

Biomass

Biomass was humanity's first source of energy, and until the twentieth century it remained the largest; even today it comes second only to fossil fuels. Wood, crop residues and other biological sources are an important energy source for more than two billion people. Mostly, this fuel is burned in fires and cooking stoves, but over recent years biomass has become a source of fossil-fuel-free electricity. As of 2005, the World Energy Council estimates biomass generating capacity to be at least 40 gigawatts, larger than any renewable resource other than wind and hydropower. Biomass can supplement coal or in some cases gas in conventional power plants. Biomass is also used in many co-generation plants that can capture 85–90% of the available energy by making use of waste heat as well as electric power.

Costs: The price of biomass electricity varies widely depending on the availability and type of the fuel and the cost of transporting it. Capital costs are similar to those for fossil-fuel plants. Power costs can be as little as $0.02 per kilowatt-hour when biomass is burned with coal in a conventional power plant, but increase to $0.03–0.05 per kilowatt-hour from a dedicated biomass power plant. Costs increase to $0.04–0.09 per kilowatt-hour for a co-generation plant, but recovery and use of the waste heat makes the process much more efficient. The biggest problem for new biomass power plants is finding a reliable and concentrated feedstock that is available locally; keeping down transportation costs means keeping biomass power plants tied to locally available fuel and quite small, which increases the capital cost per megawatt.

Capacity: Biomass is limited by the available land surface, the efficiency of photosynthesis, and the supply of water. An OECD round table in 2007 estimated that there is perhaps half a billion hectares of land not in agricultural use that would be suitable for rain-fed biomass production, and suggested that by 2050 this land, plus crop residues, forest residues and organic waste might provide enough burnable material each year to provide 68,000 terawatt-hours. Converted to electricity at an efficiency of 40%, that could provide a maximum of 3 terawatts. The Intergovernmental Panel on Climate Change pegs the potential at roughly 120,000 terawatt-hours in 2050, which equates to slightly more than 5 terawatts on the basis of a larger estimate of available land.

These projections involve some fairly extreme assumptions about converting land to the production of energy crops. And even to the extent that these assumptions prove viable, electricity is not the only potential use for such plantations. By storing solar energy in the form of chemical bonds, biomass lends itself better than other renewable energy resources to the production of fuel for transportation (see page 841). Although turning biomass to biofuel is not as efficient as just burning the stuff, it can produce a higher-value product. Biofuels might easily beat electricity generation as a use for biomass in most settings.

Advantages: Plants are by nature carbon-neutral and renewable, although agriculture does use up resources, especially if it requires large amounts of fertilizer. The technologies needed to burn biomass are mature and efficient, especially in the case of co-generation. Small systems using crop residues can minimize transportation costs.

If burned in power plants fitted with carbon-capture-and-storage hardware, biomass goes from being carbon neutral to carbon negative, effectively sucking carbon dioxide out of the atmosphere and storing it in the ground (see 'Carbon capture and storage', page 822). This makes it the only energy technology that can actually reduce carbon dioxide levels in the atmosphere. As with coal, however, there are costs involved in carbon capture, both in terms of capital set-up and in terms of efficiency.

Disadvantages: There is only so much land in the world, and much of it will be needed to provide food for the growing global population. It is not clear whether letting market mechanisms drive the allocation of land between fuel and food is desirable or politically feasible. Changing climate could itself alter the availability of suitable land. There is likely to be opposition to increased and increasingly intense cultivation of energy crops. Use of waste and residues may remove carbon from the land that would otherwise have enriched the soil; long-term sustainability may not be achievable.

Bioenergy dependence could also open the doors to energy crises caused by drought or pestilence, and land-use changes can have climate effects of their own: clearing land for energy crops may produce emissions at a rate the crops themselves are hard put to offset.

Verdict: If a large increase in energy crops proves acceptable and sustainable, much of it may be used up in the fuel sector. However, small-scale systems may be desirable in an increasing number of settings, and the possibility of carbon-negative systems — which are plausible for electricity generation but not for biofuels — is a unique and attractive capability.

Wind

Wind power is expanding faster than even its fiercest advocates could have wished a few years ago. The United States added 5.3 gigawatts of wind capacity in 2007 — 35% of the country's new generating capacity — and has another 225 gigawatts in the planning stages. There is more wind-generating capacity being planned in the United States than for coal and gas plants combined. Globally, capacity has risen by nearly 25% in each of the past five years, according to the Global Wind Energy Council.

Wind Power Monthly estimates that the world's installed capacity for wind as of January 2008 was 94 gigawatts. If growth continued at 21%, that figure would triple over six years.

Despite this, the numbers remain small on a global scale, especially given that wind farms have historically generated just 20% of their capacity.

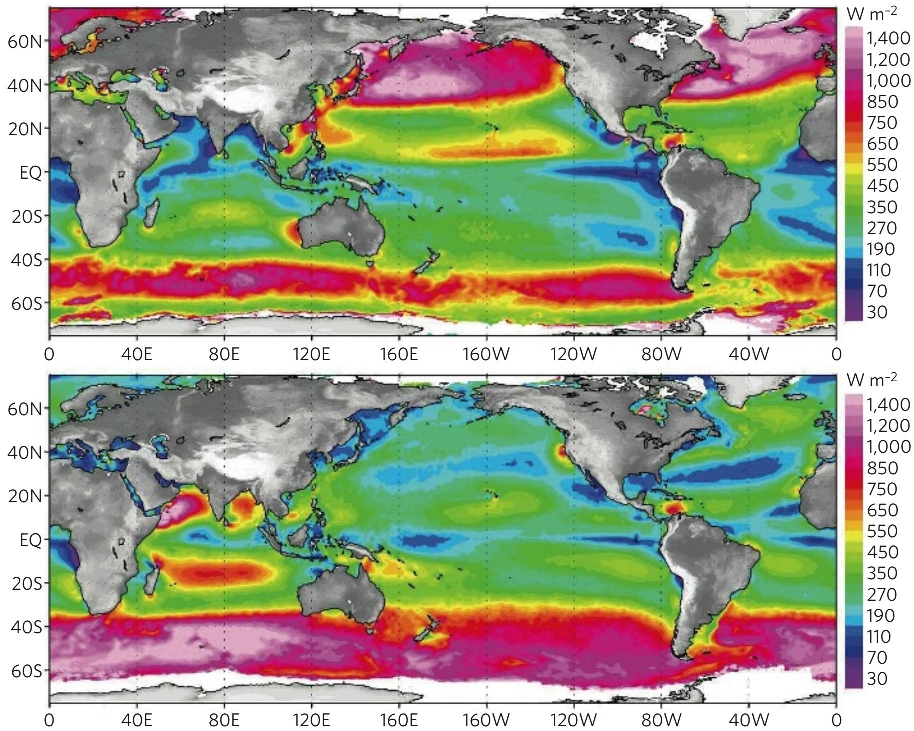
Costs: Installation costs for wind power are around US$1.8 million per megawatt for onshore developments and between $2.4 million and $3 million for offshore projects. That translates to $0.05–0.09 per kilowatt-hour, making wind competitive with coal at the lower end of the range. With subsidies, as enjoyed in many countries, the costs come in well below those for coal — hence the boom. The main limit on wind-power installation at the moment is how fast manufacturers can make turbines.

These costs represent significant improvements in the technology. In 1981, a wind farm might have consisted of an array of 50-kilowatt turbines that produced power for roughly $0.40 per kilowatt-hour. Today's turbines can produce 30 times as much power at one-fifth the price with much less down time.

Capacity: The amount of energy generated by the movement of Earth's atmosphere is vast — hundreds of terawatts. In a 2005 paper, a pair of researchers from Stanford University calculated that at least 72 terawatts could be effectively generated using 2.5 million of today's larger turbines placed at the 13% of locations around the world that have wind speeds of at least 6.9 metres per second and are thus practical sites (C. L. Archer and M. Z. Jacobson *J. Geophys. Res.* **110,** D12110; 2005).

Advantages: The main advantage of wind is that, like hydropower, it doesn't need fuel. The only costs therefore come from building and maintaining the turbines and power lines. Turbines are getting bigger and more reliable. The development of technologies for capturing wind at high altitudes could provide sources with small footprints capable of generating power in a much more sustained way.

Disadvantages: Wind's ultimate limitation might be its intermittency. Providing up to 20% of a grid's capacity from wind is not too difficult. Beyond that, utilities and grid operators need to take extra steps to deal with the variability. Another grid issue, and one that is definitely limiting in the near term, is that the windiest places are seldom the most populous, and so electricity from the wind needs infrastructure development — especially for offshore settings.



Average power of the world's winds during the boreal winter (top) and summer. The recoupable energy is some two orders of magnitude lower because of turbine spacing and engineering constraints.

W. T. LIU *ET AL. GEOPHYS. RES. LETT.* **35,** L13808; 2008

As well as being intermittent, wind power is, like other renewable energy sources, inherently quite low density. A large wind farm typically generates a few watts per square metre — 10 is very high. Wind power thus depends on cheap land, or on land being used for other things at the same time, or both. It is also hard to deploy in an area where the population sets great store by the value of a turbine-free landscape.

Wind power is also unequally distributed: it favours nations with access to windy seas and their onshore breezes or great empty plains. Germany has covered much of its windiest land with turbines, but despite these pioneering efforts, its combined capacity of 22 GW supplies less than 7% of the country's electricity needs. Britain, which has been much slower to adopt wind power, has by far the largest offshore potential in Europe — enough to meet its electricity needs three times over, according to the British Wind Energy Association. Industry estimates suggest that the European Union could meet 25% of its current electricity needs by developing less than 5% of the North Sea.

Such truly large-scale deployment of wind-power schemes could affect local, and potentially global, climate by altering wind patterns, according to research by David Keith, head of the Energy and Environmental Systems Group at the University of Calgary in Canada. Wind tends to cool things down, so temperatures around a very large wind farm could rise as turbines slow the wind to extract its energy. Keith and his team suggest that 2 TW of wind capacity could affect temperatures by about 0.5 °C, with warming at mid-latitudes and cooling at the poles — perhaps in that respect offsetting the effect of global warming (D. W. Keith *et al. Proc. Natl Acad. Sci. USA* **101,** 16115–16120; 2004).

Verdict: With large deployments on the plains of the United States and China, and cheaper access to offshore, a wind-power capacity of a terawatt or more is plausible.

Geothermal

Earth's interior contains vast amounts of heat, some of it left over from the planet's original coalescence, some of it generated by the decay of radioactive elements. Because rock conducts heat poorly, the rate at which this heat flows to the surface is very slow; if it were quicker, Earth's core would have frozen and its continents ceased to drift long ago.

The slow flow of Earth's heat makes it a hard resource to use for electricity generation except in a few specific places, such as those with abundant hot springs. Only a couple of dozen countries produce geothermal electricity, and only five of those — Costa Rica, El Salvador, Iceland, Kenya and the Philippines — generate more than 15% of their electricity this way. The world's installed geothermal electricity capacity is about 10 gigawatts, and is growing only slowly — about 3% per year in the first half of this decade. A decade ago, geothermal capacity was greater than wind capacity; now it is almost a factor of ten less.

Earth's heat can also be used directly. Indeed, small geothermal heat pumps that warm houses and businesses directly may represent the greatest contribution that Earth's warmth can make to the world's energy budget.

Costs: The cost of a geothermal system depends on the geological setting. Jefferson Tester, a chemical engineer who was part of a team that produced an influential Massachusetts Institute of Technology (MIT) report on geothermal technology in 2006, explains the situation as being "similar to mineral resources. There is a continuum of resource grades — from shallow, high-temperature regions of high-porosity rock, to deeper low-porosity regions that are more challenging to exploit". That report put the cost of exploiting the best sites — those with a lot of hot water circulating close to the surface — at about US$0.05 per kilowatt-hour. Much more abundant low-grade resources are exploitable with current technology only at much higher prices.

Absolute capacity: Earth loses heat at between 40 TW and 50 TW a year, which works out at an average of a bit less than a tenth of a watt per square metre. For comparison, sunlight comes in at an average of 200 watts per square metre. With today's technology, 70 GW of the global heat flux is seen as exploitable. With more advanced technologies, at least twice that could be used. The MIT

study suggested that using enhanced systems that inject water at depth using sophisticated drilling systems, it would be possible to set up 100 GW of geothermal electricity in the United States alone. With similar assumptions a global figure of a terawatt or so can be reached, suggesting that geothermal could, with a great deal of investment, provide as much electricity as dams do today.

Advantages: Geothermal resources require no fuel. They are ideally suited to supplying base-load electricity, because they are driven by a very regular energy supply. At 75%, geothermal sources boast a higher capacity factor than any other renewable. Low-grade heat left over after generation can be used for domestic heating or for industrial processes.

Surveying and drilling previously unexploited geothermal resources has become much easier thanks to mapping technology and drilling equipment designed by the oil industry. A significant technology development programme — Tester suggests $1 billion over 10 years — could greatly expand the achievable capacity as lower-grade resources are opened up.

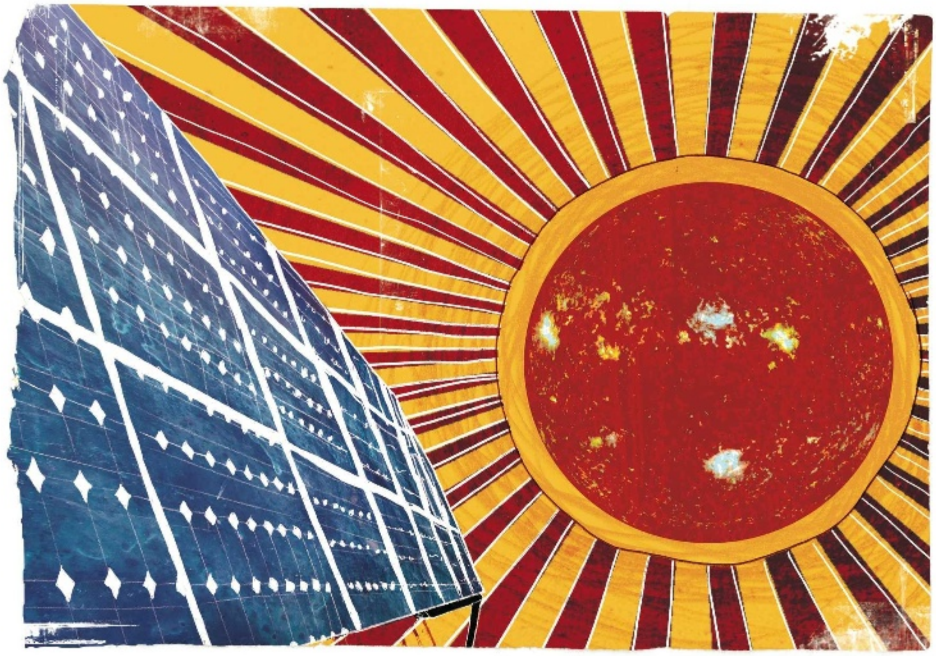
Disadvantages: High-grade resources are quite rare, and even low-grade resources are not evenly distributed. Carbon dioxide can leak out of some geothermal fields, and there can be contamination issues; the water that brings the heat to the surface can carry compounds that shouldn't be released into aquifers. In dry regions, water availability can be a constraint. Large-scale exploitation requires technologies that, although plausible, have not been demonstrated in the form of robust, working systems.

Verdict: Capacity might be increased by more than an order of magnitude. Without spectacular improvements, it is unlikely to outstrip hydro and wind and reach a terawatt.

Farther out

Fusion power could meet all Earth's energy needs. It just requires two heavy isotopes of hydrogen and the technology to use them. The reactors would produce some low-level radioactive waste, but only a minor amount compared with nuclear fission. The problem is the necessary technology — commercial reactors are unlikely before the 2040s.

Another far-off dream is the space-based solar power satellite. In orbit, solar panels could soak up sunshine 24/7, beaming it to Earth as microwaves. This requires really cheap space travel to lift thousands of tonnes of solar cells into orbit. At the moment, unfortunately, space travel is really expensive.



Solar

Not to take anything away from the miracle of photosynthesis, but even under the best conditions plants can only turn about 1% of the solar radiation that hits their surfaces into energy that anyone else can use. For comparison, a standard commercial solar photovoltaic panel can convert 12–18% of the energy of sunlight into useable electricity; high-end models come in above 20% efficiency. Increasing manufacturing capacity and decreasing costs have led to remarkable growth in the industry over the past five years: in 2002, 550 MW of cells were shipped worldwide; in 2007 the figure was six times that. Total installed solar-cell capacity is estimated at 9 GW or so. The actual amount of electricity generated, though, is considerably less, as night and clouds decrease the power available. Of all renewables, solar currently has the lowest capacity factor, at about 14%.

Solar cells are not the only technology by which sunlight can be turned into electricity. Concentrated solar thermal systems use mirrors to focus the Sun's heat, typically heating up a working fluid that in turn drives a turbine. The mirrors can be set in troughs, in parabolas that track the Sun, or in arrays that focus the heat on a central tower. As yet, the installed capacity is quite small, and the technology will always remain limited to places where there are a lot of cloud-free days — it needs direct sun, whereas photovoltaics can make do with more diffuse light.

Costs: The manufacturing cost of solar cells is currently US$1.50–2.50 for a watt's worth of generating capacity, and prices are in the $2.50–3.50 per watt range. Installation costs are extra; the price of a full system is normally about twice the price of the cells. What this means in terms of cost per kilowatt-hour over the life of an installation varies according to the location, but it comes out at around $0.25–0.40. Manufacturing costs are dropping, and installation costs will also fall as photovoltaic cells integrated into building materials replace free-standing panels for domestic applications. Current technologies should be manufacturing at less than $1 per watt within a few years (see *Nature* **454,** 558–559; 2008).

The cost per kilowatt-hour of concentrated solar thermal power is estimated by the US National Renewable Energy Laboratory (NREL) in Golden, Colorado, at about $0.17.

Capacity: Earth receives about 100,000 TW of solar power at its surface — enough energy every hour to supply humanity's energy needs for a year. There are parts of the Sahara Desert, the Gobi Desert in central Asia, the Atacama in Peru or the Great Basin in the United States where a gigawatt of electricity could be generated using today's photovoltaic cells in an array 7 or 8 kilometres across. Theoretically, the world's entire primary energy needs could be served by less than a tenth of the area of the Sahara.

Advocates of solar cells point to a calculation by the NREL claiming that solar panels on all usable residential and commercial roof surfaces could provide the United States with as much electricity per annum as the country used in 2004. In more temperate climes things are not so promising: in Britain one might expect an annual insolation of about 1,000 kilowatt-hours per metre on a south-facing panel tilted to take account of latitude: at 10% efficiency, that means more than 60 square metres per person would be needed to meet current UK electricity consumption.

Advantages: The Sun represents an effectively unlimited supply of fuel at no cost, which is widely distributed and leaves no residue. The public accepts solar technology and in most places approves of it — it is subject to less geopolitical, environmental and aesthetic concern than nuclear, wind or hydro, although extremely large desert installations might elicit protests.

Photovoltaics can often be installed piecemeal — house by house and business by business. In these settings, the cost of generation has to compete with the retail price of electricity, rather than the cost of generating it by other means, which gives solar a considerable boost. The technology is also obviously well suited to off-grid generation and thus to areas without well developed infrastructure.

Both photovoltaic and concentrated solar thermal technologies have clear room for improvement. It is not unreasonable to imagine that in a decade or two new technologies could lower the cost per watt for photovoltaics by a factor of ten, something that is almost unimaginable for any other non-carbon electricity source.

Disadvantages: The ultimate limitation on solar power is darkness. Solar cells do not generate electricity at night, and in places with frequent and extensive cloud cover, generation fluctuates unpredictably during the day. Some concentrated solar thermal systems get around this by storing up heat during the day for use at night (molten salt is one possible storage medium), which is one of the reasons they might be preferred over photovoltaics for large installations. Another possibility is distributed storage, perhaps in the batteries of electric and hybrid cars (see page 810).

Another problem is that large installations will usually be in deserts, and so the distribution of the electricity generated will pose problems. A 2006 study by the German Aerospace Centre proposed that by 2050 Europe could be importing 100 GW from an assortment of photovoltaic and solar thermal plants across the Middle East and North Africa. But the report also noted that this would require new direct-current high-voltage electricity distribution systems.

A possible drawback of some advanced photovoltaic cells is that they use rare elements that might be subject to increases in cost and restriction in supply. It is not clear, however, whether any of these elements is either truly constrained — more reserves might be made economically viable if demand were higher — or irreplaceable.

Verdict: In the middle to long run, the size of the resource and the potential for further technological development make it hard not to see solar power as the most promising carbon-free technology. But without significantly enhanced storage options it cannot solve the problem in its entirety.

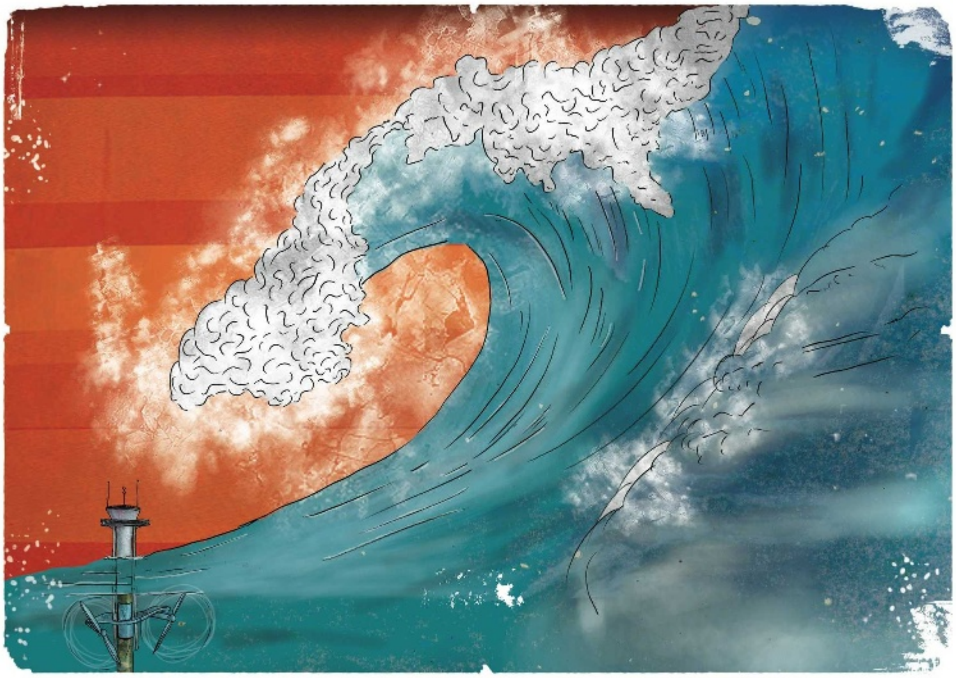
Carbon capture and storage

An alternative to renouncing fossil fuels is not to release their CO_2 into the atmosphere. Carbon capture and storage (CCS) technology strips CO_2 out of exhaust gases and stores it underground. The technology could reduce carbon emissions from power stations by 80–90%, although after taking life-cycle factors into account, that number could drop to as little as 67%. Estimates of the extra cost of CCS vary widely depending on technology and location, but it could add US$0.01–0.05 to the cost of a kilowatt-hour. On coal-fired power plants the technology could be competitive if CO_2 were priced at around $50 per tonne.

Part of the extra cost of CCS is the capital invested in new plant; part is due to decreased efficiency because of the energy costs of removing the carbon. For a conventional coal plant, the efficiency loss could be as much as 40%. In more modern integrated gasification combined-cycle (IGCC) power plants, the capital costs of which are higher, the gasification step produces a CO_2 stream that is more easily handled. CCS thus reduces the efficiency of IGCC plants by less than 20% — and their efficiency is higher to start with. As yet there are very few IGCC plants, but the possibility of carbon taxes, or indeed more expensive coal, may tip the market their way.

Although early implementations of CCS will probably concentrate on pumping CO_2 into depleted oil fields (where it is used already to help extract the dregs), the technology is likely ultimately to be targeted at saline aquifers, which represent by far the largest CO_2 storage capacity. Estimates of global aquifer capacity range from 2,000 Gt CO_2 to nearly 11,000 Gt CO_2, although this resource is not evenly distributed around the world. The Global Energy Technology Strategy Program, led by researchers at the University of Maryland in College Park, estimates that the 8,100 major facilities worldwide that might be candidates for CCS currently emit about 15 Gt CO_2 annually. Aquifers could thus offer centuries of storage at current levels of CO_2, and also allow the use of coal to continue while work progresses on making a less dirty baseload technology possible.

The task is enormous, and serious industrial proof-of-concept studies of the feasibility of CCS have barely begun. The probability of CCS being widespread in 10 or even 20 years is very low unless the technology is promoted much more aggressively. The biggest problem is scale. Capturing 60% of the CO_2 from US coal-fired power stations would mean handling a volume of CO_2 daily that rivals the 20 million barrels of oil moved around by the oil industry, according to a 2007 Massachusetts Institute of Technology study. Creating such an infrastructure is not impossible, but setting it up in a decade or two is a tall order.



Ocean energy

The oceans offer two sorts of available kinetic energy — that of the tides and that of the waves. Neither currently makes a significant contribution to world electricity generation, but this has not stopped enthusiasts from developing schemes to make use of them. There are undoubtedly some places where, thanks to peculiarities of geography, tides offer a powerful resource. In some situations that potential would best be harnessed by a barrage that creates a reservoir not unlike that of a hydroelectric dam, except that it is refilled regularly by the pull of the Moon and the Sun, rather than being topped up slowly by the runoff of falling rain. But although there are various schemes for tidal barrages under discussion — most notably the Severn Barrage between England and Wales, which proponents claim could offer as much as 8 GW — the plant on the Rance estuary in Brittany, rated at 240 MW, remains the world's largest tidal-power plant more than 40 years after it came into use.

There are also locations well suited to tidal-stream systems — submerged turbines that spin in the flowing tide like windmills in the air. The 1.2 MW turbine installed this summer in the mouth of Strangford Lough, Northern Ireland, is the largest such system so far installed.

Most technologies for capturing wave power remain firmly in the testing phase. Individual companies are working through an array of potential designs, including machines that undulate on waves like a snake, bob up and down as water passes over them, or nestle on the coastline to be regularly overtopped by waves that power turbines as the water drains off. The European Marine Energy Centre's test bed off the United Kingdom's Orkney Islands, where manufacturers can hook up prototypes to a marine electricity grid and test how well they withstand the pounding waves, is a leading centre of research. Pelamis Wave Power, a company based in Edinburgh, UK, for instance, has moved from testing there to installing three machines off the coast of Portugal, which together will eventually generate 2.25 MW.

Costs: Barrage costs differ markedly from site to site, but are broadly comparable to costs for hydropower. At an estimated cost of £15 billion (US$30 billion) or more, the capital costs of the Severn Barrage would be about $4 million per megawatt. A 2006 report from the British Carbon Trust, which spurs investment in non-carbon energy, puts the costs of tidal-stream electricity in the $0.20–0.40 per kilowatt-hour range, with wave systems running up to $0.90 per kilowatt-hour. Neither technology is anywhere close to the large-scale production needed to significantly drive such costs down.

Capacity: The interaction of Earth's mass with the gravitational fields of the Moon and the Sun is estimated to produce about 3 TW of tidal energy— rather modest for such an astronomical source (although enough to play a key role in keeping the oceans mixed — see *Nature* **447,** 522–524; 2007). Of this, perhaps 1 TW is in shallow enough waters to be easily exploited, and only a small part of that is realistically available. EDF, a French power company developing tidal power off Brittany, says that the tidal-stream potential off France is 80% of that available all round Europe, and yet it is still little more than a gigawatt.

The power of ocean waves is estimated at more than 100 TW. The European Ocean Energy Association estimates that the accessible global resource is between 1 and 10 terawatts, but sees much less than that as recoverable with current technologies. An analysis in the *MRS Bulletin* in April 2008 holds that about 2% of the world's coastline has waves with an energy density of 30 kW m^{-1}, which would offer a technical potential of about 500 GW for devices working at 40% efficiency. Thus even with a huge amount of development, wave power would be unlikely to get close to the current installed hydroelectric capacity.

Advantages: Tides are eminently predictable, and in some places barrages really do offer the potential for large-scale generation that would be significant on a countrywide scale. Barrages also offer some built-in storage potential. Waves are not constant — but they are more reliable than winds.

Disadvantages: The available resource varies wildly with geography; not every country has a coastline, and not every coastline has strong tides or tidal streams, or particularly impressive waves. The particularly hot wave sites include Australia's west coast, South Africa, the western coast of North America and western European coastlines. Building turbines that can survive for decades at sea in violent conditions is tough. Barrages have environmental impacts, typically flooding previously intertidal wetlands, and wave systems that flank long stretches of dramatic coastline might be hard for the public to accept. Tides and waves tend by their nature to be found at the far end of electricity grids, so bringing back the energy represents an extra difficulty. Surfers have also been known to object…

Verdict: Marginal on the global scale. ■

Reported and written by Quirin Schiermeier, Jeff Tollefson, Tony Scully, Alexandra Witze and Oliver Morton.

See Editorial, page 805.

SOURCE MATERIAL AND FURTHER READING

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