G. BAKER/AP

PUTTING THE CARBON BACK

One way to keep carbon dioxide out of the atmosphere is to put it back in the ground. In the first of two News Features on carbon sequestration, **Quirin Schiermeier** asks when the world's coal-fired power plants will start storing away their carbon. In the second, **Emma Marris** joins the enthusiasts who think that enriching Earth's soils with charcoal can help avert global warming, reduce the need for fertilizers, and greatly increase the size of turnips.

The hundred billion tonne challenge

Ketzin, a dozy village of 4,000 people west of Berlin, hardly looks like a vision of the future. Nestled in the Havel countryside — an idyllic mix of rivers and forests — it has a small tourist industry and, as is typical for such parts of eastern Germany, a not-so-small unemployment problem. "There's no news at the moment", says the community's website.

But there could be news soon. In 2004, Ketzin was chosen as the site of mainland Europe's first large-scale carbon storage demonstration project. By the end of the year, drilling will start at a former gas storage facility on the edge of town. In the next two years, some 60,000 tonnes of carbon dioxide (roughly the annual carbon dioxide output of 40,000 cars) will be injected into an aquifer of salty water 700 metres beneath the surface.

The Ketzin project will test the 'storage' part of carbon capture and storage (CCS), a strategy designed to allow energy to be generated from fossil fuels without the carbon dioxide produced in the process ending up in the atmosphere.

Little more than a fringe idea five years ago, CCS was singled out at the 2005 G8 summit as a technology that could make a difference to climate change. Experts see it as a central part of any strategy for maintaining the generation of energy at today's levels: as Vassilios Kougionas, a European Commission officer in charge of clean-coal initiatives and international energy relations, puts it, "Without CCS there is no point in continuing with fossil fuels."

And yet, for all this enthusiasm, there is a distinct lack of urgency in government approaches. The countries most interested in CCS have, at best, preliminary plans for it; most haven't even got that far. Meanwhile, the number of power stations whose carbon dioxide is neither captured nor stored is rising inexorably, as is the atmospheric level of the gas.

To some observers, this represents a failure not of science or technology, but of will. "It does require quite substantial research and technology efforts to make CCS better and more efficient — but we could still start today if desired," says Hans Ziock, a physicist at Los Alamos National Laboratory in New Mexico, who has worked on carbon dioxide capture technologies for more than a decade. David Hawkins, director of the National Resources Defense Council's Climate Center in Washington DC, goes further: "Global efforts are completely out of scale with what is needed."

Act now or pay later

The International Energy Agency (IEA) predicts that by 2030, global energy demand will grow by 1.7% a year. Although contributions from nuclear and renewable sources may increase, the IEA predicts that 85% of the rise in demand will be met by greater use of fossil fuels. This means the overall capacity of coal-fired power plants will have to double in that time, from 1,100 gigawatts to 2,200 gigawatts[1]. Taking into account the existing plants that will be shut down, the world is looking at 1,400 gigawatts' worth of new coal plants (see graphic on page 623). This doubling of capacity is the greatest expansion of power generation in the planet's history.

Since 1750, humanity's burning of coal has released about 150 billion tonnes (gigatonnes) of carbon into the atmosphere. During their lifetimes, the new generation of plants will

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release 140 gigatonnes. Meanwhile, climate scientists are arguing that carbon dioxide levels should not be allowed to get much higher than 550 parts per million (p.p.m.); the current level is 380 p.p.m., which compares with 280 p.p.m. in the eighteenth century. Some argue that the ceiling needs to be a lot lower.

Robert Socolow is a physicist and co-principal investigator of the Carbon Mitigation Initiative at Princeton University in New Jersey. He calculates that if carbon dioxide levels are to be kept in the desired range, then humanity needs to avoid about a third of the emissions expected in the next 50 years. That means finding a way to not release 175 gigatonnes of carbon. "If we get going now," he says, "the job will be less than half as difficult. If we don't it means we're running a very costly strategy."

The good news is that, in principle, such vast amounts of gas could indeed be tackled by CCS. Deep aquifers in the world's sedimentary basins have a total storage capacity estimated at between 1,000 and 10,000 gigatonnes[2]. Pumping carbon dioxide into them is a straightforward matter. Oil companies already pump carbon dioxide into petroleum reservoirs on a routine basis as a way of flushing out the hydrocarbons. And experience with oil shows that such reservoirs can keep their contents stored away for geological lengths of time, points out Günter Borm, director of geo-engineering at Germany's National Research Centre for Geosciences in Potsdam and coordinator for the European Union-funded Ketzin project.

Not all reservoirs are as well adapted to CCS as a 100-million-year-old oilfield might be. Some may leak, and in some there might be a risk of sudden, catastrophic releases of gas. In low-lying land, such leakages could suffocate people because carbon dioxide is heavier than air, so will fill up valleys and basins. Under the sea, gas-filled reservoirs could potentially trigger landslides and thus tsunamis. But provided storage sites are chosen carefully, designed for safe operation, and properly monitored, the risks are manageable, says Lynn Orr, director of the Global Climate and Energy Project at Stanford University in California.

At Ketzin, scientists will keep track of any undesired chemical interactions between carbon dioxide and minerals, which could in principle dissolve the 'cap-rock' that seals a storage site, or contaminate drinkable ground water. Scientists monitoring a smaller storage project, the Frio Brine Pilot Experiment in Texas, recently reported that the injection of carbon dioxide had made the brine 1,500 metres down substantially more acid[3]; such acidic brine could potentially eat through the surrounding rock and escape into higher aquifers.

But Hawkins counsels against too much pilot-project research of this type. He thinks that each reservoir will have unique geological characteristics that will need to be assessed *in situ*. He also points out that even if some reservoirs leak, it still makes more sense to use them, and thus spread out emissions over time rather than do nothing.

Everyone agrees that large-scale carbon dioxide storage would be a gargantuan technical feat. Locking away 250 million tonnes of carbon per year — equivalent to 4% of annual global emissions — would require an injection of 25 million to 35 million barrels per day, depending on compression density. That's equivalent to about a third of the flow of oil currently coming from reservoirs.

According to Orr, if the infrastructure used to pump carbon dioxide into the ground was roughly the same size as the infrastructure currently deployed to bring oil to the surface, it could deal with about a seventh of the world's production of fossil-fuel-generated carbon. That is less than half the amount produced at power stations and large factories — the sources for which CCS is best suited.

"If we get going now, the job will be less than half as difficult." — Robert Socolow

Ground work

"It's a big enterprise," says Socolow. But pipeline building and well-drilling are mature and remarkably inexpensive technologies, and running costs would be extremely low. Experts calculate that setting up storage facilities, each capturing several million tonnes of carbon per year, for the carbon dioxide produced from hundreds or thousands of plants, might cost as much as $80 billion. In a world set to invest $16 trillion in energy by 2030, $80 billion is not an unthinkable amount; the cost of deep disposal for Britain's nuclear waste has recently been estimated as £11.3 billion ($21 billion). What's more, the figure might come down as the technology matures and economies of scale cut in.

As yet, industrial-scale CCS activities are limited to just three sites — in Norway, Canada and Algeria — and to megatonnes rather than gigatonnes of carbon. Since it began in 1996, the Norwegian project has pumped around 10 million tonnes of carbon dioxide 1,000 metres beneath the North Sea bed into the Utsira Sand formation; the carbon dioxide is a contaminant in natural gas from the Sleipner West field. In the Canadian and Algerian projects, the gas being stored away is also being used to enhance the productivity of oilfields, which covers some of the costs. All these sites have been continuously monitored for possible leakages, but none seems to have occurred.

In total, 11 or so full-scale CCS projects are planned, or have been proposed, in the United States, Canada, Britain, Germany, Norway and Australia. But given present trends, experts think it unlikely that CCS will be employed at any substantial level before 2030, by which time the 1,400-gigawatts' worth of power stations will already have been built. For CCS to


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STATOIL

Flow reversal: Statoil has pumped around 10 million tonnes of carbon dioxide, separated from the Sleipner West natural gas field, beneath the North Sea bed.

make a difference, the mechanisms it requires must be available to a substantial fraction of those plants after they have been built.

Conventional coal-burning technology, which will probably be used to produce 1,200 of the 1,400 gigawatts, produces flue gases that are about 14% carbon dioxide. If the carbon dioxide is to be captured and stored it must first be 'scrubbed' from the gas stream, typically by running the gases through an amine solution. This takes up the carbon dioxide and then, when heated, releases it in pure form. The problem with using this technique is that the equipment needed not only costs money — it also takes up a lot of space. Fitting such equipment into a plant not designed for it is expensive.

The main alternative to the conventional plant is the integrated gasification combined cycle (IGCC). The capital costs for IGCC plants are 20% greater than for conventional plants. But they have environmental benefits — among which is being cheaper to kit out for CCS.

In IGCC plants, the fuel — coal, fuel oil or biomass — is introduced into a hot gasifier along with oxygen and steam. This produces a fuel gas consisting mainly of carbon monoxide and hydrogen. The carbon monoxide then goes through a second 'shift' reaction with steam, making carbon dioxide and more hydrogen. The carbon dioxide can be relatively easily separated at this point.

Four IGCC plants are currently in operation — two in the United States, one in the Netherlands and one in Spain. Although more expensive, and less profitable, than conventional plants, they have very low emissions of sulphur dioxide and other pollutants. Carbon dioxide capture from plants such as these would be significantly easier and cheaper than from conventional plants.

Making it pay

At the moment, the efficiency of IGCC plants is about 40%, which is roughly the same as that for good conventional plants. CCS would drop the efficiency of both sorts of plant to about 30%. But IGCC plants use two thermodynamic cycles; the hydrogen from the gasifier and the shift reaction drives a gas turbine while the heat from that turbine and the gasifier drives a separate steam turbine. Having more than one cycle means that, in principle, it should be possible to push the overall efficiency much higher, to the point where, even when paying the energy penalty associated with CCS, the plants would still be competitive. "First comes efficiency, then CCS," says Jacek Podkanski, a senior energy technology specialist with the IEA.

The US 'FutureGen' initiative, a \$1-billion public–private partnership to design, build, and operate a coal-fuelled zero-emissions power plant by 2015, aims to prove the technical and economic feasibility of a commercial-scale IGCC plant fitted with CCS. In Europe,

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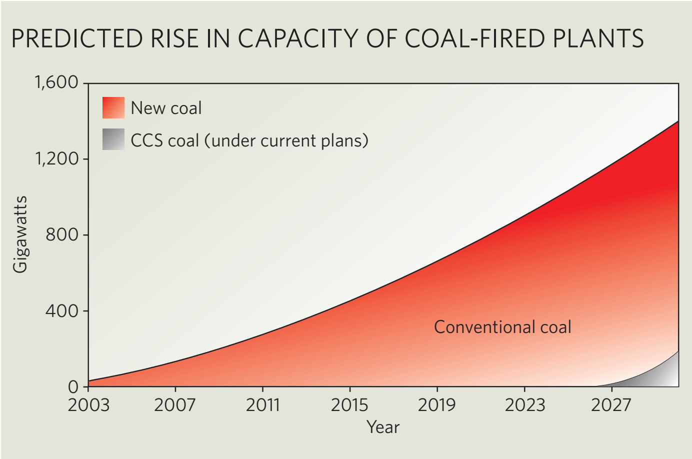

the German energy company RWE Power has recently announced that it will invest €1 billion (US$1.3 billion) in the construction of a 450-megawatt IGCC plant in Germany. The plant, fully equipped for CCS, could become operational in 2014. Other companies, such as Swedish Vattenfall, are also experimenting with ways to get more efficiency out of traditional plants, and with 'oxyfuel' plants in which the coal is burned in pure oxygen, producing a flue gas that is richer in carbon dioxide and so better suited to CCS.

"We're by no means proceeding as though there were all the time in the world, but new technologies need time," says Johannes Ewers, head of new power-plant technologies at RWE. "We do know that if we want to burn coal we have to reduce carbon dioxide."

In theory, the EU's emissions trading system should be providing incentives for such developments by putting a price on emissions. Such incentives have been shown to work: the sequestration of carbon dioxide from the Sleipner platform in Norway is the oil and gas company Statoil's response to the country's $50 per tonne of carbon dioxide tax on emission-intensive industries. The cost of capturing, transporting and storing a tonne of carbon dioxide is estimated by the Intergovernmental Panel on Climate Change to be between $20 and $70, which is why the Statoil sequestering project makes sense. But emitting a tonne of carbon dioxide currently costs less than $20 on the European exchange, and analysts doubt that the price is likely to increase much in the future. "The price of emitting carbon dioxide must rise, otherwise it just won't work," says Borm.

"CCS is perfectly doable at modest costs," says Jon Gibbins, a CCS expert at Imperial College London and project manager with the UK Carbon Capture and Storage Consortium. "But politically we're unfortunately in a very chaotic situation where it's hard to look forward for more than one or two years. If you want to tackle climate change you should do it aggressively or not bother at all."

"The price of carbon dioxide must rise; otherwise it just won't work"
— Günter Borm

The road ahead

For Gibbins, the best way forward is to ensure that every new plant is 'capture-ready' — that is, designed in such a way that CCS mechanisms can be relatively easily incorporated at a later date. The UK government is considering requiring that all new coal-fired plants are capture-ready. The idea is also part of an EU–Chinese 'memorandum of understanding' on near-zero-emissions power generation technology, and was highlighted in the 2005 G8 action plan.

But some fear that capture-readiness will just provide a cheap way of doing a small amount to cut emissions. "The term 'capture-ready' is pretty meaningless, because its definition includes subsequent installation of unidentified equipment," says Hawkins.

To him, it would make more sense for governments to set up well-defined performance standards for power-generating facilities, such as a maximum carbon dioxide output allowed per unit of electricity. Such standards could become gradually more strenuous as better technologies become available. Another possibility, Socolow points out, would be simply to subsidize the technology. He thinks 2–3 cents per kilowatt-hour would make CCS a profitable route for a new coal-fired plant using today's technologies. That is only a little more than the 1.8-cent subsidy the United States currently gives producers of wind-generated electricity.

No matter which technological options and economic or regulatory incentives are used, CCS will cost society money. "Electricity will clearly become more expensive," says Ewers. How expensive depends on technology choices and geographical circumstances, but rough estimates suggest that the average production costs of electricity will double, from 4 to 7 cents per kilowatt-hour. This might be bad news for coal producers, as, all other things being equal, it would make the fuel they sell much less desirable, tilting the market towards natural gas. But it would not necessarily be a terrible burden for consumers, says Socolow. As the costs of distribution and transmission are hardly affected, he calculates that the retail cost of electricity would increase by just 20%.

These costs, says Gibbins, are trifles compared to the long-term benefits of allowing companies to go on generating power with proven technology but without adding to the greenhouse effect. He also points to a peculiar long-term advantage. If fossil fuels are left unburned, they could be used in the future. If burned with CCS, they are gone for good, with the environment unchanged. "It doesn't make a lot of difference in which form carbon stays in the ground," he says. "But with carbon dioxide rather than desirable fossil fuels in the ground you have a very different path ahead." ■

Quirin Schiermeier is *Nature*'s German correspondent.

1. International Energy Agency *World Energy Outlook 2004* www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1266
2. *IPCC Special Report: Carbon Dioxide Capture and Storage* http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/ccsspm.pdf (2005).
3. Kharaka, Y. K. *et al. Geology* **34,** 577–580 (2006).

M. DUFFY/ALAMY

Mechanisms to store carbon will draw on well-established technologies already used by the oil industry.

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