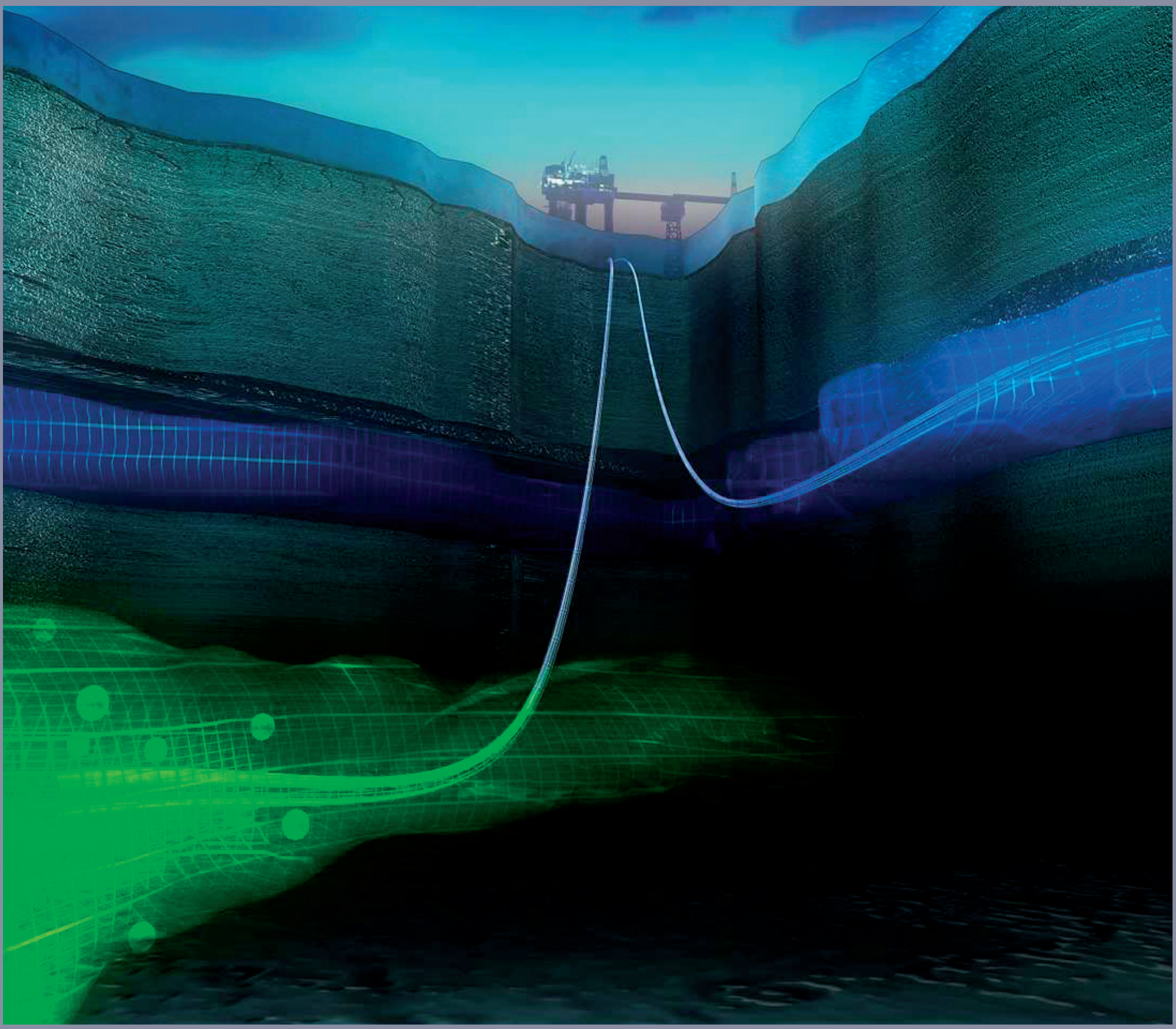
Carbon capture and storage



A seminar held on 5 December 2007 to discuss methods of sequestering carbon dioxide produced from burning fossil fuels as a means of countering global warming.

RSC Advancing the Chemical Sciences
IOP Institute of Physics
INSTITUTE of BIOLOGY

Carbon Capture and Storage

Introduction

There is increasing evidence that if carbon dioxide (CO_2) from human activity continues to be emitted into the atmosphere at current or higher levels, it will cause irreversible climate change. Both scientists and governments are now urgently exploring technological and political strategies to reduce CO_2 emissions by controlling energy use and developing alternative carbon-free energy sources. Even so, energy requirements, particularly in developing countries, are likely to grow and the world still has large reserves of fossil fuels, in particular coal, which future generations will want to exploit.

There is, however, one encouraging solution to controlling atmospheric CO_2 that would allow us to optimise the use of fossil fuels, and that is to collect and sequester the resulting emissions. A few facilities around the world already utilise carbon capture and storage (CCS) technologies, and further, highly ingenious ideas for CCS are now being developed.

The **Rt Hon Hilary Benn MP**, secretary of state for environment, food and rural affairs, described the UK government's plans to drive forward the implementation of CCS strategies both on a domestic and on a global scale. **Prof. Peter Styles**, director of the Research Institute for the Environment, Physical Sciences and Applied Mathematics at Keele University, explained the main methodologies for capturing and storing CO_2 in the ground.

Dr Carol Turley, a microbial ecologist at the Plymouth Marine Laboratory (PML), discussed whether CO_2 could be stored in or under the oceans and the potential role of marine microorganisms in capturing CO_2. Finally, **Prof. Klaus Lackner**, professor of geophysics at the Earth Engineering Center, Columbia University, US, looked at ways of implementing a zero-carbon emissions strategy using clean-coal power generation combined with CCS and schemes in which CO_2 is absorbed directly from the atmosphere.

Carbon Capture and Storage

Opening the seminar, Hilary Benn stated that there is a need to act urgently to prevent dangerous climate change. The *2007 World Energy Outlook,* [1] published by the International Energy Agency, predicts that if governments stick to existing policies, global energy-related emissions of CO_2 will increase by nearly 60% by 2030. If these trends continue then, according to the latest report of the Intergovernmental Panel on Climate Change,[2] by 2100 temperatures could rise by up to 6.4 °C and sea levels could rise by up to 60 cm, with devastating consequences for ecosystems, food and water supplies, and human habitation. The *Stern Review: the Economics of Climate Change* [3] reported that a consequence would be that the global GDP would decrease by at least 5%. In contrast, the costs of action to reduce greenhouse emissions to avoid the worst impacts of climate change could be limited to an annual 1% of global GDP.

UK government plans

Mr Benn explained that the UK government's Climate Change Bill[4] will enshrine, for the first time anywhere in the world, a legally binding long-term framework to cut CO_2 emissions and to adapt to climate change. The bill proposes targets to reduce CO_2, through action on both domestic and international fronts, by at least 60% by 2050 and by 26–32% by 2020 (using 1990 figures as the baseline). It introduces a system of five-year carbon budgets, which will provide certainty for investors, businesses and consumers about what it is that we need to do, said Mr Benn. The government will also create a Committee on Climate Change to provide advice about the pathway to the 2020 and 2050 targets, and will also consider whether the long-term target should be increased to 80%.

A major challenge is that, for many countries, coal will remain the cheapest and most readily available form of energy. Even by 2050, fossil fuels will still make up about half of all energy supplies, especially with increasing demand in China and India. In China alone last year, one new coal-fired power station was completed every four days, with coal-fired power generation capacity set to increase by nearly 900 GW by 2030. "If we are to have a chance of meeting our global climate energy goals, we have got to find ways of reducing CO_2 emitted into the atmosphere from the burning of these fuels, and CCS is currently the main technology that can deal with this," asserted Mr Benn.

To this end, the government has launched a competition for the UK's first commercial-scale demonstration of the full chain of capture, transport and storage in a power station. The UK is one of only three countries in the world to support such a commercial demonstration. It is also the only country to support post-combustion capture in a coal-fired station: a technology that has the greatest global relevance because it can be retrofitted to power plants already operating as well as those being planned.

The government will also back CCS technologies through its Environmental Transformation Fund, which includes a £35m programme for industry-led demonstrations for carbon-abatement technologies. The new £600m Energy Technologies Institute is considering CCS as one of its key themes.

Developing the right regulatory framework for managing the risks associated with the long-term storage of CO_2 is also an important ingredient. The government will continue to work with the EU on proposals for the regulation of and policy on CCS, together with the review of the EU Emission Trading Scheme Directive, where the UK will be looking to push for the inclusion of CCS to help to provide an incentive to operators to invest in CCS technology. "If we can show that CCS is technologically and commercially viable, we will also consider whether it should be made mandatory for all British fossil-fuel plants," said Mr Benn.

CCS needs to be deployed on a global scale if it is to be effective in reducing emissions. Mr Benn explained that the UK is leading the EU's near-zero emissions coal initiative in China, which is aimed at demonstrating the deployment of CCS, with the possibility of developing a similar project with India.

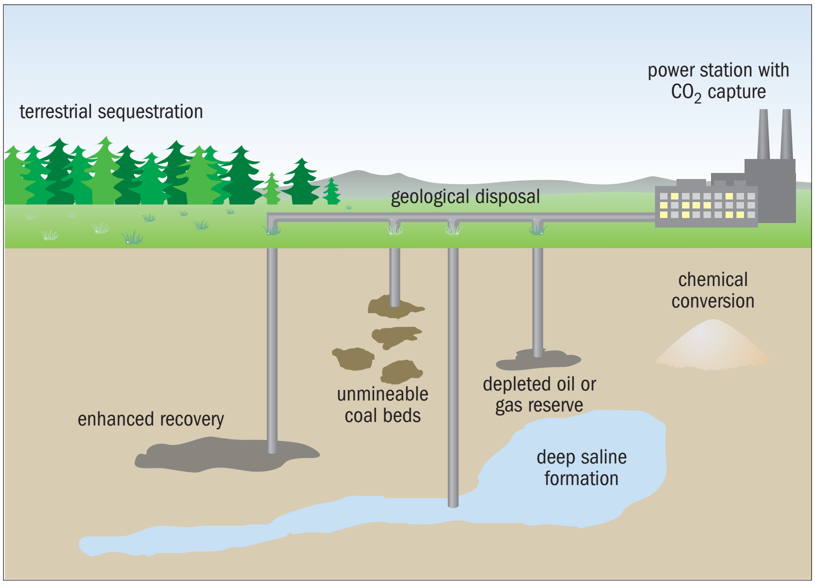
Finally, Mr Benn warned that the political choices would be uncomfortable and difficult: "The hardest political challenges are those which require you to act today in return for a long-term benefit long after any of us are still alive. But if we don't find the means to reduce emissions and deal with the risk, those generations that come after us will say to us: 'what on Earth were you thinking of, when you knew what was going on and you didn't do anything about it?' To me that is the scariest question of all. That is why we must act now and why CCS is absolutely vital."

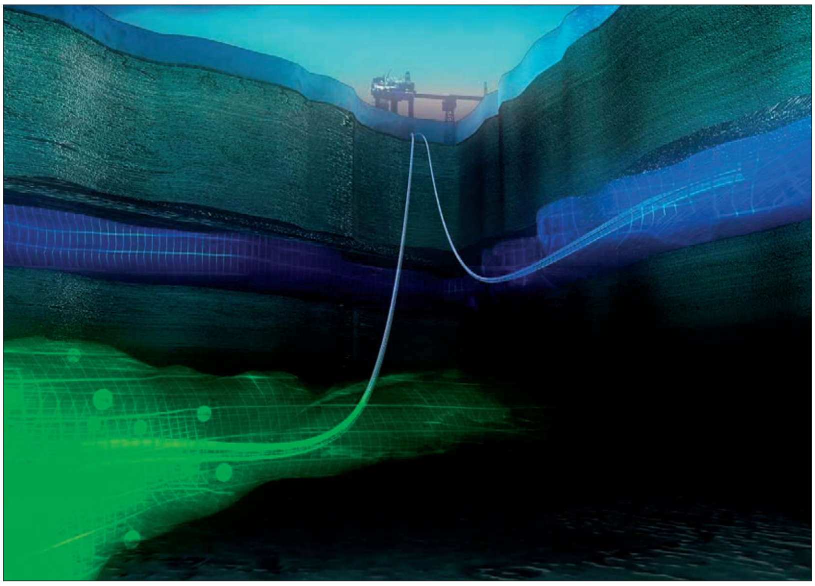
Geological sequestration of CO_2

Peter Styles outlined various approaches to sequestering CO_2 (figure 1). One solution is to store it in geological formations. Under the right conditions, they can trap fluid and gas for hundreds of millions of years, as is shown, of course, by the presence of huge, natural reservoirs of hydrocarbons in many areas of the world. In the past 30 years the technological advances associated with oil exploration, particularly in the North Sea, have meant that the geological conditions and extraction processes are well understood, explained Prof. Styles. North Sea gas can be pumped into, as well as out of, geological formations and is successfully stored in this way.

Figure 1 (top): Carbon sequestration options.

Figure 2 (bottom): At the Sleipner gas field in Norway, 1 million tonnes of CO_2 are buried every year. Courtesy: Statoil





Storage in ageing oilfields
Similarly, CO_2 can be stored by injecting it under pressure into ageing oilfields below 800 m, where it remains trapped as a dense, "supercritical" liquid. This approach has the advantage of forcing out the remaining oil (enhanced oil recovery). About 5 Gt (billion tonnes) of CO_2 could be stored in depleted oilfields (10 years' worth of current CO_2 emissions), with a further 11–15 Gt stored in depleted gas fields (30 years' worth), commented Prof. Styles.

Storage in unmineable coal seams
Unmineable coal seams are another possibility for storing CO_2, since coal readily binds CO_2 to its surface. The added bonus is that it would displace coal-bound methane, with twice the amount of CO_2 as methane being absorbed. The dispelled natural gas could then be collected and used as fuel.

Storage in saline aquifers
A favoured solution for the UK is to store CO_2 in deep porous sandstones and limestone which contain water that is too salty to use for drinking or agriculture. The pressurised CO_2 sits in the rock pores until it dissolves in the ground water, eventually sinking and precipitating out as solid mineral carbonates, thus locking up the CO_2 more permanently. This process has potential because 500 years of UK emissions could be stored within our aquifers, said Prof. Styles.

Statoil's Sleipner West field (figure 2) in the Norwegian North Sea[5] is the first commercial-scale operation for extracting and storing CO_2 from gas production. The CO_2 is pumped 1000 m underground into the Utsira sandstone formation. At the moment, 1 million tonnes are injected annually, but the company believes that the aquifer could accommodate 600 Gt, the entire inventory of emissions from European power stations for the foreseeable future, and it would be unlikely to leak out again for several hundred years.

Storage as mineral carbonates
Another approach is to bind CO_2 to minerals that naturally react with it, such as serpentinite (hydrated magnesium silicate), which then forms magnesite (magnesium carbonate). This happens during the weathering of rocks but is quite slow. To

be of industrial use, the process would have to be considerably speeded up through chemical engineering. Magnesium-rich minerals are to be found at many sites around the world where there has been volcanic activity.

Industrial use

Waste CO_2 can also be utilised industrially. The extraction of aluminium from its ore (bauxite) leaves behind an alkaline mixture of minerals that require storage. Treatment with CO_2 reduces the alkalinity, and the product can then be reused in building materials or for soil remediation. The world's leading aluminium producer, Alcoa,[6] says that its Kwinana carbonation plant will lock up 70 000 t of CO_2 a year in this way, the equivalent of taking more than 17 500 cars off the road.

Possible problems

CO_2 emissions are about 25 Gt a year worldwide. These options offer a storage capacity of up to 11 000 Gt. So what are the possible problems? Could the CO_2 could leak out? The same kind of testing and monitoring is needed as is applied to nuclear waste disposal, said Prof. Styles.

In oil-bearing rocks, the CO_2 should remain trapped in the pore spaces under layers of impermeable cap rocks (an impermeable layer sealing petroleum in the rocks below). In the case of sequestration in saline aquifers, results from a pilot test site in the Frio formation on the US Gulf Coast[7] have suggested that the carbonate could dissolve, creating pathways whereby CO_2 and brine could rise to the surface. The dissolution of minerals such as iron hydroxides could also mobilise any toxic trace metals present. Also being considered is whether large amounts of CO_2 could suddenly reach the surface and cause a toxic hazard.

Even if technological and environmental factors are favourable, the ultimate drivers for progress are economic. Statoil, Shell and BP have all pulled out of projects in the North Sea that employ enhanced oil recovery combined with CCS because the approach has proved to be not as economic as first thought. In the case of carbon sequestration in saline aquifers, the cost of capture and transport of CO_2 is significant and there is no added-value by-product to compensate for this.

In the future it seems likely that coal will provide the main source of energy, especially in the developing world. In the UK, for example, 30% of the land is underlain by coal and much more lies beneath the North Sea (figure 3). An important approach, therefore, will be to combine CCS with the production of gas fuels from coal. One method is enhanced coalbed methane production, whereby ground water is pumped out, releasing methane from the coal-bed in the process and allowing CO_2 to be pumped in (figure 4).

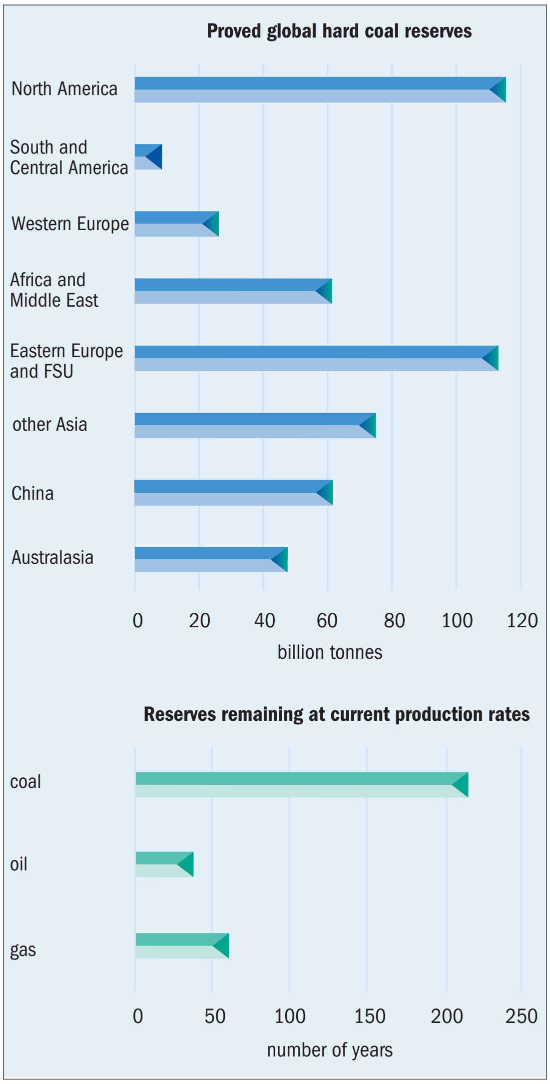
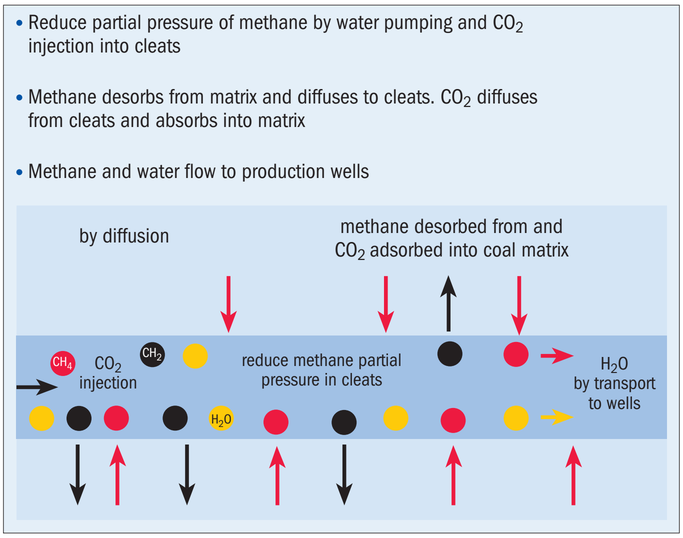
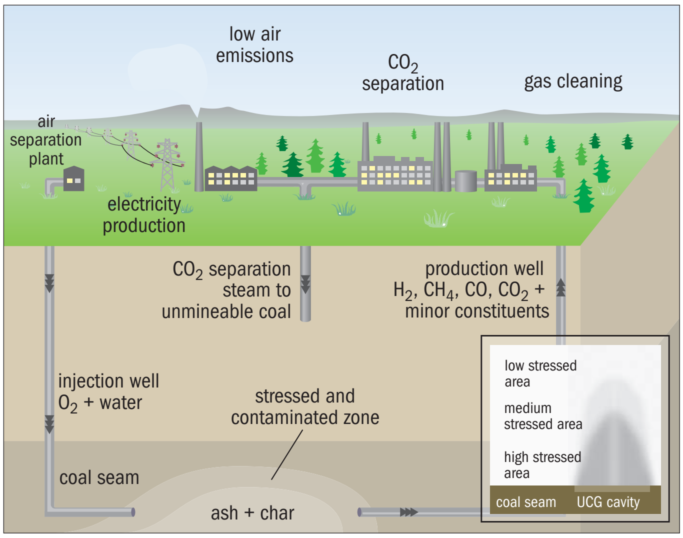


Figure 3: Coal will outlast oil by six to seven times, and gas by four times. Based on 2001 statistics from the World Coal Institute and BP Statistics.

Coal can also be burned underground in the presence of water and oxygen (underground coal gasification; figure 5) to produce syngas – a mixture of carbon monoxide, methane and hydrogen. The process increases rock permeability and allows more CO_2 to be captured and stored. "These methods need to be given much more prominence in terms of providing a global solution for future energy supplies," concluded Prof. Styles.





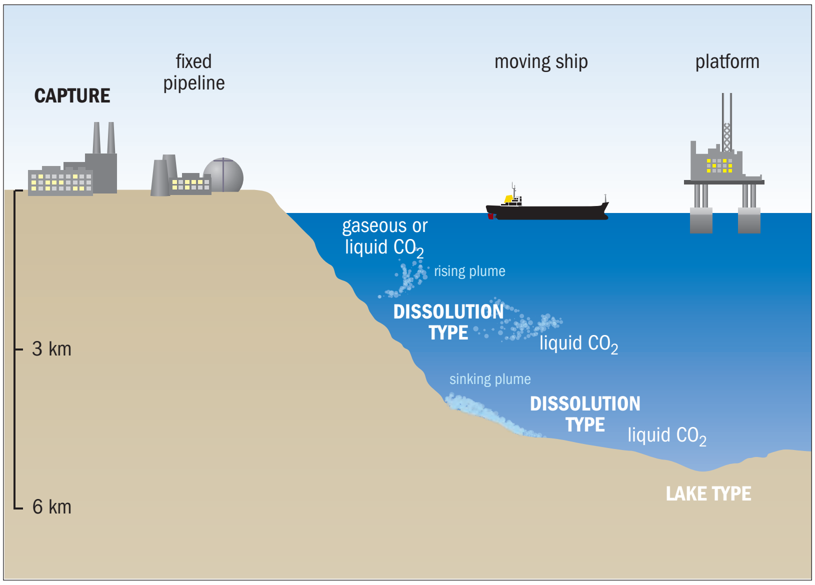


Figure 4 (top left): Enhanced coal-bed methane production by CO_2 injection. Courtesy: EPSAM

Figure 5 (top right): Underground coal gasification can and should be combined with the sequestration of CO_2 on coal seams. Courtesy: EPSAM

Figure 6 (bottom): Direct ocean sequestration of CO_2. Courtesy: EPSAM

Carbon capture and storage by oceans

Carol Turley described the marine options for carbon storage: " The world's oceans are a major CO_2 sink in the global carbon cycle. They have already taken up half of the CO_2 produced from the burning of fossil fuels over the past 200 years."

Storage in the oceans

One possibility is that CO_2 could be extracted from power plants and pumped directly into the ocean, to levels deep enough to liquefy it or form a solid hydrate (figure 6). The CO_2 would remain sequestered for several hundreds of years, before ocean circulation would bring it back to the surface. However, there are many unknowns, such as the length of time of sequestration, the amount retained and the effects on the ocean environment. Deep-ocean sequestration would change the local marine chemistry and harm deep-sea organisms, and it could eventually affect the whole ocean by increasing the acidity of the water. Recent plans to test the feasibility of ocean sequestration by carrying out experiments at sea have been dropped as a result of these environmental concerns.[8]

Storage under the oceans

Another possibility is to store CO_2 in geological formations under the sea. The geological strata below the North Sea potentially offer an enormous reservoir for sequestering CO_2. However, the waters above are enormously productive and any leaks could cause serious local damage to the marine ecosystem.

The continued uptake of increasing atmospheric CO_2 levels by the oceans will cause surface waters to acidify on a global scale, reducing calcification in organisms, affecting corals and shellfish, and potentially affecting the availability of nutrients, thereby reducing biodiversity and affecting food webs.[9,10] Indeed, studies by scientists at the PML indicate that the North Sea would suffer a substantial increase in ocean acidity far greater than what could occur in the event of a massive leak of the CO_2 sequestered in the rocks below. Nevertheless, although the geological storage of CO_2 seems like a good strategy, Dr Turley emphasised that it is also important to ensure that the risk of CO_2 leakage into the marine environment is minimised.

Microalgae and carbon capture

Ocean fertilisation

Marine microalgae (figure 7) play an important role in fixing carbon through photosynthesis and they are responsible for around 50% of the Earth's primary productivity of organic material. They are the earliest precursors to plant life and created the oil and gas reserves on the planet.

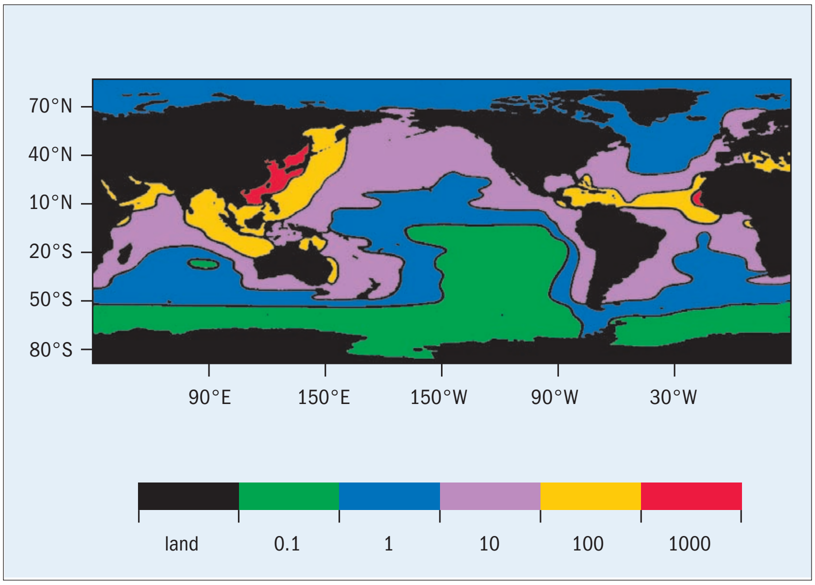
However, some areas of the globe, such as the southern oceans, have low concentrations of these phytoplankton, despite the availability of high levels of macronutrients. Their restricted growth is thought to result from low levels of iron, which is an important micronutrient. One suggestion based on this "iron hypothesis" is to seed the ocean with iron.[11] This would encourage these microorganisms to multiply, resulting in enhanced photosynthesis, and thus drawing down more of the CO_2 from the atmosphere into the oceans. Small, kilometre-scale experiments carried out at sea appear to support the idea of iron fertilisation (figure 8).

There are concerns, however, that iron fertilisation on an ocean scale could alter the food web and stimulate the release of other greenhouse gases, and it is not clear what the final carbon balance would be. A company called Climos would like to carry out larger-scale experiments to establish the wider environmental consequences and to see if CO_2 can be sequestered effectively in this way. Other proposed schemes involve delivering nitrogen into barren areas of the ocean to stimulate photosynthesis.

Ocean pumps

Another suggestion is to pump up nutrient-rich water from the ocean depths into nutrient-depleted regions so as to stimulate photosynthesis and thus fix more CO_2 (figure 9). The carbon-rich organic matter generated would then sink back into the deep ocean, thereby sequestering the CO_2. Again, there are concerns about the impact on ocean chemistry and ecosystems, as well as the effectiveness of this method for carbon sequestration.

All of these schemes require a much better understanding of the oceans and their delicate but crucial ecosystems, as well as raising a number of ethical questions.



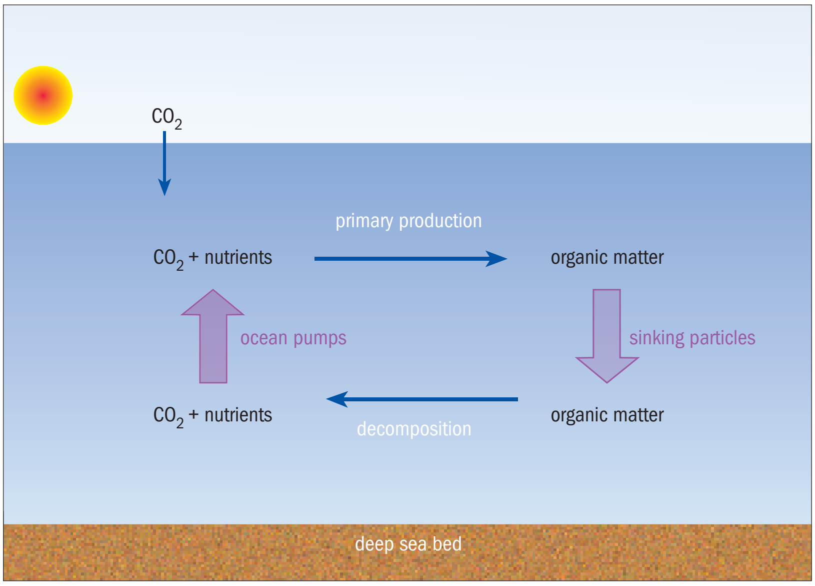


Figure 7 (top): Microalgae.

Figure 8 (centre): Global iron concentrations compared with nitrate and chlorophyll concentrations.

Figure 9 (bottom): Ocean pumps bring nutrient and CO_2-rich waters to the ocean surface.

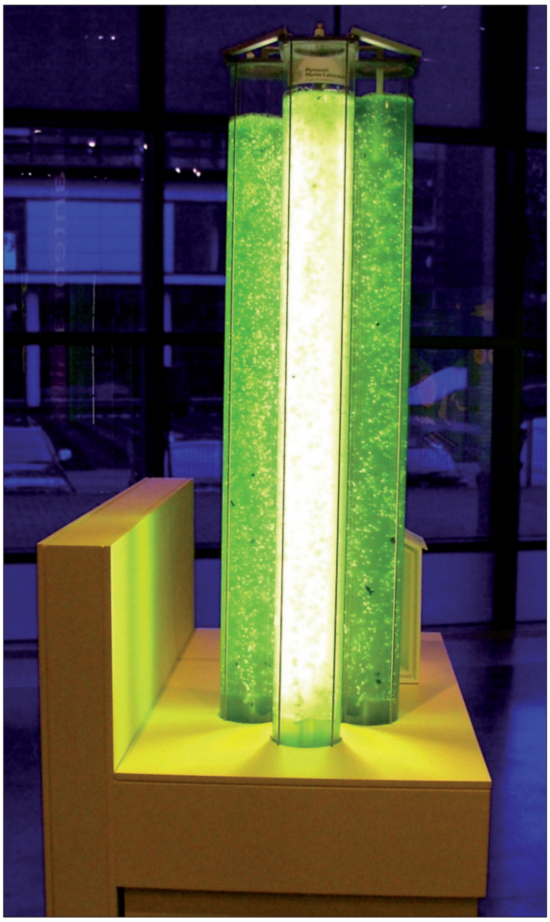


Figure 10 (left): A demonstration bioreactor. Courtesy: PML

Figure 11 (right): Marine algae collectively fix around half of the global primary production of CO_2. Courtesy: PML

Microalgae and bioreactors

A more practical, safer approach is to utilise microalgae directly in carbon capture[12] (figure 10). They have the highest carbon-fixation rate of any plants and can be grown on brown-field sites or even in desert areas, where biodiversity is not an issue and there is no competition with food crops. If grown in bioreactors, which can easily be scaled up, they can be linked to CO_2 outputs from power stations as part of a carbon-neutral scheme (figure 11). The technology can incorporate waste-water treatment and nutrient recycling as well, and the biomass produced can be used for fuel and other materials, according to Dr Turley.

Managing emissions from fossil energy resources

Klaus Lackner concluded the seminar by summarising the options for managing CO_2 emissions.[13] He pointed out that primary energy consumption will rise with economic growth, particularly in developing countries, and he emphasised that as of 1996 only 300 Gt of fossil carbon, out of an estimated 5000 Gt, had been consumed. While most of this carbon is in the form of coal, synthetic fuel can be produced economically via coal gasification, as demonstrated by the Sasol process used in South Africa. "These 5000 Gt will tempt our children and our grandchildren, so we have to figure out how to manage it," said Prof. Lackner. "The current patterns of energy use and CO_2 emissions will result in severe climate change and unacceptable ocean acidification. We cannot go there."

Prof. Lackner asserted that managing energy supplies for a much larger future world population of, say, 10 billion, requires us to aim at zero CO_2 emissions. This inevitably means safe and permanent disposal from small, distributed, mobile sources as well as large, concentrated sources, such as power plants.

While geological storage should be developed on larger scales, Prof. Lackner favoured sequestering CO_2 in mineral deposits, as it can be done safely and permanently above ground without concern over CO_2 leakage. However, this process is still expensive and needs to be speeded up.

Clean coal schemes

Before CO_2 is stored it has to be captured. Optimising a new generation of efficient and clean power plants that capture and deliver CO_2 for safe, permanent storage will promote dramatically different designs, said Prof. Lackner. The cost of CCS will favour highly-efficient power plants.

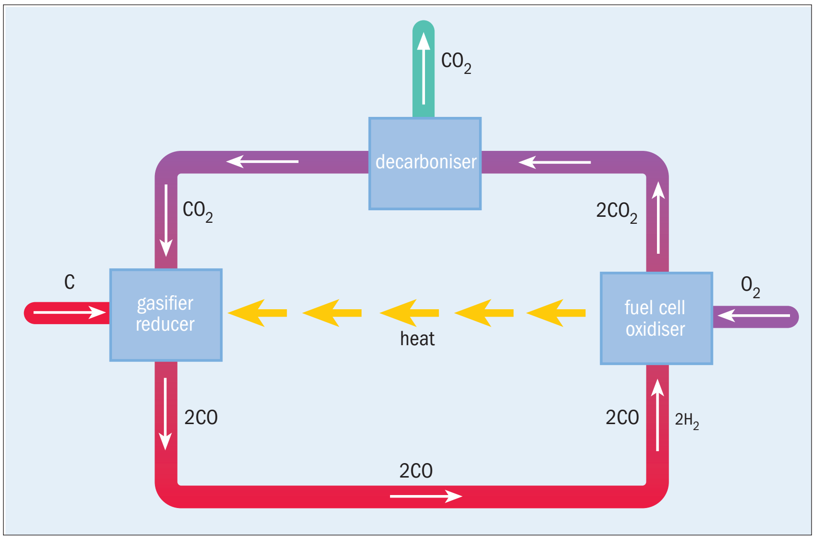
Today, oxyfuel combustion, which uses oxygen rather than air in coal combustion, and the integrated gasification combined cycle plant, which combines coal gasification with two power-generating cycles, could produce a concentrated stream of CO_2 that could easily be captured and sequestered.[14] Future concepts incorporating fuel cells could achieve extremely high-energy conversion efficiencies while also delivering CO_2 in a concentrated stream.

The well known Boudouard reaction (figure 12), in which carbon (coal) and CO_2 reversibly combine to form carbon monoxide, could be the basis of an efficient energy scheme. The carbon monoxide could be utilised in a solid-oxide fuel cell producing CO_2, of which half would be stored and the other half used to gasify more coal. The fuel cell would also deliver the heat required for gasification, thus raising the efficiency even further.

Removing atmospheric CO_2

A zero-emissions policy also requires schemes to remove CO_2 directly from the atmosphere, as liquid fossil fuels are likely to remain the energy source of choice for transport for the foreseeable future. Microalgae offer one solution, but another approach is to strip CO_2 directly out of the air using an absorbent such as calcium hydroxide. A device absorbing 3 kg of CO_2 per second would need to have a frontal area facing the wind of about 3000 sq. m, but it could take care of the emissions from 20 000 cars, said Prof. Lackner. This could be done for \$30 per tonne of CO_2 and would add 25 cents to the cost of a gallon of gasoline[15,16,17] (figures 13, 14).

Prof. Lackner suggested that air-capture technology would make it possible to create energy cycles using carbon-based fuels, even without fossil energy



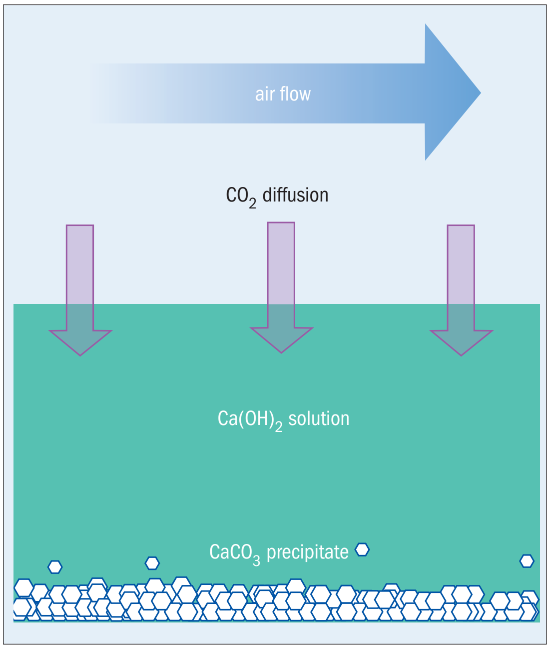


Figure 12 (top): The Boudouard reaction. Courtesy: Lenfest Centre for Sustainable Energy

Figure 13 (centre): CO_2 absorption using calcium hydroxide. Mass transfer of CO_2 is limited by diffusion in the air boundary layer.

Figure 14 (bottom): Global Research Technologies' prototype equipment will absorb 100 kg per day of atmospheric CO_2. Courtesy: Stonehaven CCS, Montreal

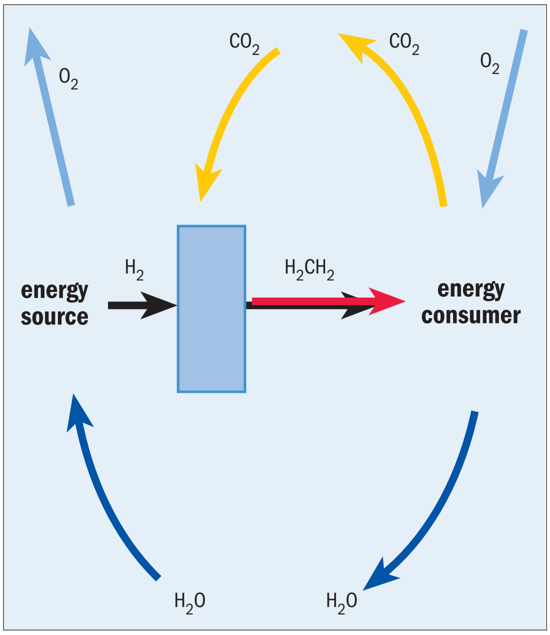


Figure 15: Materially closed energy cycles. Courtesy: Lenfest Centre for Sustainable Energy

sources. In such a scenario, energy is delivered as a liquid hydrocarbon fuel, which at the point of consumption is converted into CO_2 and water. The CO_2 is recaptured from the air, providing the material feedstock for fresh fuel that stores non-fossil energy (figure 15). It is possible to create highly efficient and environmentally friendly energy scenarios based on closed material cycles involving simple compounds of hydrogen, oxygen and carbon.

None of this will happen unless we have the institutional and policy means to make it happen, he concluded. "To go to a zero-carbon economy means that, as long as we use fossil fuels, for every tonne of carbon coming out of the ground, another tonne of CO_2 has to be sequestered." Prof. Lackner believes that the long-term answer is to issue certificates of carbon sequestration that could be traded as offsets against emissions.

References

1. World Energy Outlook 2007 *China and India Insights* (International Energy Authority) ISBN 978 9 2640 2730 5, www.worldenergyoutlook.org/2007.asp.
2. www.ipcc.ch/ipccreports/index.htm.
3. Nicholas Stern 2007 *The Stern Review: the Economics of Climate Change* (Cambridge University Press/ HMSO) ISBN 978 0 5217 0080 1, www.hm-treasury.gov.uk/media/4/3/Executive_Summary.pdf.
4. www.defra.gov.uk/corporate/consult/climatechange-bill.
5. www.statoil.com/statoilcom/svg00990.nsf/web/sleipneren?opendocument.
6. www.alcoa.com/australia/en/info_page/pots_rd.asp.
7. www.fossil.energy.gov/news/techlines/2004/tl_frio_injection.html.
8. H J Schellnhuber, W Cramer, N Nakicenovic , T Wigley and G Yohe (eds) 2006 *Avoiding Dangerous Climate Change* (Cambridge University Press).
9. P M Haugan, C Turley and H O Poertner 2006 Effects on the marine environment of ocean acidification resulting from elevated levels of CO_2 in the atmosphere *DN-utredning* **1** 1.
10. J Raven *et al* 2006 Ocean acidification due to increasing atmospheric carbon dioxide *The Royal Society Policy Document 12/05* p68.
11. D J Cooper, A J Watson and P D Nightingale 1996 Large decrease in ocean-surface CO_2 fugacity in response to *in situ* iron fertilization *Nature* **383** 511.
12. B Hankamer *et al* 2007 Photosynthetic biomass and H_2 production by green algae: from bioengineering to bioreactor scale-up *Physiologia Plantarum* **131** 10.
13. The Lenfest Center for Sustainable Energy, www.energy.columbia.edu/carbon-management.
14. http://en.wikipedia.org/wiki/Integrated_Gasification_Combined_Cycle.
15. K Lackner, P Grimes and H J-Ziock Capturing carbon dioxide from air, www.netl.doe.gov/publications/proceedings/01/carbon_seq/7b1.pdf.
16. K Lackner, H J-Ziock and P Grimes The case for carbon dioxide extraction from air, www.americanenergyindependence.com/Reddy8.pdf.
17. Global Research Technologies, www.grestech.com.

About the societies

The Institute of Physics is a scientific membership organisation devoted to increasing the understanding and application of physics. It has an extensive worldwide membership and is a leading communicator of physics with all audiences, from specialists through government to the general public. Its publishing company, IOP Publishing, is a world leader in scientific publishing and the electronic dissemination of physics.

The Royal Society of Chemistry is the largest organisation in Europe for the advancement of the chemical sciences. Supported by a network of more than 43 000 members worldwide and an internationally acclaimed publishing business, its activities span education, training, conferences and science policy, and the promotion of the chemical sciences to the public.

The Institute of Biology is the professional body for UK biologists. Its members work in industry, research, education and healthcare, among other areas. It was founded in 1950, obtained a Royal Charter in 1979 and is a registered charity with more than 13 000 members and more than 40 affiliated societies, covering every area of the biosciences.

Carbon capture and storage

A seminar organised by the Institute of Physics,
the Royal Society of Chemistry and the Institute of Biology

For further information, or a large-print version, please contact:

Rosie Davies
Institute of Physics
76 Portland Place
London W1B 1NT UK
Tel +44 (0) 20 7470 4800
Fax +44 (0) 20 7470 4848
E-mail rosie.davies@iop.org
Web **www.iop.org**
Registered charity no. 293851