False Hope

Why carbon capture and storage won't save the climate

greenpeace.org

Catalysing an energy revolution

For more information contact:
enquiries@int.greenpeace.org

Lead Author: Emily Rochon
Editor: Jo Kuper
Contributing Authors: Dr Erika Bjureby,
Dr Paul Johnston, Robin Oakley,
Dr David Santillo, Nina Schulz,
Dr Gabriela von Goerne

Printed on 100% recycled
post-consumer waste with
vegetable based inks.

JN 136

Published in May 2008
by Greenpeace International
Ottho Heldringstraat 5
1066 AZ Amsterdam
The Netherlands
Tel: +31 20 7182000
Fax: +31 20 5148151

greenpeace.org

Design: **neo**
Communications for Positive Change
www.neocreative.co.uk

cover image Cogeneration
electric power generation site near
Midland, Pennsylvania, USA.

©GREENPEACE / R VISSER

image Smokestacks from
LTV Steel Co with Cleveland,
Ohio, USA.

©GREENPEACE / R VISSER

Contents

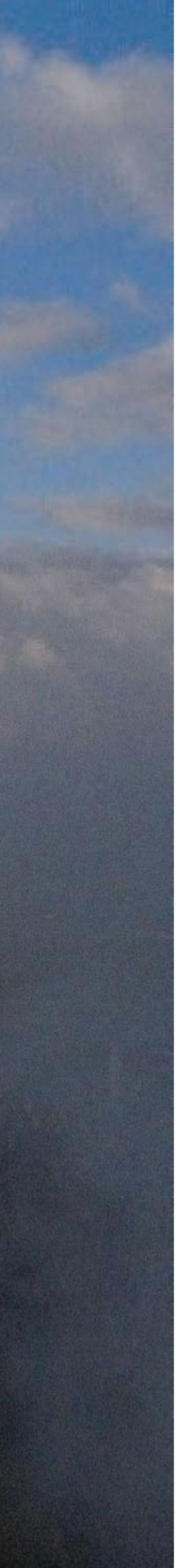
Sections

List of tables

List of figures

image View of Prunerov coal-fired power plant, Czech Republic. One of the many sites where Greenpeace has staged climate change protests.

©GREENPEACE / K DAVISON



1

Executive summary

Carbon capture and storage (CCS) aims to reduce the climate impact of burning fossil fuels by capturing carbon dioxide (CO_2) from power station smokestacks and disposing of it underground. Its future development has been widely promoted by the coal industry as a justification for the construction of new coal-fired power plants. However, the technology is largely unproven and will not be ready in time to save the climate.

This report, based on peer-reviewed independent scientific research shows that:

CCS cannot deliver in time to avoid dangerous climate change. The earliest possibility for deployment of CCS at utility scale is not expected before 2030.[1] To avoid the worst impacts of climate change, global greenhouse gas emissions have to start falling after 2015, just seven years away.

CCS wastes energy. The technology uses between 10 and 40% of the energy produced by a power station.[2] Wide scale adoption of CCS is expected to erase the efficiency gains of the last 50 years, and increase resource consumption by one third.[3]

Storing carbon underground is risky. Safe and permanent storage of CO_2 cannot be guaranteed. Even very low leakage rates could undermine any climate mitigation efforts.

CCS is expensive. It could lead to a doubling of plant costs, and an electricity price increase of 21-91%.[4] Money spent on CCS will divert investments away from sustainable solutions to climate change.

CCS carries significant liability risks. It poses a threat to health, ecosystems and the climate. It is unclear how severe these risks will be.

The climate crisis requires urgent action. Climate scientists warn that to avoid the worst effects, global greenhouse gas emissions must peak by 2015 and then start falling by at least 50% by 2050, compared to 1990 levels. Coal is the most polluting of all fossil fuels, and the single greatest threat to the climate. If current plans to invest hundreds of billions of dollars in coal plants are realised, CO_2 emissions from coal could increase 60% by 2030.

Concerns about the feasibility, costs, safety, and liability of CCS make it a dangerous gamble. A survey of 1000 “climate decision-makers and influencers” around the world reveals substantial doubt in the ability of CCS to deliver. Just 34% were confident that retrofitting ‘clean coal technology’ to existing power plants could reduce CO_2 emissions over the next 25 years without unacceptable side effects, and only 36% were confident in its ability to deliver low-carbon energy from new power stations.[5]

The real solutions to stopping dangerous climate change lie in renewable energy and energy efficiency that can start protecting the climate today. Huge reductions in energy demand are possible with efficiency measures that save more money than they cost to implement. Technically accessible renewable energy sources – such as wind, wave and solar- are capable of providing six times more energy than the world currently consumes – forever.

> **“CCS will arrive on the battlefield far too late to help the world avoid dangerous climate change.”[7]**

Greenpeace’s Energy [R]evolution[6] provides a practical blueprint that shows how renewable energy, combined with greater energy efficiency, can cut global CO_2 emissions by almost 50%, and deliver half the world’s energy needs by 2050.

What is CCS?

CCS is an integrated process, made up of three distinct parts: carbon capture, transport, and storage (including measurement, monitoring and verification).

Capture technology aims to produce a concentrated stream of CO_2 that can be compressed, transported, and stored. Transport of captured CO_2 to storage locations is most likely to be via pipeline.

Storage of the captured carbon is the final part of the process. The vast majority of CO_2 storage is expected to occur in geological sites on land, or below the seabed. Disposing of waste CO_2 in the ocean has also been proposed but this method has been largely discounted due to the significant impacts CO_2 would have on the ocean ecosystem and legal constraints that effectively prohibit it.

CCS cannot deliver in time

The urgency of the climate crisis means solutions must be ready for large-scale use as soon as possible. CCS simply cannot deliver in time. As the United Nations Development Programme (UNDP) says “CCS will arrive on the battlefield far too late to help the world avoid dangerous climate change”[8] At present, there are no large-scale coal-fired power plants in the world capturing carbon, let alone any that are integrated with storage operations.[9]

The earliest CCS may be technically feasible at utility scale is 2030.[10] The Intergovernmental Panel on Climate Change (IPCC) does not expect CCS to become commercially viable until at least the second half of this century.[11] Even then, plants responsible for 40-70% of electricity sector CO2 emissions will not be suitable for carbon capture’.[12]

Despite this, CCS is being used as an excuse by power companies and utilities to push ahead with plans to build new coal-fired power plants; branding them “capture-ready.” The International Energy Agency (IEA) describes a “capture-ready” plant as one “which can be retrofitted with CO_2 capture when the necessary regulatory or economic drivers are in place”.[13] This definition is broad enough to make any station theoretically “capture-ready”, and the term meaningless.

The very real danger of “capture-ready” power stations is that promises to retrofit are unlikely to be kept. Retrofits are very expensive and can carry such high efficiency losses that plants become uneconomic.[14] Furthermore, even if a plant is technically suitable for carbon capture there is no guarantee that there will be accessible storage locations.

In the UK, a proposed new coal-fired power plant at Kingsnorth, Kent, is being sold as “capture ready”; able to incorporate CCS should the technology ever become available in the future. However, no one has any idea if and when this might be. In the meantime, and possibly for its entire lifetime, Kingsnorth (if built) will pump out around 8 million tonnes of CO_2 per year, an amount equivalent to the total annual CO_2 emissions of Ghana.[15]

If CCS is ever able to deliver at all, it will be too little, too late.

CCS wastes energy

Capturing and storing carbon uses lots of energy, anywhere from 10-40% of a power station’s capacity.[16] An energy penalty of just 20% would require the construction of an extra power station for every four built.[17]

These reductions in efficiency will require more coal to be mined, transported, and burned, for a power station to produce the same amount of energy as it did without CCS.

CCS will also use more precious resources. Power stations with capture technology will need 90% more freshwater than those without. This will worsen water shortages, already aggravated by climate change.[18] Overall, wide-scale adoption of CCS is expected to erase the efficiency gains of the last 50 years, and increase resource consumption by one third.[19]

Storing carbon underground is risky

The IEA estimates that for CCS to deliver any meaningful climate mitigation effects by 2050, 6000 projects each injecting a million tonnes of CO_2 per year into the ground would be required.[20] At the moment, it is not clear that it will be technically feasible to capture and bury this much carbon, i.e. whether there are enough storage sites, or that they will be located close enough to power plants. Transport of CO_2 over distances greater than 100 kilometres is likely to be prohibitively expensive.[21]

©GREENPEACE / S YASHWANT

image Smoke stacks of the lignite (brown coal) fuelled Mae Moh power plant discharging smoke, Mae Moh, Lampang province Thailand.

Efforts to capture CO_2 make no sense if there is not adequate accessible space to store it permanently. Even if it is feasible to bury hundreds of thousands of gigatonnes of CO_2 there is no way to guarantee that storage locations will be appropriately designed and managed over the timescales required.

As long as CO_2 is in geological sites, there is a risk of leakage. While it is not currently possible to quantify the exact risks, any CO_2 release has the potential to impact the surrounding environment; air, groundwater or soil. Continuous leakage, even at rates as low as 1%, could negate climate mitigation efforts.[22] Remediation may be possible for CO_2 leaks, but there is no track record or cost estimates for these measures.[23]

A natural example of the danger of CO_2 leakage occurred at Lake Nyos, Cameroon in 1986. Following a volcanic eruption, large quantities of CO_2 that had accumulated on the bottom of the lake were suddenly release, killing 1700 people and thousands of cattle over a range of 25 km.[24]

CCS is expensive and undermines funding for sustainable solutions

While cost estimates for CCS vary considerably, one thing is certain – it is extremely expensive.

CCS will require significant funding to construct the power station and necessary infrastructure to transport and store carbon. Existing policy mechanisms, such as a price on carbon, would need to be significantly increased (by as much as five times higher than their current levels) and supplemented by additional policy commitments and financial incentives.[25]

The US Department of Energy (US DOE) calculates that installing carbon capture systems will almost double plant costs.[26] This will lead to electricity price hikes of anywhere between 21 and 91%.[27]

Providing the substantial levels of support needed to get CCS off the ground comes at the expense of real solutions. Current research shows electricity generated from coal-fired power stations equipped with CCS will be more expensive than other less-polluting sources, such as wind power and many types of sustainable biomass.[28]

In recent years, coal's share of research and development budgets in countries pursuing CCS has ballooned. Meanwhile, funding for renewable technologies and efficiency has stagnated or declined.

In the US, the Department of Energy has asked for a 26.4% budget increase for CCS-related programmes (to US$623.6 million) while at the same time scaling back renewable energy and efficiency research by 27.1% (to US$146.2 million). [29] Australia has three research centres for fossil fuels, including one committed to CCS; there is not one for renewable energy technology.[30] The Norwegian government recently committed 20 billion NOK (US$4 billion) for two CCS projects at the expense of investment in renewable technologies.

Spending money on CSS is diverting urgent funding away from renewable energy solutions for the climate crisis. Even assuming that at some stage carbon capture becomes technically feasible, commercially viable, capable of long-term storage and environmentally safe, it would still only have a limited impact and would come at a high cost. In contrast, as Greenpeace's Futu[r]e Investment report shows, investing in a renewable energy future would save US$180 billion annually and cut CO_2 emissions in half by 2050.[31]

CCS and liability: risky business

Large-scale applications of CCS pose significant liability risks, including negative health effects and damage to ecosystems, groundwater contamination including pollution of drinking water, and increased greenhouse gas emissions resulting from leakage. There is no reliable basis for estimating the probability or severity of these risks. As current regulations are not designed to adequately manage them, significant questions as to who is liable remain unanswered [32]

Industry views liability as a barrier to wider deployment of CCS[33] and is unwilling to fully invest in CCS without a framework that protects it from long-term liability. The risk is so great that some utilities are unwilling to make CO_2 available for storage unless they are relieved of ownership upon transfer of the CO_2 off the property of the power station.[34] Potential operators are urging that they only retain legal liability for permanently stored carbon for ten years.[35]

A survey of 1000 "climate decision-makers and influencers" around the world reveals substantial doubt about CCS. Just 34% were confident that retrofitting 'clean coal technology' could reduce CO_2 emissions over the next 25 years without unacceptable side effects, and only 36% were confident in its ability to deliver low carbon energy with new power stations. In contrast, 74% expressed confidence in solar hot water, 62% in offshore wind farms, and 60% in onshore wind farms.[36]

CCS proponents are demanding almost complete legal protection from governments, including mechanisms that completely shield operators from legal challenges, transfer ownership to government and/or limit the amount of money that can be recouped should damage occur.[37] It is expected that the public will assume the risk for, and pay for the damages resulting from, CO_2 storage projects.

The extent of support offered to the recently collapsed FutureGen project in the US gives some idea of the real costs of CCS. FutureGen was the Bush Administration's flagship CCS project, a public-private partnership between the US government and industry giants including Rio Tinto and American Electric Power Service Corp. FutureGen not only was promised unprecedented public funds (to the tune of US$1.3 billion) but was also protected from financial and legal liability in the event of an unanticipated release of carbon dioxide,[38] indemnified from lawsuits, and even had its insurance policies paid for.[39]

The world already has the solutions to the climate crisis

Investment in CCS risks locking the world into an energy future that fails to save the climate. Those technologies with the greatest potential to provide energy security and reduce emissions, and to provide renewable energy and energy efficiency, need to be prioritised.

Greenpeace's Energy [R]evolution blueprint shows how renewable energy, combined with greater energy efficiency, can cut global CO_2 emissions by almost 50%, and deliver half the world's energy needs by 2050.[40]

The renewable energy market is booming; in 2007, global annual investment in renewables exceeded US$100 billion.[41] Decades of technological progress have seen renewable energy technologies such as wind turbines, solar photovoltaic panels, biomass power plants and solar thermal collectors move steadily into the mainstream. The same climate decision-makers who were sceptical about CCS believed far more in the ability of renewable technologies to deliver reductions in greenhouse gas emissions: 74% expressed confidence in solar hot water, 62% in offshore wind farms, and 60% in onshore wind farms.[42]

Many nations have recognised the potential of these true climate solutions and are pressing ahead with ambitious plans for energy revolutions within their borders. New Zealand plans to achieve carbon neutrality by mid-century. Renewable energy and energy efficiency, not CCS, are leading the way. New Zealand already obtains 70% of its electricity from renewable resources and aims to increase it to 90% by 2025.[43] In Germany, renewable energy use has increased 300% in the past 10 years. In the US, over 5,200 megawatts (MW) of wind energy were installed in 2007, accounting for 30% of new power installed that year; an increase of 45% in one year.[44]

The urgency of the climate crisis means solutions must be ready for large-scale deployment in the short-term. CCS simply cannot deliver in time. The technology is highly speculative, risky and unlikely to be technically feasible in the next twenty years. Letting CCS be used as a smokescreen for building new coal-fired power stations is unacceptable and irresponsible. "Capture ready" coal plants pose a significant threat to the climate.

The world can fight climate change but only if it reduces its dependence on fossil fuels, particularly coal. Renewable energy and energy efficiency are safe, cost-effective solutions that carry none of the risks of CCS, and are available today to cut emissions and save the climate.

2

Introduction

This report starts by giving a technical introduction to carbon capture and storage, explaining the process as well as the system components. It then details why CCS technology will not be ready in time to save the climate and also explains how CCS being used as a smokescreen to get the green light to build new coal-fired power plants. It then moves on to look at how CCS technology actually wastes energy by making power plants less efficient.

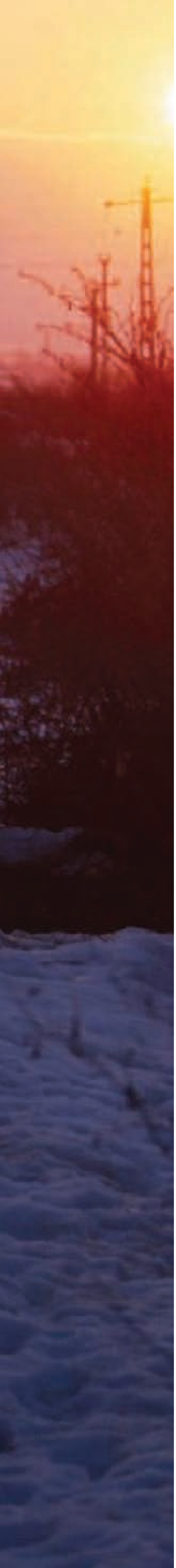
Next, the report considers the substantial challenges related to storing massive quantities of CO_2 underground and the fact that safe and permanent storage cannot be guaranteed, as well as the many risks posed by CO_2 leakage. After this, the report details how large-scale applications of CCS are prohibitively expensive and threaten to undermine investments in renewable energy and energy efficiency measures urgently needed to save the climate.

The report then considers the significant environmental, economic, legal, political, technological and sustainability risks associated with CCS. It details how current regulations are not designed to adequately manage these, leaving unanswered significant questions as to who is liable.

Finally, the report outlines how the world already has the real solutions to the climate crisis. Greenpeace's Energy [R]evolution provides a practical blueprint that shows how renewable energy combined with greater energy efficiency can cut global CO_2 emissions by almost 50%, and deliver half the world's energy by 2050.[45]

image Pipeline network in Romania.

©GREENPEACE / J HODSON



3

CCS technically speaking

The following review is by no means exhaustive, but is intended to provide a general understanding of the different stages of carbon capture, transport and storage, as well as the system components.

CCS aims to capture carbon dioxide resulting from various combustion and industrial processes, and store it underground or below the sea floor. Its application is proposed for large point sources of CO_2, such as fossil fuel power stations.

As an integrated process, CCS consists of three distinct components: carbon capture, transport and storage (including measurement, monitoring and verification). These components are explained in greater detail below.

Capture

By far the most energy intensive portion of the CCS process, carbon capture produces a concentrated stream of CO_2 that can be compressed, transported, and eventually stored. Depending on the process or power station in question, three approaches to capture exist; pre-combustion, post-combustion and oxyfuel combustion. Pre- and post-combustion capture rates are typically between 85-95% of the CO_2 emitted, while oxyfuel combustion capture rates are nearer to 98%.[46]

Pre-combustion capture systems remove CO_2 prior to combustion. This is accomplished via gasification. Gasification of fossil fuels produces a “synthesis gas” (syngas), which is primarily a mixture of carbon monoxide, methane and hydrogen. Before combustion, the syngas is reacted with steam to produce CO_2 that is then scrubbed from the gas stream, usually by a physical or chemical absorption process.[47] Pre-combustion systems are not a mature market technology but are intended for deployment in conjunction with Integrated Gasification and Combined Cycle (IGCC) power stations. However, significant engineering challenges need to be overcome before large-scale integration of coal-based IGCC and CCS can occur.[48]

Post-combustion techniques are the standard practice for removing pollutants, such as sulphur, from the flue gas of coal-fired power stations. Flue gas typically contains up to 14% CO_2, which must be separated either through absorption (chemical or physical), cryogenics or membrane technologies. For CO_2 capture, chemical absorption with amines, such as monoethanolamine (MEA), is currently the process of choice.[49] Once recovered, the CO_2 is cooled, dried and compressed for transport. Post-combustion systems are promoted as a possible carbon mitigation solution for existing coal-fired power plants worldwide.

"There is no operational experience with carbon capture from coal plants and certainly not with an integrated sequestration operation."[50] It is believed that the earliest CCS might become feasible is 2030.[51]

Oxyfuel combustion burns fossil fuels in 95% pure oxygen instead of air. This results in a flue gas with high CO_2 concentrations (greater than 80%) that can be condensed and compressed for transport and storage. Substantial issues relating to controlling combustion and the cost of producing oxygen must be overcome before this technology is viable.[52] To date, this form of carbon capture has only been demonstrated at laboratory and pilot scale (up to 3 MW).[53]

Transport

Once CO_2 has been captured, it needs to be transported to a storage location. Options for moving the gas from one location to another include pipelines, ships, rail and road transport. Cost considerations and proximity to water bodies leaves pipelines as the likely choice for most CCS operations.[54]

Transporting carbon dioxide via pipelines requires compression of the gas to a supercritical (dense) or liquid state to reduce its volume. It also requires a dry, pure stream of CO_2 to reduce the risk of pipeline corrosion. Though mixed wet streams of CO_2 can be transported they may require the use of corrosion-resistant steel, which is more expensive than the materials typically used.[55] The dangers associated with transporting CO_2 are relatively low as it is neither flammable nor explosive. However, CO_2 is denser than air and tends to pool in low-lying, poorly ventilated areas posing a hazard to human health if it reaches concentration levels higher than 3% by volume.[56]

Pipeline transport of CO_2 is currently used in the US. Over 2500 km of CO_2 pipelines exist in the western half of the country where 50 million tons[57] (Mt)CO_2/yr (an amount equivalent to the annual output of about sixteen 500 MW coal-fired power stations) is carried to enhanced oil recovery (EOR) projects in west Texas and elsewhere.[58] Currently, no such infrastructure exists in Europe.[59] The construction of a dedicated network of pipelines for the movement of CO_2 from power stations to disposal sites is likely to require a considerable outlay of capital.[60]

Storage

The final component of CCS is storage, i.e. the long-term isolation of CO_2 from the atmosphere. A number of "storage options" and associated techniques are in different stages of research and development. They include methods for ocean and geological storage. As well as the actual physical storage of CO_2 in these locations, the subsequent measuring, monitoring and verification processes needed to ensure that the integrity of the storage site is maintained are under development.

Ocean storage is the disposal of CO_2 into the water column or at the seabed in deep waters. However, major concerns regarding both the efficacy and direct adverse impacts around the injection site means this approach is now largely discredited.

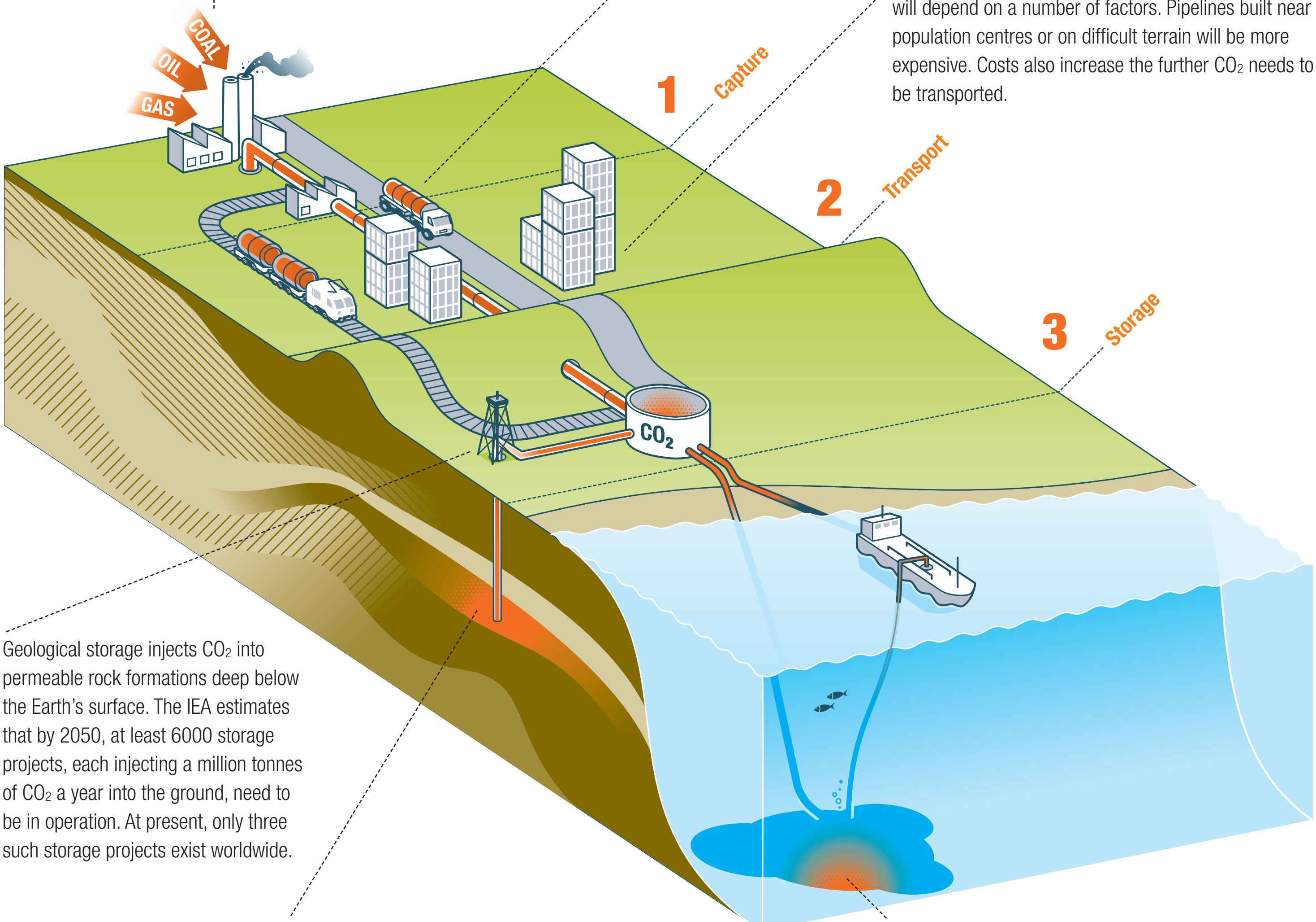
There is no question that oceans serve as natural carbon sinks; CO_2 in the atmosphere gradually dissolves into ocean surface waters until an equilibrium is reached. Oceans have absorbed about 500 gigatonnes (Gt) CO_2 of the total 1,300 GtCO_2 emitted by human processes in the past 200 years.[61] Proponents of ocean storage of CO_2 seek to "accelerate" this natural process by injecting CO_2 directly into the water or directly on the ocean floor via pipelines. However, the storage is not permanent. Once in the ocean, the CO_2 eventually dissolves, disperses and returns to the atmosphere as part of the global carbon cycle. Some computer models estimate that injected CO_2 would be isolated from the atmosphere for several hundred years at most, with the length of storage dependent on injection depth.[62]

In addition to lack of permanency, there are many other substantial concerns with ocean storage. CO_2 stored in this way cannot be easily monitored or controlled and negative impacts on the ocean environment due to acidification and other changes in ocean chemistry are unavoidable.[63] Ocean storage remains in research stages, and has not yet been deployed or demonstrated even at pilot scale.[64] International legal instruments, such as the London Protocol[65] and OSPAR Convention, already effectively prohibit it.

©GREENPEACE / M LODEWIJKX

image Oil spill and pipelines in Nizhnevartovsk, West-Siberia

Carbon capture and storage at a glance



Carbon capture is the most energy-intensive part of the process. Carbon capture systems have yet to be applied to a single utility scale coal-fired power station anywhere in the world. Costs for installation are estimated to result in a near doubling of plant costs. Retrofits could be even more costly.

CO_2 can be transported to a storage location via pipelines, ships, rail or road transport. Cost considerations and proximity to water bodies leaves pipelines as the likely choice for most CCS operations.

The construction of a network of pipelines for CCS is likely to require a considerable outlay of capital. Costs will depend on a number of factors. Pipelines built near population centres or on difficult terrain will be more expensive. Costs also increase the further CO_2 needs to be transported.

Geological storage injects CO_2 into permeable rock formations deep below the Earth's surface. The IEA estimates that by 2050, at least 6000 storage projects, each injecting a million tonnes of CO_2 a year into the ground, need to be in operation. At present, only three such storage projects exist worldwide.

It is not currently possible to quantify the exact risk of leakage, however any CO_2 release has the potential to impact the surrounding environment; air, groundwater or soil. A leakage rate as low as 1% could undermine any climate benefit of CCS.

Ocean storage of CO_2 has largely been ruled out due to unavoidable negative impacts on the ocean environment from acidification and other changes in ocean chemistry.

Assuming that commercial viability is reached, scenario studies indicate that by 2050 only 20-40% of global fossil fuel CO_2 emissions could be technically suitable for capture. This includes 30-60% of emissions from the power sector.[66] Therefore, up to 70% of emissions from electricity generation in 2050 may not even be technically suited to CCS.

Geological storage involves the injection of CO_2 into permeable rock formations sealed by impermeable, dense rock units (cap rocks) more than 800 metres below the Earth's surface. In practical terms, both onshore and offshore sedimentary formations can serve as repositories. Geological storage involves a combination of physical and geochemical trapping mechanisms (see Table 1). One of these mechanisms involves trapping of CO_2 as precipitates or in adsorbed phases via reactions with aquifer solids. This process, known as mineral trapping, is slow, and continues over long time frames compared to solubility trapping (see Figure 1). In this case, the mechanism of storage involves dissolution or mixing of CO_2 with formation water. When CO_2 is pumped into a reservoir it also displaces formation water. The exact chemical processes involved depend on both the rock formation and the purity of the CO_2 stream.

The four types of geological sinks that have received the most attention are: deep saline aquifers, depleted oil and gas reservoirs, enhanced oil recovery and deep coal seams.

- **Deep saline aquifers** are porous rock and contain very saline water. Their depth and high concentrations of solids means they hold little economic value, therefore they are considered appealing storage locations. Capacity estimates are highly uncertain but most assume a technical storage potential of at least 1000 Gt of CO_2.[67] The major obstacle to full exploitation of this storage option is demonstrating that safety and environmental protection can be assured.[68]

  Since 1996, a deep saline storage project, Sleipner, has operated off the coast of Norway, in the North Sea. Sleipner is a non-power application of carbon storage that strips CO_2 from natural gas as it is brought up from the sea floor and re-injects it into a deep saline reservoir, known as the Utsira sandstone formation. The injection rate for this project is approximately 1 Mt CO_2 per year,[69] an amount equal to the CO_2 emissions from a typical 150 MW coal-fired power station in the US.[70]

- **Depleted oil and gas reservoirs** have a combination of water and hydrocarbons in their pore spaces as not all oil and gas can be recovered during exploitation. These reservoirs are probably the best characterised of all available storage options. The IPCC Special Report on CCS estimates that the technical potential for storage in these reservoirs ranges from 675 to 900 $GtCO_2$.[71]

- **Enhanced oil recovery** involves injecting CO_2 into geological formations to achieve greater oil recovery. The best-known CO_2 – EOR project is located in southeastern Saskatchewan, Canada, at the Weyburn Field. This project uses waste CO_2 piped from a gasification plant in North Dakota. It is the only CO_2 – EOR project to date that is being monitored specifically to understand CO_2 storage. At Weyburn, the CO_2 storage-to-oil production ratio is about one-to-one, on a per ton basis.[72] Over the 25-year lifespan of the project, it is expected that about 18 million tons of CO_2 injected into the ground will yield approximately 130 million barrels of oil.[73]

  CCS supporters advocate the potential value of this form of geological storage as it provides supplementary revenue streams (through the sale of the recovered oil), lowering the overall cost of the CCS. While this may be true for some small projects deployed in the early phases of CCS development, "EOR sites are ultimately too few and too geographically isolated to accommodate much of the CO_2 from widespread industrial CO_2 capture operations."[74] Furthermore, as *"Oil fails to pay for CCS"* (page 28) shows, EOR is not always able to offset CCS costs.

- **Deep coal seams** are coal deposits that cannot be mined due to technological or economic constraints. CO_2 is stored in these sites via a gas adsorption mechanism that leads to the release of methane. This Enhanced Coal Bed Methane (ECBM) could potentially be recovered and used to offset the costs of CCS. Substantial technical concerns related to the injection of CO_2 and subsequent storage processes limit the immediate attractiveness of these sites.[75] Technical storage capacity is uncertain and could be as little as 3 $GtCO_2$ or as high as 200 $GtCO_2$.[76]

image Hatfield's Ferry Power Station, located near Masontown, Pennsylvania.

Figure 1 **Trapping mechanisms**

The storage of CO_2 underground is based on the ability of physical and chemical trapping mechanisms to immobilise CO_2 permanently and store it forever.
Source: IPCC, 2005

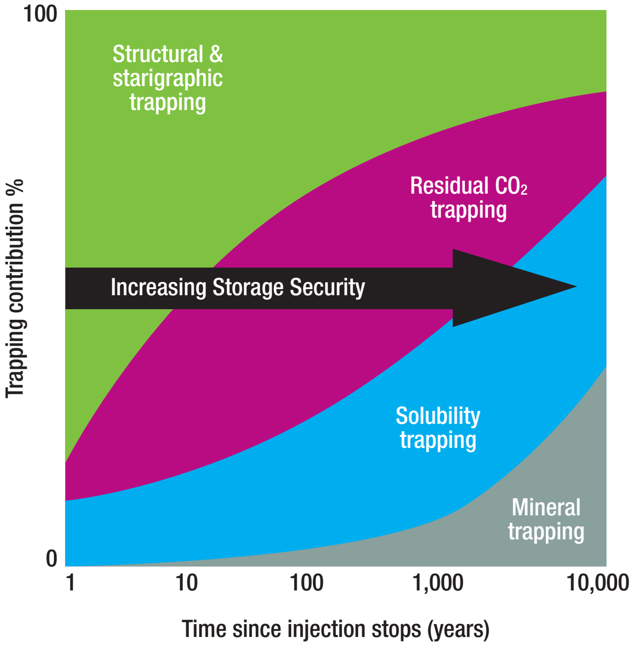


Table 1 **Geological trapping mechanisms**

Structural	When CO_2 is pumped deep underground, it is initially more buoyant than water and will rise up through the porous rocks until it reaches the top of the formation where it can become trapped by an impermeable layer of cap rock, such as shale.
Residual	As CO_2 migrates through a formation, some of it is retained in pore space by capillary forces. This can immobilise significant amounts of CO_2.
Solubility trapping	When CO_2 dissolves into rock formation water, CO_2 no longer exists as a separate phase and the buoyant force that drives it upwards is eliminated. Dissolution is rapid when formation water and CO_2 share the same pore space.
Mineral	CO_2, when dissolved in water, is weakly acidic and can react with minerals in the rock formation. This may result in the conversion of CO_2 to stable carbonate minerals, the most permanent form of geological storage.

Source: IPCC, 2005

image Cementa cement factory, Gotland, Sweden.

©GREENPEACE / J CUNNINGHAM

4

Lifting the smokescreen

CCS is not the catch-all climate solution its proponents' claim, and in any case it is years away from being market-ready. At present "there are still many unanswered questions regarding the safe, socially compatible as well as ecological and economic sound applications of CCS."[77] Energy companies and power utilities tend to gloss over these while proposing to build "capture-ready" plants that will exacerbate the climate crisis.

Below are five reasons why CCS should not be accepted as either justification for building new coal-fired power plants or for continuing our dependence on coal in the longer term.

4.1

CCS cannot deliver in time to save the climate

Every decision made about new power plants today will influence the energy mix of the next 30-40 years. The urgency of the climate crisis means solutions must be ready for large-scale deployment in the short-term. CCS simply cannot deliver in time.

While some system components of CCS are already in commercial use – mostly in the oil and gas industry- "there is no operational experience with carbon capture from coal plants and certainly not with an integrated sequestration operation".[78] While plans for demonstration facilities are underway, it is believed that the earliest CCS might become feasible is 2030.[79]

The UNDP concludes that CCS "will arrive on the battlefield far too late to help the world avoid dangerous climate change."[80]

"Capture ready" power stations

Proponents of CCS circumvent the fact that the technology is not ready, by proposing to build "capture ready" power stations. This term refers not to a particular type of technology but more a state of being for a power station. While there is no strict definition of "capture ready", the IEA describes a capture ready plant as "[one] which can be retrofitted with CO_2 capture when the necessary regulatory or economic drivers are in place."[81] This is sufficiently broad to make any station theoretically capture ready, and the term meaningless.

The concept of "capture ready" power stations allows new coal-fired power stations to be built today while providing no guarantee that emissions will be mitigated in the future. In lieu of delivering a concrete solution to fighting climate change, it banks on the promise of an unproven technology and risks locking us into an energy future that fails to protect the climate.

In the UK, for example, a proposed new coal-fired power plant at Kingsnorth, Kent is being sold as "capture ready." Yet this doesn't mean that the new plant will be able to capture and store carbon; it will just be ready to incorporate CCS should the technology ever become viable in the future; and no-one has any idea if and when this might be. In the meantime, and possibly for its entire lifetime, Kingsnorth (if built) will pump out around 8 million

CCS wastes energy and resources. Power plants with carbon capture will use 10-40% more energy than those without. A 20% increase in the energy requirement due to carbon capture would require the construction of an additional power plant for every four built to offset the energy loss.

---

tonnes of CO_2 per year, an amount equivalent to the total annual CO_2 emissions of Ghana.[82]

Recent project cancellations highlight some of the technical and economic concerns tied to CCS. In 2007, at least 11 CCS projects were scrapped; plans for new projects stagnated; and the pace of development for existing projects slowed considerably.[83] Most recently, the US DOE pulled out of its flagship CCS project, FutureGen, citing cost concerns (see *"US abandons CCS flagship programme"*, page 34). Delays and cost overruns have also led to project cancellations in the UK, Canada, and Norway.

The vote of no confidence that CCS received in a survey of 1000 "climate decision-makers and influencers" from around the world is also significant. The survey, conducted by GlobeScan, the World Conservation Union, IUCN and the World Bank, reveals substantial doubt about CCS. Only 34% of those polled were confident that retrofitting clean coal technology could reduce CO_2 emissions over the next 25 years without unacceptable side effects, and only 36% in the ability of 'clean coal technology' to deliver low carbon energy with new power stations. In contrast, 74% expressed confidence in the ability of solar hot water to deliver, 62% for offshore wind farms, 60% for onshore wind farms, and 51% for combined heat and power plants.[84]

"Capture ready" or not, a coal-fired power station built today aggravates the climate crisis. Maintaining the status quo in the hope that CCS might some day be able to deliver is not a climate mitigation strategy.

Emission reduction potential

Even if CCS were ready, the IPCC notes that deployment would only take place if the appropriate subsidy mechanisms and policy drivers (including a price on carbon) were put in place. As a result, it estimates that the bulk of the technology's adoption would not happen until the second half of this century.[85]

Assuming that commercial viability is reached, scenario studies indicate that by 2050 only 20-40% of global fossil fuel CO_2 emissions could be technically suitable for capture[86]. This includes 30-60% of emissions from the power sector.[87] Therefore up to 70% of emissions from electricity generation in 2050 may not even be technically suited to CCS. Furthermore, this figure does not account for the fact that power stations will often be far away from storage sites.

In Australia, CCS would lead, at best, to a 9% emissions reduction in 2030 and a cumulative emissions reduction from 2005 to 2030 of only 2.4%.[88] This is partly due to the lack of suitable storage locations. For example, in the Newcastle-Sydney-Wollongong area of New South Wales and at Port Augusta in South Australia, which together produce about 39% of Australia's current net CO_2 emissions from electricity generation, there are no identified storage sites within 500 km of the coal-fired power stations.[89] In comparison, a modest improvement in energy efficiency could – at zero or even negative cost – decrease emissions in 2030 by about the same amount, and cumulative emissions by twice as much.[90]

Climate scientists warn global emissions must peak by 2015, just seven years away. CCS is unable to deliver the necessary greenhouse gas emission reductions to meet this goal.

image Germany's most polluting coal fired power station, RWE brown coal power plant, Frimmersdorf

4.2

CCS wastes energy

Relying on CCS to mitigate CO_2 emissions means accepting a 10-40% energy penalty at the power station, depending on the type of technology used.[91] An energy penalty of just 20% would require the construction of an additional power station for every four of the same size built with CCS, to maintain the same net output before the CCS was fitted.[92]

These reductions in efficiency will require more coal to be mined, transported and burned to produce the same amount of energy as power stations without CCS. A new 500 MWe sub-critical pulverised coal (PC) unit with carbon capture will have to burn an additional 76,000 kg of coal per hour to maintain the same net output as a similar sized plant without capture. An ultra-critical PC unit would require a boost in its coal feed rate of 44,000 kg/h (see Table 2).[93] CCS would not only worsen fuel security issues but intensify the major localised environmental problems associated with extraction and transport of coal, including habitat destruction**,** damage to rivers and waterways and air pollution.

Power station efficiency losses would be most pronounced when capture systems are retrofitted to existing infrastructure. This is because technical mismatches between power stations and capture systems means components function below their design capacity levels. These mismatches are most pronounced with pulverised sub-critical coal units. A study by Alstom Power, Inc estimates that the addition of MEA flue gas scrubbing to a 500 MWe pulverised coal unit would reduce efficiency by 14.5% points (from 35% efficiency to 20.5%) and cost as much as US$1600/kWe.[94] The substantial loss in efficiency, coupled with the high cost of retrofitting these types of plants, means a large proportion of existing coal power stations are unlikely ever to be retrofitted for capture.

The decision on whether or not to retrofit also hinges on a power station's proximity to a storage site; the necessary infrastructure to deliver the CO_2 to it; and the availability of additional resources, such as water. The numerous coal-fired power stations scheduled to be built between now and whenever CCS may be ready for commercial deployment will most likely never have their carbon captured and will continue to pollute unabated until they are closed down.

CCS not only cuts energy efficiency but also increases resource consumption. A study by Rubin et al. (2005), quantified the impacts of capture systems on plant resource consumption and emission rates. For a 500MWe PC unit fitted with carbon capture, a 24% energy penalty was estimated to have resulted in an increase of approximately 25% for fuel, limestone (for the flue gas desulphurisation system) and ammonia (for nitrogen oxide control) inputs (see Table 3).[95] A US DOE analysis on the freshwater requirements for carbon capture found that in 2030, deploying CCS in PC plants with scrubbers and IGCC plants would increase water consumption in all scenarios examined by 90% (anywhere from 2.2 to 4.3 billion gallons of water per day).[96] In a report for the German Department for the Environment, the Fraunhofer Institute estimates that wide-scale adoption of CCS could erase the efficiency gains of the last 50 years and increase resource consumption by one third.[97]

Greater energy efficiency is half of the solution to tackling the climate crisis. Employing a technology that reduces the energy efficiency of coal-fired power plants will not bring about the sustainable energy future needed to protect the climate.

The IEA estimates that the magnitude of CO_2 emissions that need to be captured and stored by 2050 is on the order of 6000 projects, each injecting a million tonnes of CO_2 a year into the ground. Currently, only three such storage projects exist worldwide.[98]

Table 2 **Performance of air-blown PC generating units with and without CCS**

	Subcritical PC		Supercritical PC		Ultra-Supercritical PC	
	w/o capture	w/capture	w/o capture	w/capture	w/o capture	w/capture
Performance						
Generating efficiency (HHV)	34.3%	25.1%	38.5%	29.3%	43.3%	34.1%
Coal feed rate, kg/h	208,000	284,000	185,000	243,000	164,000	209,000
CO_2 emitted, kg/h	466,000	63,600	415,000	54,500	369,000	46,800
CO_2 emitted, g/kWe-h*	931	127	830	109	738	94

Reference plant is 500 MWe, 85% capacity factor; *assumes a 90% capture rate
Source: MT, 2007

Table 3 **Impact of CCS system on resource consumption and emission rates**

Capture plant parameter	Reference plant*	Reference plant with capture
	Rate	Increase
Resource consumption (all values in kg/MWh)		
Fuel	390	93
Limestone	27.5	6.8
Ammonia	0.80	0.19
CCS Reagents	2.76	2.76
Solid wastes/by-product		
Ash/slag	28.1	6.7
FGD residues	49.6	12.2
Spent CCS sorbent	–	4.05

*Reference plant is a 500 MWe new pulverised coal-fired power station. Energy penalty associated with installation of CCS is assumed to be 24%
Source: Rubin et al., 2005b

image Industrial pipeline in Portman Bay, near Cartagena, Spain

4.3

CCS storage – where will all the CO_2 go, will it stay there permanently?

Most scenarios for stabilisation of atmospheric CO_2 levels between 450 and 750 parts per million (ppm) place the economic potential of CCS anywhere from 220-2200 gigatonnes (Gt)CO_2 cumulatively.[99] It is likely that a vast majority of captured CO_2 would be disposed of in geological sites. The challenge of storing many gigatonnes worth of carbon dioxide underground is ensuring it stays there. To have any potential climate benefit, buried CO_2 must remain underground forever. However, safe, permanent storage cannot be assured; the world has no experience with the deliberate long-term storage of anything, let alone CO_2. The longest running storage project, Sleipner in Norway, is only 12 years old. While some geological reservoirs could have the specific combination of physical features and chemical processes that trap injected CO_2 and essentially hold it for all time, there is insufficient data or practical experience to know whether there are enough.

Storage estimates

Efforts to capture carbon dioxide make no sense if there is not adequate space to dispose of it permanently. Global anthropogenic CO_2 emissions are close to 26 Gt[100] annually and growing at a rate of about 0.5 % per annum.[101] From a purely technical perspective, estimates excluding economics and transport factors indicate that there is enough capacity to store CO_2 emissions for several decades, up to several hundreds of years.[102] Deep saline aquifers are believed to have the greatest potential, followed by depleted oil and gas fields, and coal seams.

The Massachusetts Institute of Technology's (MIT) *The Future of Coal* report, however, notes that there is a great degree of uncertainty associated with storage estimates. While most "support the contention that sufficient capacity exists to store many 100's to many 1000's of Gigatonnes of CO_2… this uncertain range is too large to inform sensible policy."[103] This stems from the use of inappropriate methodology, lack of reliable data and the diverse nature of geological settings. There is very little of the information needed to assess the majority of the potential storage reservoirs available; national level estimates are largely based on modelled average values and therefore remain a source of considerable uncertainty.[104]

The vast majority of these estimates quantify technical capacity assuming that the whole of a reservoir is accessible to store CO_2 in its pore volume.[105] This can easily lead to unrealistically high numbers as the fraction of pore volume that can be used for CO_2 storage is site-specific and depends on factors such as injection rate, relative permeability, density and mobility of fluids and rock heterogeneity.[106] A geological reservoir with enormous capacity but no injectivity would for example, be included in a technical capacity estimate, even though it could never be used.[107]

The technical, regulatory and economic limitations that will always prevent full usage of storage capacity quickly reduce capacity estimates. For example, deep saline formations appear to have the greatest storage potential (see Table 4) but several capacity estimates factoring in both technological and economic constraints put the actual feasible storage capacity at 200-500 $GtCO_2$.[108] Adding in the limits of co-location of CO_2 sources and storage sites (also known as source-to-sink matching) could easily decrease these numbers further and is a determinant factor.

Costs increase the further CO_2 needs to be transported. Australia's Commonwealth Scientific and Industry Research Organisation (CSIRO) finds "transport of carbon dioxide over distances of more than a hundred kilometres can become prohibitively expensive... Unless the cost can be significantly reduced, it will not be feasible to pipe carbon dioxide long distances".[109] High quality storage sites are of no use if the source of CO_2 is too far away from them. Current estimates clearly fail to portray the realistic storage capacity available for CO_2 sequestration.

Overview of geological storage options

1. Deep coal seams

In these formations, CO_2 is stored via a mechanism that leads to the release of methane. Substantial technical concerns related to the injection of CO_2 and subsequent storage processes limit the immediate attractiveness of these sites.

2. Depleted oil and gas reservoirs

These reservoirs tend to be the best characterised of all available storage options. However, the multiple bore holes and wells drilled to find and extract oil and gas can increase the leakage risk for storage operations.

3. Enhanced Oil Recovery (EOR)

EOR involves injecting CO_2 into geological formations to achieve greater oil recovery. EOR sites are ultimately too few and too geographically isolated to accommodate much of the CO_2 from widespread capture operations.

4. Deep saline formations (a) onshore (b) offshore

Deep saline aquifers are porous rock, which contain very saline water. The major obstacles to full exploitation of this storage option are accurate characterisation and demonstration that safety and environmental protection can be assured.

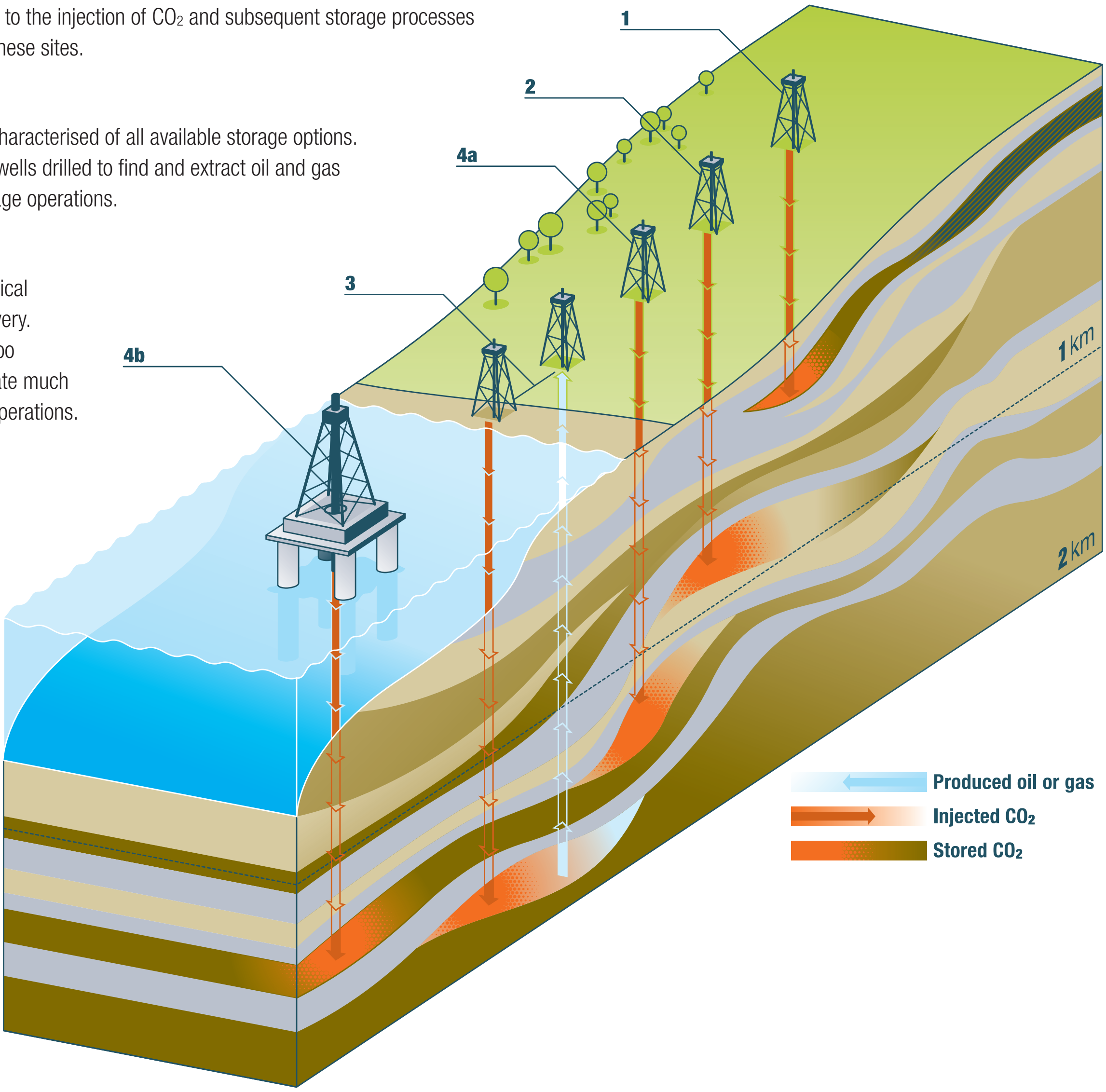


Table 4 **Geological storage capacity estimates**

Reservoir type	Range ($GtCO_2$)
Deep saline formations	1000-uncertain, but possibly 10,000
Oil and gas fields	675-900
Deep coal seams	3-200

Source: IPCC, 2005

image The Philippines biggest coal-fired power station, Sual, in the province of Pangasinan.

Scaling up

Achieving the substantial CO_2 emissions reductions required to avoid catastrophic climate change would require broad deployment of CCS in a relatively short period of time. Global emissions from coal are currently 2.5 Gt of carbon per year. Sequestering just 1 Gt of carbon (3.6 Gt of CO_2) would require the injection of approximately 50 million barrels of supercritical CO_2 per day from about six hundred 1000 MWe coal plants.[110] The IEA estimates that the magnitude of CO_2 emissions that need to be captured and stored by 2050 is in the order of 6000 projects each injecting a million tonnes of CO_2 a year into the ground.[111] The vast infrastructure required to capture and transport CO_2 from diverse and widely distributed point sources would also need to be built.

In the US alone, reducing CO_2 emissions from the electricity sector could require 200 projects, each with injection rates ten times bigger than Sleipner.[112] The US DOE estimates the country has enough technical capacity to store CO_2 for tens to hundreds of years.[113] However, a recent Congressional Research Services report shows that on the ground realities complicate the picture substantially. The report examines several scenarios for pipeline development in a seven-state region. The model scenario considered CO_2 emissions from the 11 largest CO_2 sources, all coal-fired power stations.[114]

In the report, the first storage option considered is Rose Run sandstone, a deep saline formation, very close to the CO_2 sources. Though its proximity is ideal, the site has many problems including limited storage capacity, low permeability and questionable integrity (i.e. high risk of leakage).[115] The second storage option examined includes a combination of coal beds and depleted oil and gas fields in the area. Further away than Rose Run, these sites would have limited utility. The coal beds lack sufficient storage capacity and the practicality of storing CO_2 in coal seams is virtually untested. The oil and gas fields also lack sufficient capacity, and leakage is a concern mostly due to the numerous boreholes drilled to extract fossil fuels from them in the first place.[116] The third storage option is the Mt. Simon formation, appealing because it is both larger and less fractured than the Rose Run location. Distance, however, is a limiting factor; Mt. Simon would require the construction of pipelines with an average length of 374km.[117]

When scaling up CCS from demonstration phases, such scenarios are likely to be repeated many times over.

Sequestering just 1 Gt of carbon would require the injection of approximately 50 million barrels of supercritical CO_2 per day from about six hundred 1000 MWe coal plants.[118]

CO_2 leakage

Storing CO_2 underground is predicated on the ability of physical and chemical trapping mechanisms to immobilise CO_2 permanently, and store it forever. Trapping mechanisms work in different ways and at different rates, from low-permeable cap rocks serving as physical barriers to CO_2 movement, to dissolving CO_2 into water.[119] The former mechanism is immediately effective, while the latter can take thousands of years to complete. The efficiency of trapping mechanisms depends on the "migration rate of the CO_2, which itself is highly dependent on the rock and fluid properties and geological characteristics of each site".[120] This means that each storage site would need to undergo detailed characterisations both to determine suitability, as well as to assess the likelihood of leakage.

As long as CO_2 is present in geological formations, there is a risk of leakage – it can migrate laterally or upwards to the surface. In contact with water, CO_2 becomes corrosive and can compromise the integrity of cap rocks, well casings and cement plugs. Undetected fractures in cap rocks or those created by injecting CO_2 at too high a pressure can provide another avenue for CO_2 to escape. Improper design and construction of wells can also create opportunities for leakage.[121] The implications for climate mitigation as well as the other environmental and public health risks make leakage a serious concern.

Preventing leaks will largely rely upon careful technology choices, project design, plant operation and reservoir selection. The IPCC notes that the fraction of CO_2 retained in "geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1000 years".[122] However, these findings are only valid for well-selected, fully characterised, properly designed and managed storage locations. At the moment, sufficient capacity in high quality reservoirs cannot be assured, nor can their appropriate design and management be guaranteed. It is likely that some CO_2 storage will occur in lower quality sites, without proper management. In these cases, the risk of leakage could be even greater.

For example, a CCS experiment in Texas (see *"Storing carbon underground can have unintended consequences"*, page 26) found CO_2 injected into saline sedimentary aquifers caused carbonates and other minerals to dissolve rapidly. This could allow CO_2 and brine to leak into the water table.[123]

While it is not currently possible to quantify the exact risk of leakage, any CO_2 release has the potential to impact the surrounding environment; air, groundwater or soil. Most computer models suggest leakage will occur fastest in the first 50-100 years of a project's lifetime, before trapping mechanisms take effect. Others indicate that little happens in the first 1000-year period with leakage most likely to occur over the following 3000 to 5000 year period.[124] Either way, even a tiny rate of leakage could undermine any putative climate benefit of CCS. A leakage rate of just 1% on 600 Gt of stored carbon (2160 $GtCO_2$ or about 100 years' worth of CO_2 emissions from fossil fuels), could release as much as 6Gt of carbon (21.6 $GtCO_2$) per year back into the atmosphere. This is roughly equivalent to current total global CO_2 emissions from fossil fuels.[125] Remediation may be possible for CO_2 leaks but there is no track record or cost estimates for these sorts of measures.[126]

The absence of a reliable risk management method is of concern, as leakage risks remain after the closure of an injection site. Monitoring would be required for long periods after closure, possibly forever. Therefore, appropriate tools to detect and protect against leaks will be essential.

image Coal Energy Power Plant

©JOSEPPI / DREAMSTIME.COM

Storing carbon underground can have unintended consequences

One of the key challenges for CCS is the safe and permanent storage of captured carbon. Even very small leakage rates could completely undermine any climate mitigation efforts.

The world has no experience of the long-term storage of anything, let alone CO_2.

As the results of a 2006 United States Geological Survey (USGS) field experiment[1] show, there is every chance that carbon dioxide will behave in ways that are totally unexpected. The USGS scientists were testing deep geological disposal of carbon dioxide at a pilot project in Frio, Texas.

The researchers were surprised when the buried CO_2 dissolved large amounts of the surrounding minerals responsible for keeping it contained.

The CO_2 reacted with salty water (brine) in the geological formation turning it as acidic as vinegar. This acidified brine then dissolved other minerals, including metals such as iron and manganese, organic material and relatively large amounts of carbonate materials. Carbonates naturally seal pores and fractures in geological sites; the reaction of the acidic brine with them is extremely concerning. Carbonate is also found in the cements used to plug abandoned oil and gas wells. If these open, CO_2 could leak into the atmosphere and/or the contaminated brine could leak into the aquifers that supply drinking and irrigation water.

In an interview with Greenpeace, lead scientist Yousif Kharaka warned that the results are “a cautionary note: for detailed and careful studies of injection sites, and a well thought out monitoring program to detect early leaks of CO_2 into shallow potable groundwater or to the atmosphere.”[2]

The results of the UGCS study show that we simply do not know enough about how stored carbon will behave to be able to assure its safe and permanent storage.

---

[1] Kharaka Y K, Cole D R, Hovorka S D, Gunter W D, Knauss K G & Freifeld B M, ‘Gas-water-rock interactions in frio formation following CO_2 injection: Implications for the storage of greenhouse gases in sedimentary basins’, Geology, vol., 34, no. 7, 2006, pp. 577–580.

[2] Kharka, Yousif, 2007, USGS, Research Hydrologist, Interview conducted over e-mail.

image Blast furnaces of LTV Steel Co, Cleveland, Ohio, USA.

4.4

CCS is too expensive

Cost estimates for CCS vary considerably depending on factors such as power station configuration, CCS technology, fuel costs, size of project and location. One thing is certain, CCS is expensive. It requires significant funds to construct the power stations and necessary infrastructure to transport and store carbon. The IPCC sets costs between US$15-75 per ton of captured CO_2.[127] A recent US DOE report found installing carbon capture systems to most modern plant technologies resulted in a near doubling of plant costs.[128] Such costs are estimated to increase the price of electricity anywhere from 21-91%.[129]

For transport, pipeline networks will need to be built to move CO_2 to storage sites. The construction of a network of pipelines for CCS is likely to require a considerable outlay of capital.[130] Costs will vary depending on a number of factors, including pipeline length, diameter and specific steel components (corrosion-resistant) as well as the volume of CO_2 to be transported. Pipelines built near population centres or on difficult terrain (such as marshy or rocky ground) are more expensive.[131] The IPCC estimates a cost range for pipelines between US$1-8/ton of CO_2 transported (see Table 5).[132] A United States Congressional Research Services report calculated capital costs for an 11-mile (18 km) pipeline in the midwestern part of the country at approximately US$6 million. The same report estimates that a dedicated interstate pipeline network in North Carolina would cost upwards of US$5 billion due to the limited geological sequestration potential in that part of the country.[133]

Storage and subsequent monitoring and verification costs are estimated to range from US$0.5-8/t$CO_2$ injected and US$0.1-0.3/t$CO_2$ injected, respectively.[134] The overall cost of CCS could serve as another barrier to its deployment.[135] EOR has been suggested as a way to offset the costs but as *"Oil fails to pay for CCS"* (page 28) shows, in reality this is questionable.[136]

CCS diverts resources away from real solutions

In recent years, the share of research and development budgets in countries pursuing CCS has ballooned, with CCS often included as part of renewable energy packages. Meanwhile, funding for real renewable technologies and efficiency has stagnated or declined.

The US DOE's fiscal year 2009 budget seeks a 26.4% increase (US$493.4 million in FY 2008 vs. US$623.6 million in FY 2009) in funding for CCS-related programmes, at the same time it is scaling back programmes tied to renewable energy and efficiency research and cutting budgets by 27.1% (US$211.1 million in FY 2008 vs. US$146.2 million in FY 2009).[137] Australia has three cooperative Research Centres for fossil fuels, one particularly committed to CCS. There is not one for renewable energy technology.[138]

In Norway, petroleum-based research receives over five times more funds than renewable energy research. A recent commitment of more than 20 billion NOK (US$4 billion) for two CCS projects aimed at capturing 2 MtCO_2 annually (see *"How CCS has crippled the Norwegian energy debate"*, page 29) further widens the gap.

Table 5 **Cost ranges for components of CCS system**

CCS system components	Cost range	Remarks
Capture from coal – or gas-fired power plant	US$15-75/t$CO_2$ net captured	Net costs of captured CO_2 compared to the same plant without capture
Transport	US$1-8/t$CO_2$ transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO_2/yr
Geological storage	US$0.5-8/t CO_2 net injected	Excluding potential revenue from EOR or ECBM
Monitoring and verification	US$0.1-0.3/t$CO_2$ injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements

Source: IPCC 2005

Oil fails to pay for CCS

Even if CCS were available, large applications are prohibitively expensive. EOR is often proposed as a way round this. Its proponents argue that the profits from the recovered oil will cover the costs of carbon capture.

However, not only are EOR sites too few and far between to accomodate much carbon from widespread CCS operations,[1] the cancellation of CCS-EOR projects due to associated costs and low returns show it is not always able to offset the extra costs.

In 2005, when production in the British Miller oil and gas field became uneconomic, BP sought government subsidies to initiate an EOR project. With EOR the life of the oil field could have been extended by up to 20 years, delaying the costly decommissioning process and allowing access to an estimated 57 million barrels of currently unrecoverable oil.[2]

The potential profits from the recovered oil, however, could not make up the difference between the cost of carbon using CCS (€38 per tonne), and the current price of carbon credits (€21 per tonne, in the EU).[3]

BP tried to convince the UK government to bridge the gap, asking for a tax break of over 50%, and a guaranteed subsidised rate of return. When the UK government decided that all proposed CCS projects had to compete for funding and tax relief, BP cancelled its plans.

The Norwegian government abandoned a similar project after the Statoil-Hydro and Shell companies withdrew. The companies argued that although CCS would probably be technically feasible, it would never make economic sense. Building the CCS technology would have meant closing oil production for a year, and completely modifying the facilities. Overall, oil production would only have increased by 2%[4] nowhere near enough to cover the costs of installing the CCS technology.

EOR is one of the main ways proposed by industry to make CCS affordable, yet as the above cases highlight, projects are often unlikely to be able to cover the costs. Funding CCS is an extremely unwise investment.

---

[1] Hannnegan, B, 2007, pg 25

[2] Shepherd & Wedderburn, "Carbon Capture and Storage: The Race is On", http://www.shepwedd.co.uk/knowledge/article/779-1610/carbon-capture-and-storage-the-race-is-on/current/, retrieved 23.1.08.

[3] http://pointcarbon.com

[4] Taz.de, "CO_2-Injektion ist kein Geschäftsmodell", http://www.taz.de/index.php?id=archiv&dig=2007/07/03/a0140, retrieved 23.1.08

How CCS has crippled the Norwegian energy debate

Despite the fact that Norway generates nearly 100% of its electricity from renewable technologies, State funding for renewable energy research is less than one-sixth of that received by the petroleum industry.[1]

Over the last decade CCS has come to dominate the energy debate in Norway, diverting resources and political attention away from renewable generation and energy efficiency measures. Though the Norwegian Parliament recently announced an increase in the total funding for renewable energy research, CCS is considered part of this[2].

Recently, the Norwegian government committed to cover all additional construction and operation costs to ensure carbon capture and storage from two natural gas-fired power plants on the Norwegian west coast, Kårstø and Mongstad. This has been estimated to amount to more than 20 billion NOK (US$4 billion) over their lifetimes.[3]

The highly controversial Kårstø plant, which emits around 1 million tonnes of CO_2 per year, began operating in November 2007. High gas costs and low electricity returns mean the plant has hardly been in operation. Full-scale carbon capture was promised from 2009 but is now postponed to 2012. Significant technological constraints will likely push back the date even further. The capture plant, the pipeline to a storage location and the storage process control facility have yet to be built.[4]

Given how much better the same money could have been spent on other climate and energy development projects, the head of the Norwegian Institute for Energy Research (IFE), called the decision to rush development of the Kårstø plant "close to immoral.[5]"

At the Mongstad refinery, known as the "European CCS test centre", two pilot plants using different capture processes (amine and carbonate) are under construction, the aim of capturing 100,000 tonnes of CO_2 per year from 2011. Yet, until 2014 at the earliest, they will simply release the captured CO_2 back into the atmosphere. This is because the pipelines to the storage sites are not due to be finished until 2014. In fact they may well not even be ready by then, as potential delays in investment decisions threaten to postpone their completion.[6]

In Norway, as in other countries pursuing CCS, the technology is failing to deliver on its promises. Renewable energy and energy efficiency are safe, cost-effective solutions to tackling climate change. Given the urgency of confronting the climate crisis, halting development of these technologies in favour of waiting for CCS really is immoral.

---

[1] Article based on Norwegian Research Council figures; http://www.klassekampen.no/49135/mod_article/item/null

[2] Climate white paper agreement http://www.stortinget.no/diverse/klimaforlik.html

[3] Kårstø report: http://nve.no/modules/module_111/news_item_view.asp?iNewsId=32570&iCategoryId=1604

[4] Rapport nr 13, CO_2-håndtering på Kårstø, Norges vassdrags- og energidirektorat, Olav Falk-Pedersen, Mari Hegg Gundersen, Asle Selfors and Pål Tore Svendsen. December 2006. Pages 31 and 42. http://www.nve.no/FileArchive/388/NVErapport13-06_b.pdf

[5] Comment to NRK radio 31.01.2008. See background statement, where they suggest a more stepwise strategy, at http://www.ife.no/ife_nyheter/2007/IFE_nei_til_CO2-haandtering_pa_Kaarstoe/view?set_language=no&cl=no

[6] Technology Weekly, "Frykter store forsinkelser på Kårstø", http://www.tu.no/energi/article148205.ece, retrived 03.04.08

A US DOE report found installing carbon capture systems to most modern plant technologies resulted in a near doubling of plant costs.[139] Such costs are estimated to increase the price of electricity anywhere from 21-91%.[140]

4.5

CCS and liability: risky business

CCS carries significant environmental, economic, legal, political, technological and sustainability risks. First is the danger that new coal plants are approved and built on the basis of being “capture-ready”, but never have the technology installed. Secondary risks arise from the large quantities of CO_2 to be injected, the prolonged storage times required for any real climate benefit, and the fact that injection wells, and other infrastructure and geological imperfections, may result in CO_2 leakage.

Environmental risks

Environmental risks of geological CO_2 storage include:

- Reservoir leakage: the slow, long-term release of CO_2 from storage sites, for example through geological faults;
- Sudden catastrophic leakage: the large-scale release of CO_2 from storage sites, for instance through failures of active or abandoned injection wells;
- Escape of CO_2 and associated substances into shallow groundwater;
- Displacement of brines and mobilisation of toxic metals and organics moving upwards leading to contamination of potable water, overlying sediments, soils or seawater;
- Escape of other hazardous captured flue gases.

The specific environmental risks associated with CO_2 leakage can be divided into two catergories: global and local. On a global scale, continuous leakage of CO_2 has the potential to undermine climate change mitigation efforts. While some leakage may be acceptable, it is generally agreed that it can only be tolerated within certain limits.[141] Even leakage rates as low as 1% per year could be too high. Leakage at this rate would reduce a given quantity of stored CO_2 to 37% of the original amount after 100 years.[142]

On a local scale, CO_2 leakage from storage sites poses a threat to human health. CO_2 is denser than air and therefore tends to pool in low-lying, poorly ventilated areas posing a hazard if it reaches levels higher than 3% by volume.[143] This risk also applies to pipeline transport of CO_2 through populated areas, raising critical issues with regard to route selection, overpressure protection, and leak detection.[144]

A natural example of the danger of CO_2 leakage occurred in a volcanically active area at Lake Nyos in Cameroon in 1986. Large quantities of CO_2 that had accumulated on the bottom of the lake were suddenly released, killing 1700 people and thousands of cattle over a range of 25 km.[145]

CO_2 rising to the shallow subsurface can have lethal effects on plants and subsoil animals and contaminate groundwater. Soil acidification and suppression of root zone respiration has been reported in volcanic and earthquake zones. In Mammoth Mountain, California, the release of CO_2 following several small earthquakes killed 100 acres of trees.[146] Migration of CO_2 can acidify waters and mobilise toxic heavy metals. Its injection can build pressure, displace brines and cause seismic activities.[147] Greater environmental damage due to increased fossil fuel extraction is another risk. The higher power demands of plants using carbon capture require higher coal and other fossil fuel use. Thus the major localised environmental problems associated with extraction and transport of fossil fuels including habitat destruction, damage to rivers and waterways (from subsidence due to longwall mining), and air pollution will also increase.

image Big oil spill, dead trees, pipelines in Nizhnevartovsk, West Siberia

Liability risks

Large-scale applications of CCS pose significant liability risks. Current regulations are not designed to adequately manage these, leaving unanswered significant questions as to who is liable.[148] At a minimum, any CCS regulatory regime would need to address: capture; transport; site characterisation and permitting; operating standards, including monitoring, measurement and verification and remediation plans; crediting of mitigated CO_2; and measures to deal with long-term storage. In the formulation of such a framework, industry's best interests (limitation of liability and costs) may run counter to public best interest (safety over unlimited timescales).

Industry views liability as a barrier to wider deployment of CCS[149] and is unwilling to fully invest in CCS unless it is protected from the risks associated with long-term CO_2 storage. The risks are so great that many utilities are unwilling to make CO_2 available for storage unless they are relieved of ownership upon transfer of the CO_2 from the power station.[150] Potential operators are urging that they only retain legal liability for permanently stored carbon for 10 years.[151]

Many factors impact the scope of liability associated with CCS. Just a few examples include the classification and purity of captured CO_2, definition of property rights and ownership of injected CO_2. Captured CO_2 can, for example, be labelled as a resource, waste product or even hazardous waste. The latter designations trigger stricter regulatory regimes for the handling, transport and disposal of CO_2 and increase the price of CCS.[152]

Another issue is the purity of the CO_2 stream. Captured CO_2 often contains various by-products of combustion processes such as nitrogen oxides (NOx) and sulphur dioxide (SO_2) as well as trace heavy metals including lead, mercury and cadmium.[153] Allowing injection of mixed streams underground is appealing as they require less scrubbing at the plant level, reducing costs. However, permitting the disposal of non-CO_2 components alters the risk profile of geological storage as well as the regulatory and legal responses.[154] For example, co-storage of CO_2 with sulphur dioxide (SO_2) increases the risk of leakage due to its chemical properties. In contact with water, SO_2 forms the highly corrosive sulphuric acid that more readily dissolves materials, such as the cement used to seal wells. A greater risk of leakage means higher likelihood of damage and liability. How much SO_2, if any, to allow in captured CO_2 streams will need to be determined. Regulations will have to account for its more corrosive nature in pipeline transport and long-term storage, in order to minimise risk.[155]

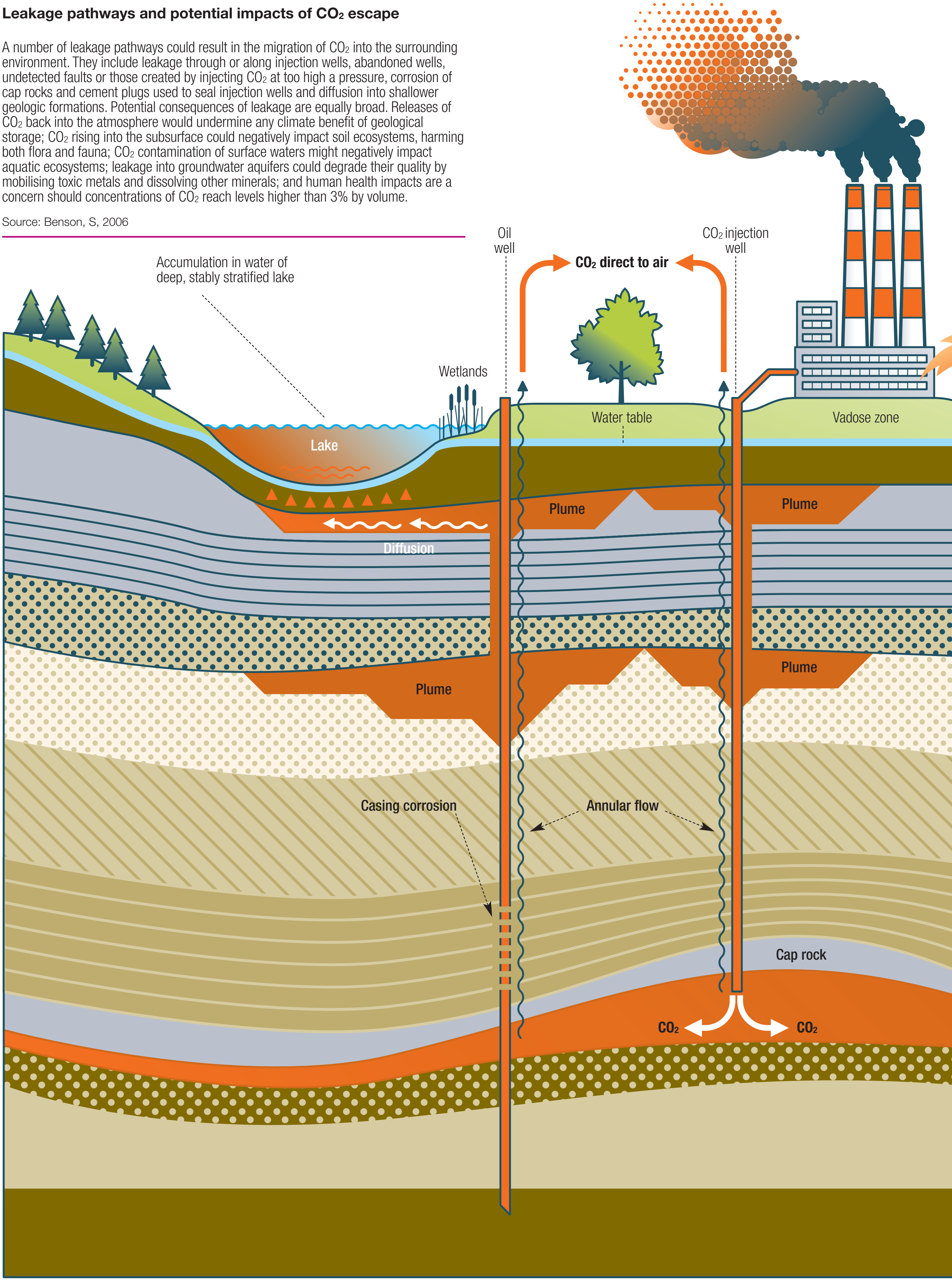
Perhaps the most critical questions relate to property rights and who is liable for the captured CO_2, particularly once the respective CCS project stops operating. The answer will determine who pays for any damage caused by CCS. Potential risks include liability for (1) health effects and damage to ecosystems from surface leakage; (2) groundwater contamination, including pollution of drinking water; (3) induced seismicity; and (4) climate effects from increased greenhouse gas emissions through surface leakage. To limit the liability of those engaged in CCS activities, liability caps, federal indemnity programmes and a complete transfer of liability from the private to public sector has been proposed.[156] These mechanisms completely shield operators from legal challenges, transfer ownership to government and/or limit the amount of money that can be recouped should damage occur. Some argue that such measures are necessary as projects will be unable to secure financing or insurance without them.[157]

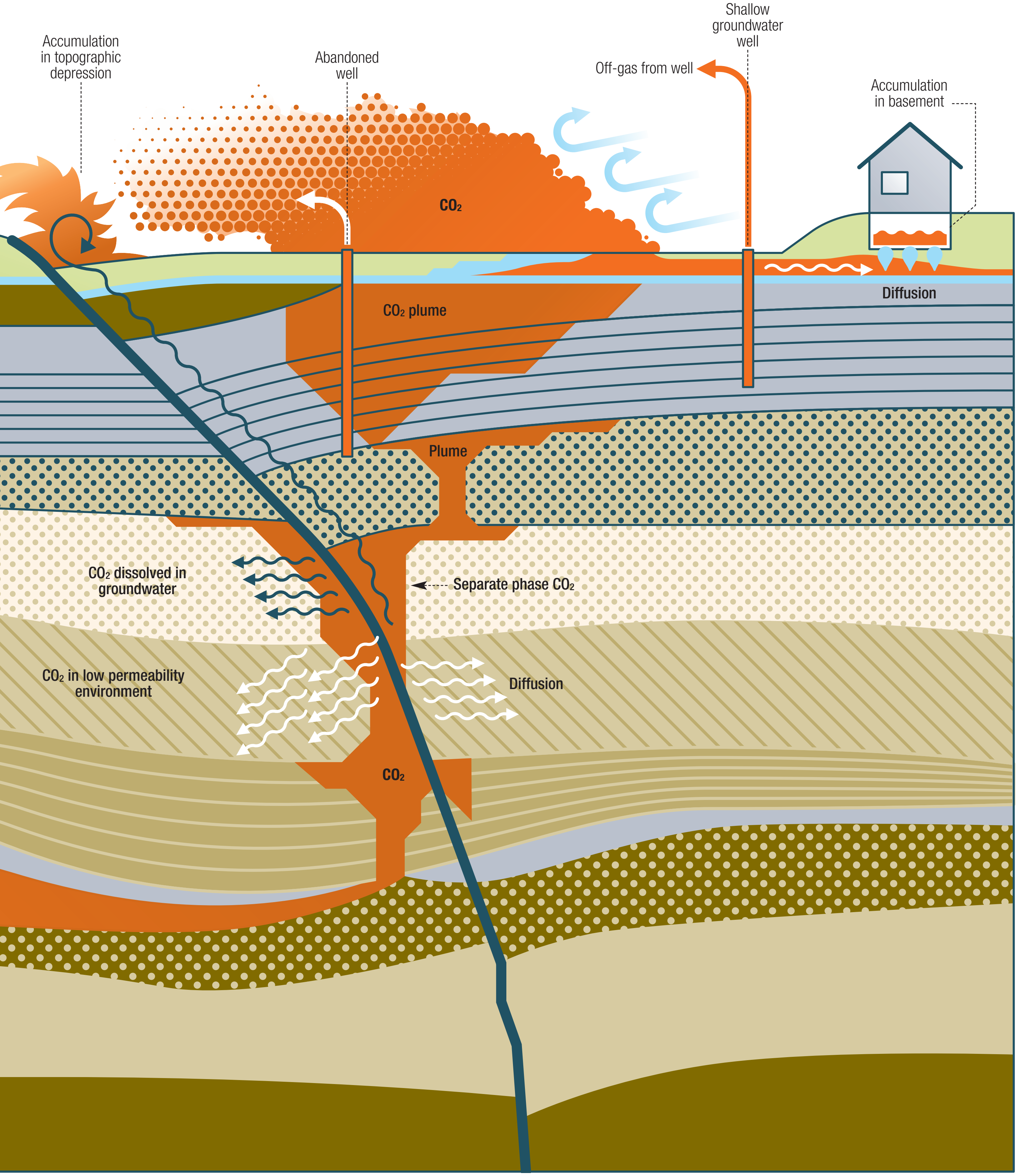
The recently collapsed FutureGen project in the US, for example, (see *"US abandons flagship CCS programme"* page 34) was protected from financial and legal liability in the event of an unanticipated release of carbon dioxide.[158] Lawmakers also agreed to indemnify FutureGen from lawsuits and pay for insurance policies to cover the plant.[159]

Leakage pathways and potential impacts of CO_2 escape

A number of leakage pathways could result in the migration of CO_2 into the surrounding environment. They include leakage through or along injection wells, abandoned wells, undetected faults or those created by injecting CO_2 at too high a pressure, corrosion of cap rocks and cement plugs used to seal injection wells and diffusion into shallower geologic formations. Potential consequences of leakage are equally broad. Releases of CO_2 back into the atmosphere would undermine any climate benefit of geological storage; CO_2 rising into the subsurface could negatively impact soil ecosystems, harming both flora and fauna; CO_2 contamination of surface waters might negatively impact aquatic ecosystems; leakage into groundwater aquifers could degrade their quality by mobilising toxic metals and dissolving other minerals; and human health impacts are a concern should concentrations of CO_2 reach levels higher than 3% by volume.

Source: Benson, S, 2006




Accumulation in topographic depression
Abandoned well
Shallow groundwater well
Off-gas from well
Accumulation in basement
CO₂
CO₂ plume
Diffusion
Plume
CO₂ dissolved in groundwater
Separate phase CO₂
CO₂ in low permeability environment
Diffusion
CO₂

FutureGen – US abandons CCS flagship programme

FutureGen, the flagship of the Bush Administration's CCS programme, was hailed as a first-of-its-kind near-zero emission coal plant[1]. Yet, in January 2008, following repeated delays and chronic cost overruns, the US government pulled the plug on FutureGen, stating "when a project doubles in cost, it's the time to sit down and rework those agreements."[2]

Announced in 2003, FutureGen was supposed to be online by 2012 but never left the development phase. The public-private partnership behind the project included the US DOE and corporate giants American Electric Power Service Corp., Anglo American, BHP Billiton, Rio Tinto, and China's largest coal-based power company, China Huaneng Group.

Federal government support for FutureGen was to be supplemented by a generous package from the State of Illinois. This included a $17 million grant, a sales tax exemption on building materials and selected equipment, and $50 million set aside for below-market-rate project loans. The State also passed a law to protect FutureGen from financial and legal liability in the event of an unanticipated release of carbon dioxide.[3] Lawmakers also agreed to indemnify FutureGen from lawsuits and pay for insurance policies to cover the plant.[4]

In 2007, the DOE reassessed the project design after costs had risen by 85% in three years to $1.8 billion.[5] The Department, orginally slated to cover 74% of the costs, asked industry to assume more of the financial burden to "prevent further cost escalation"[7]. However, the head of FutureGen estimated that every month of delay cost the project $10 million; "solely due to inflation".[8]

What happens to FutureGen now is unclear. Industry partners, promised their costs would be capped at $400 million, will have to finance it themselves to continue. This seems highly unlikely given how much the project relied on public financing and liability.

FutureGen collapsed despite being promised an unprecedented level of support; a total of US$1.3 billion of public funds, and being shielded from any legal responsibility. The debacle should serve as a stark warning to governments and industry considering investing in CCS.

---

[1] FutureGen Alliance, http://www.futuregenalliance.org/faqs.stm, retrieved 11.03.08

[2] Helenair.com, "Senators press official on carbon projects", http://www.helenair.com/articles/2008/02/01/national/100na_080201_carbon.txt, retrieved 27.02.08.

[3] Illinois Department of Commerce and Economic Opportunity, "Gov. Blagojevish Appluads the Passage of Important Legislation to Continue Illinois' Strong Bipartisan Push to Bring FutureGen to Illinois", http://www.ildceo.net/dceo/News/pr07262007-2.htm, retrieved 23.1.08.

[4] Gatehouse News Service, "Mattoon gets FutureGen nod, but hurdles remain", http://www.gatehousenewsservice.com/regional_news/midwest/illinois/x1414531785, retrieved 23.1.08.

[5] US Department of Energy, "Statement from US Department of Energy Acting Principal Deputy Assistant Secretary for Fossil Energy James Slutz", http://www.energy.gov/news/5779.htm, retrieved 23.1.08

[6] USA Today, "Emissions-free coal plant's costs worries feds", http://www.usatoday.com/money/industries/energy/2008-01-06-futuregen_N.htm retrieved 23.1.08.

[7] US Department of Energy, "Statement from US Department of Energy Acting Principal Deputy Assistant Secretary for Fossil Energy James Slutz", http://www.energy.gov/news/5779.htm, retrieved 23.1.08

[8] USA Today, "Emissions-free coal plant's costs worries feds", http://www.usatoday.com/money/industries/energy/2008-01-06-futuregen_N.htm retrieved 23.1.08.

image Cementa cement factory, Gotland, Sweden.

Financial risks

Immense amounts of money have already been spent supporting fossil-fuel power plants that are the main contributors to climate change. Implementation of CCS would require governments not only to continue but augment this support with additional subsidies and policy drivers. CCS adoption will only be possible with extremely heavy incentives. The technology is very expensive, and there are no guarantees that it will ever work. Economic analysis of absolute costs for CCS is characterised by a high level of uncertainty. For power stations, the IPCC estimates a range of US$14 to $91 per tonne of CO_2 avoided for the entire CCS process.[160] A more recent assessment placed the cost of merely capturing the CO_2 anywhere from €24-75 per tonne CO_2 avoided.[161]

Carbon emission cap-and-trade schemes have been promoted by CCS supporters as a way to lower the cost barriers of technology adoption.[162] However, in order for CCS to be profitable, the price for carbon emissions would have to be even higher than the additional costs associated with deploying the technology. Current CO_2 market prices of around €21 per tonne as well as future projections for the 2008-2012 period of the Emissions Trading Scheme are insufficient to spur deployment of CCS.[163] Prices as high as €100 per tonne might be needed to support initial projects.[164] However, not even a high price on carbon is enough to ensure a future for CCS.[165]

To make projects viable, however, carbon prices would need to be coupled with additional policy commitments and financial incentives.[166] Additional mechanisms proposed to supplement carbon prices include direct investment support, loan guarantees and public-private partnerships.[167] Instead of polluters being asked to pay for these programmes, deployment of CCS envisages a scheme where governments, and ultimately taxpayers, pay polluters to try not to pollute. If costs turn out to be higher than expected, the conditions for commercial viability may never be met and the money spent will have been wasted.

Providing the substantial levels of support to get CCS off the ground raises a serious question about priorities when current research shows that electricity generated from coal equipped with CCS will be more expensive than other less polluting sources, such as gas, wind power and many types of sustainable biomass. It is also much more expensive than increasing energy efficiency.[168] Even assuming that, at some stage, carbon capture becomes technically feasible, capable of long-term storage, environmentally safe and commercially viable, its impact would be limited and come at a high cost.

Meanwhile, as Greenpeace's Futu[r]e Investment report[169] shows, investing in a renewable energy future would save US$180 billion annually and cut CO_2 emissions in half by 2050.

image Tour around the South East of Asia to promote the use of clean energy, Manila, Philippines.

©GREENPEACE / K DAVISON

5

The world already has the real solutions to the climate crisis

The promise of CCS diverts attention away from sustainable energy solutions and risks locking the world into an energy future that fails to save the climate. Priority should be given to investments in renewable energy and energy efficiency which have the greatest potential to provide energy security and reduce emissions.

Greenpeace's Energy [R]evolution scenario provides a practical blueprint that shows how renewable energy, combined with greater energy efficiency, can cut global CO_2 emissions by almost 50%, and deliver half the world's energy by 2050.[170] Decades of technological progress have seen renewable energy technologies such as wind turbines, solar photovoltaic panels, biomass power plants and solar thermal collectors move steadily into the mainstream. The market for renewable energy is growing dramatically; in 2007 global annual investment in renewables exceeded US$100 billion.[171] At the same time, there is enormous potential for reducing our consumption of energy, even while providing the same level of "energy services".

Many nations have recognised the potential of these true climate solutions and are pressing ahead with ambitious plans for energy revolutions within their borders. New Zealand plans to achieve carbon neutrality by mid-century. Renewable energy and energy efficiency, not CCS, are leading the way. New Zealand already obtains 70% of its electricity from renewable resources and aims to increase it to 90% by 2025.[172] In Germany, renewable energy supply has increased 300% in the past 10 years. New legislation will require all homes built after 1 January 2009 to install renewable energy heating systems.[173] In the US, over 5,200 MW of wind energy were installed in 2007, accounting for 30% of new power installed that year; an increase of 45% in one year.[174] These are just a few examples of the renewable energy boom.

The urgency of the climate crisis means solutions must be ready for large-scale deployment in the short term. CCS simply cannot deliver in time. The technology is highly speculative, risky and unlikely to be technically feasible in the next 20 years. Allowing CCS to be used as a smokescreen for building new coal-fired power stations is unacceptable and irresponsible. "Capture-ready" coal-fired power plants pose a significant threat to the climate. To tackle the climate crisis, the world needs to reduce the amount of CO_2 produced, not bury it underground and hope that it stays there. Dirty energy sources, such as coal, must be phased out while investments in sustainable energy solutions must be increased. Renewable energy and energy efficiency are safe, cost-effective solutions that carry none of the risks of CCS and are available now to cut emissions and save the climate.

6

References

Abanades, J C et al., 2005. *Summary for Policymakers* in *IPCC Special Report on Carbon Dioxide Capture and Storage*, B. Metz et al., Editors. 2005, Cambridge University Press: Cambridge, U.K.

Azar, C et al, 2006, *Carbon Capture and Storage from Fossil Fuels and Biomass – Costs and Potential Role in Stabilizing the Atmosphere*, Climactic Change vol. 74, 2006, pp. 47-79.

Bachu, S et al., 2007. *CO_2 storage capacity estimation: Methodology and gaps*, International Journal of Greenhouse Gas Control I, 2007, pp. 430-443.

Benson, S, 2004. *Carbon Dioxide Capture and Storage in Underground Geologic Formations*, Lawrence Berkley National Laboratory, Berkeley 2004, <http://www.pewclimate.org/docUploads/10-50_Benson.pdf>.

Benson, S, 2006. *Liability Issues Related to Geological Storage of CO_2.* Lawrence Berkley National Laboratory. Presentation for WRI Workshop on Carbon Capture and Storage Liability, Washington, DC, September, 2006.'

Benson, S et al., 2005. *Underground Geological Storage* in *IPCC Special Report on Carbon Dioxide Capture and Storage*, B. Metz et al., Editors. 2005, Cambridge University Press: Cambridge, U.K.

Bradshaw, J et al., 2007. *CO_2 storage capacity estimation: Issues and development of standards*, International Journal of Greenhouse Gas Control 1, 2007, pp. 62-68.

Bruant, R, et al., 2002. *Safe Storage of CO_2 in Deep Saline Aquifers,* Environ. Sci. and Technol. vol. 36, issue 11, 2002, pp. 240a-245a.

Carbon Capture Journal (CCJ), 2008. *Only 34% confidence in clean coal- climate decision-makers*. Keith Forward, Editor. January/February 2008, Issue 1.

Damen, K et al., 2006. Healthy, *Safety and Environmental Risks of Underground CO_2 Storage – Overview of Mechanisms and Current Knowledge*. Climactic Change, vol. 74, 2006, pp. 289-318.

de Figueiredo, M et al., 2005. *Framing the Long-Term In Situ Liability Issue for Geologic Carbon Storage in the United States*, Mitigation and Adaptation Strategies for Global Change vol. 10, 2005, pp. 647-657.

Diesendorf, M, 2006. *Can geosequestration save the coal industry?*, in J Byrne, L Glvoer & N Toly (eds), *Transforming power: Energy as a social project*, Energy and Environmental Policy Series vol. 9, 2006, pp. 223-248.

Doctor, R et al., 2005. *Transport of CO_2* in *IPCC Special Report on Carbon Dioxide Capture and Storage*, B. Metz et al., Editors. 2005, Cambridge University Press: Cambridge, U.K.

Energy Information Administration (EIA), 2007. *The International Energy Outlook 2007*, US Department of Energy, Washington, DC, May 2007, < http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2007).pdf>.

Forbes, S, 2002. *Regulatory Barriers for Carbon Capture Storage and Sequestration*. National Energy Technology Laboratory, November 2002.

Gough, C & Shackley, S, 2006. *Towards a Multi-Criteria Methodology for Assessment of Geological Carbon Storage Options, Climactic Change* 74, 2006, pp. 141-174.

Groenenberg, H & de Coninck, H, 2007. *Technological support for an enabling policy framework for carbon dioxide capture and geological storage, Task 3: Incentivising CO_2 capture and storage in the European Union*, April 2007.

Hannegan, B, 2007. Testimony for Hearing of the Science, Technology and Innovation Subcommittee of the Committee on Commerce, Science, and Transportation. 110th Cong., 1st Sess. 7 November 2007.

Heddle, G et al., 2003. The *Economics of CO_2 Storage*, MIT, August 2003, < http://sequestration.mit.edu/pdf/LFEE_2003-003_RP.pdf>.

Herzog, H & Golomb, D, 2004. *Carbon Capture and Storage from Fossil Fuel Use* in Energy Encyclopaedia, C. Cleveland, Editor. 2004. Elsevier: Amsterdam, Netherlands.

International Energy Agency (IEA) Greenhouse Gas R&D Programme, 2007a. *CO_2 capture ready plants*, 2007/4, May 2007.

International Energy Agency (IEA), 2007b. *Near-term Opportunities for Carbon Dioxide Capture and Storage,* Global Assessments Workshop in Support of the G8 Plan of Action, June 2007.

IPCC, 2005. *Carbon Dioxide Capture and Storage*: *Special Report of the Intergovernmental Panel on Climate Change*, IPCC, Geneva 2005, <http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/SRCCS_WholeReport.pdf>.

Johnston, P. & Santillo, D., 2003. *Carbon Capture and Sequestration: Potential Environmental Impacts*. Proceedings of IPCC Workshop on Carbon Dioxide Capture and Storage, Regina, Canada 18-21 November 2002, publ. Energy Research Centre of the Netherlands (ECN): 95-110.

Kharaka Y et al., 2006. *Gas-water-rock interactions in frio formation following CO_2 injection: Implications for the storage of greenhouse gases in sedimentary basins*, Geology, vol. 34, no. 7, 2006, pp. 577–580.

Levinson, Marc, 2007. *Carbon Capture and Sequestration*, The London Accord, JP Morgan, 2007. <http://www.london-accord.co.uk/final_report/ reports/pdf/c6.pdf>

Massachusetts Institute of Technology (MIT), 2007. *The Future of Coal*, MIT, Boston 2007, < http://web.mit.edu/coal/The_Future_of_Coal.pdf>.

McFarland, J et al., 2000. *Economic Modeling of the Global Adoption of Carbon Capture and Sequestration Technologies*, in Proceedings of the Sixth International Conference of Greenhouse Gas Control Technologies. Editors J Gale and Y Kaya, 2000.

National Energy Technology Laboratory (NETL), 2006. *International Carbon Capture and Storage Projects Overcoming Legal Barriers*. NETL, June 2006, < http://www.netl.doe.gov/energy analyses/pubs/ CCSregulatorypaperFinalReport.pdf>.

National Energy Technology Laboratory (NETL), 2007, *Cost and Performance Baseline for Fossil Energy Plants*, NETL, August 2007, < http://www.netl.doe.gov/energy-analyses/pubs/ Bituminous%20Baseline_Final%20Report.pdf>

Pacala, S et al., 2004. *Stabilization Wedges: Solving the Climate Problem for the Next 50 years with Current Technologies*. Science, vol. 305, no. 968, 2006, pp.968-972.

Parfomak, P & Folger, P, 2008. *Pipelines for Carbon Dioxide (CO_2) Control: Network Needs and Cost Uncertainties*. 2008. Congressional Research Services: Washington, DC.

Ragden, P et al., 2006. *Technologies for CO_2 capture and storage, Summary*. Westermann, B, Editor. 2006. Federal Environmental Agency: Berlin, Germany.

REN21, 2007. *Renewables 2007 Global Status Report,* A pre-publication for the UNFCCC COP13, Bali, Indonesia, 2007, < http://www.ren21.net/pdf/REN21_GSR2007_Prepub_web.pdf>.

Rubin, E et al., 2005a. *Technical Summary* in *IPCC Special Report on Carbon Dioxide Capture and Storage*, B. Metz et al., Editors. 2005, Cambridge University Press: Cambridge, U.K.

Rubin, E et al., 2005b. *Comparative Assessments of Fossil Fuel Power Plants with CO_2 Capture and Storage.* Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, Vancouver, Canada, September 5-9, 2004, Volume 1:; Peer-Reviewed and Overviews, E.S. Rubin, D.W> Keith ad C.F. Gilboy (eds), Elsevier, 2005 (in press).

Saddler, H, et al., 2004, *Geosequestration: What is it and how much can it contribute to a sustainable energy policy for Australia?*, The Australia Institute, Anu, 2004.

Shuster, E et al., 2007. *Estimating Freshwater Needs to Meet Future Thermoelectic Generation Requirements*, 2007, National Energy Technology Laboratories: Pittsburgh, PA.

Spreng, D et al., 2007. *CO_2 capture and storage: Another Faustian Bargain?* Energy Policy, vol. 35, 2007 pp. 850-854.

Thambimuthu, K et al., 2005. *Capture of CO_2* in *IPCC Special Report on Carbon Dioxide Capture and Storage*, B. Metz et al., Editors. 2005, Cambridge University Press: Cambridge, U.K.

The Interstate Oil and Gas Compact Commission, 2007. *Storage of Carbon Dioxide in Geologic Structures: A Legals and Regulatory Guide for States and Provinces*. Task Force on Carbon Capture and Geologic Storage, September 2007.

United Nations Development Programme (UNDP), 2007. *Avoiding Dangerous Climate Change: Strategies for Mitigation*, Human Development Report 2007/2008.

United Nations Foundation, 2007. *Confronting Climate Change: Avoiding the Unmanageable and Managing the Unavoidable*, <http://www.unfoundation.org/SEG/>.

US Department of Energy (US DOE), Office of Fossil Energy, 2007. *Carbon Sequestration Atlas of the United States and Canada*, 2007. <http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlas/>.

Vajjhala, S et al., 2007. *An International Regulatory Framework for Risk Governance of Carbon Capture and Storage*. CICERO, May 2007.

Van der Zwaan, B, & Smekens, K, 2007. *CO_2 Capture and Storage with Leakage in an Energy Climate Model, Environ Model Assess*, August 2007.

Viebahn, P, et al., 2007. *Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany*, International Journal of Greenhouse Gas Control, vol 1, pt 1, 2007, pp 121-133.

von Goerne, G, 2002. *Implication of CO_2 impurities on the integrity of caprocks during CO_2 Sequestration in Sub-Seabed Geological Structures.* Greenpeace, May 2006.

Wilson, E et al., 2007. *Research for Deployment: Incorporating Risk, Regulation, and Liability for Carbon Capture and Sequestration* Environ. Sci. Technol. vol. 41, 2007, pp. 5945-5952.

World Business Council for Sustainable Development (WBCSD), 2006. 'Facts and Trends- Carbon Capture and Storage', 2006. < http://www.wbcsd.org/web/publications/facts&trends-ccs.pdf>.

Endnotes

[1] World Business Council for Sustainable Development (hereafter "WBSCD"), 2006

[2] Abanades, J C et al., 2005, pg 3

[3] Ragden et al., 2006, pg 24

[4] Rubin et al., 2005a, pg 40

[5] Carbon Capture Journal (hereafter "CCJ"), 2008, pg 14

[6] Greenpeace's Energy [R]evolution was produced in conjunction with the European Renewable Energy Council and the German Aerospace laboratories – it is available at www.greenpeace.org/energyrevolution

[7] United Nations Development Programme (hereafter "UNDP"), 2007 pg 145-146

[8] Ibid

[9] Massachusetts Institute of Technology (hereafter "MIT"), 2007, pg xiii

[10] WBSCD, 2006

[11] Rubin et al., 2005a, pg 41

[12] Abanades, J C et al., 2005, pg 8

[13] International Energy Agency Greenhouse Gas R&D Programme (hereafter "IEA"), 2007 a, i

[14] MIT, 2007, pg 29

[15] CAIT institute, http://cait.wri.org/

[16] Abanades, J C et al., 2005, pg 3

[17] In other words: 20% reduced efficiency for each of these 4 power stations leads to an overall extra demand for power of 4 x 20% = 80% = 1 extra power station of the same size. The remaining 20% is needed for CCS for the fifth power plant.

[18] Shuster et al., 2007, pg 60

[19] Ragden et al., pg 24

[20] IEA, 2007a, pg 7

[21] CSIRO submission to the Australian Parliamentary House of Representatives Inquiry in Geosequestration Technology, August 2006.

[22] Azar et al., 2006

[23] Benson et al., 2005, pg 264

[24] Diesendorf, M, 2006, p. 16

[25] IEA Clean Coal Centre, http://www.iea-epl.co.uk/content/default.asp?PageId=885

[26] National Energy Technologies Laboratory (hereafter "NETL") 2007, ii

[27] Rubin et al., 2005a, pg 40

[28] Saddler, H et al., 2004, xi

[29] US DOE, FY 2009 Congressional Budget Request, February 2008

[30] Diesendorf, M, 2006, pg 13

[31] http://www.greenpeace.org/raw/content/international/press/reports/future-investment.pdf

[32] Wilson, E et al., pg 5945

[33] IEA Clean Coal Centre, http://www.iea-epl.co.uk/content/default.asp?PageId=885

[34] Levinson, Marc 2007, pg 14

[35] The Interstate Oil and gas Compact Commission 2007, pg 11

[36] CCJ, 2008, pg 14

[37] NETL, 2006

[38] Illinois Department of Commerce and Economic Opportunity, "Gov. Blagojevish Appluads the Passage of Important Legislation to Continue Illinois' Strong Bipartisan Push to Bring FutureGen to Illinois", http://www.ildceo.net/dceo/News/pr07262007-2.htm, retrieved 23.1.08.

[39] Gatehouse News Service, "Mattoon gets FutureGen nod, but hurdles remain", http://www.gatehousenewsservice.com/regional_news/midwest/illinois/x1414531785, retrieved 23.1.08.

[40] Energy [R]evolution: *A Sustainable World Energy Outlook*, Greenpeace and EREC, Jan 2007 – http://www.greenpeace.org/energyrevolution

[41] REN21, 2007, pg 2

[42] CCJ, 2008, pg 14

[43] Renewable Energy Access, New Zealand Commits to 90% Renewable Electricity by 2025, September 26 2007, http://www.renewableenergyaccess.com/rea/news/story?id=50075

[44] AWEA, US Wind Energy Power Surges 45%, Again Shatters Record, Wind Energy Weekly, vol 27, issue 1273, January 18 2007, http://www.awea.org/windenergyweekly/WEW1273.html#Article1

[45] www.greenpeace.org/energyrevolution

[46] Thambimuthu, K et al., 2005, pg 107

[47] Ibid, pg 109

[48] Hannegan, B,2007, pg 20

[49] MIT, 2007, pg 24

[50] Ibid, pg 13

[51] WBSCD, 2006

[52] Ragden, P et al., 2006, pg 14

[53] Hannegan, B, 2007, pg 22

[54] Rubin, E et al., 2005a, pg 27

[55] Doctor, R et al., 2005, pg 182

[56] Spreng, D et al., 2007, pg 851

---

[57] These are US (imperial) tons (2240lbs). Both US tons and metric tonnes,(1000kg) are used in this report. The spelling (tons or tonnes) indicates whether they are imperial or metric.

[58] Doctor, R et al., 2005, pg181

[59] Ragden, P et al., 2006, pg 18

[60] Ibid

[61] Rubin, E et al., 2005a, pg 34

[62] Rubin, E et al., 2005a, pg 35

[63] Johnson, P and Santillo, D, 2003

[64] Rubin, E et al., 2005a, pg 34

[65] Most recently, the international London Convention (1972) adopted protocol that expressly forbids the dumping of CO_2 streams unless: “(1) disposal is into a sub-seabed geological formation; (2) they [the streams] consist overwhelmingly of carbon dioxide; and (3) no waste is added for the purpose of its disposal. In other words, these rules do not permit CO_2 sequestration in the deep oceans themselves.” http://www.londonconvention.org

[66] Abanades, J C et al., 2005, pg 8

[67] Benson, S et al., 2005, pg 197

[68] Bruant et al., 2002

[69] Benson, S et al., 2005, pg 202

[70] Forbes, S, 2002

[71] Benson, S et al., 2005, pg 197

[72] At the Weyburn Field storage project, it is estimated that for every barrel of oil produced, approximately 85 standard cubic meters (scm) of CO_2 remains underground. As one scm of CO_2 weighs 1.56 kg and one barrel of oil equals 130 kg then 130 kg oil/(85 scm * 1.56 kg/scm)= 0.97 kg of oil per kg of CO_2, essentially a ratio of 1:1 so that 1 ton of CO_2 stored underground yields approximately 1 ton of oil (Heddle, G et al, 2003, pg 33).

[73] Herzog, H & Golomb, D, 2004, pg 6

[74] Hannnegan, B, 2007, pg 25

[75] MIT, 2007, pg 159

[76] Benson, S et al., 2005, pg 197

[77] Viebahn, P et al., 2007 pg 1 and 2

[78] MIT, 2007, pg xiii

[79] WBSCD, 2006

[80] UNDP, 2007, pg 145-146

[81] IEA, 2007 a, i

[82] CAIT institute , http://cait.wri.org/

[83] Cited in Point Carbon, 9.1.08

[84] CCJ, 2008, pg 14

[85] Rubin et al., 2005a, pg 41

[86] Abanades, J C et al., 2005, pg 8

[87] Ibid, pg 8

[88] Saddler, H et al., 2004, xii

[89] Ibid, x

[90] Ibid, xii

[91] Abanades, J C et al., 2005, pg 3

[92] In other words: 20% reduced efficiency for each of these 4 power stations leads to an overall extra demand for power of 4 x 20% = 80% = 1 extra power station of the same size. The remaining 20% is needed for CCS for the fifth power plant.

[93] MIT, 2007, pg 24 and 25

[94] Ibid, pg 146 and 147

[95] Rubin et al., 2005b, pg 8

[96] Shuster et al., 2007, pg 60

[97] Ragden et al., 2006, pg 24

[98] IEA, 2007, pg 7

[99] Abanades, J C et al.,2005, pg 10

[100] Herzog, H & Golomb, D, 2004, pg 5

[101] Energy Information Administration (herefter “EIA), 2007, pg 73

[102] Damen, K et al., 2006, pg 290

[103] Pg 45

[104] Gough, C & Shackley, S, 2006, pg 159

[105] Bradshaw et al., 2007, pg 66

[106] Gough, C, Shackley, S, 2006, pg 159

[107] Bachu, S et al., 2007, pg 432

[108] Bruant et al., 2002

[109] CSIRO submission to the Australian Parliamentary House of Representatives Inquiry in Geosequestration Technology, August 2006.

[110] MIT, 2007, pg xii

[111] IEA, 2007 b, pg 7

[112] Benson, S, 2004, pg 15

[113] US Department of Energy (hereafter “US DOE”), 2007

[114] Parfomak, P & Folger, P, 2008, pg 4

[115] Ibid, pg 6

[116] Ibid, pg 7

[117] Ibid, pg 8

[118] MIT, 2007, pg xii’

[119] Damen, K et al., 2006, pg 293

[120] Bradshaw et al., 2007, pg 66

[121] MIT, 2007, pg 50

---

[122] Pg 13

[123] http://www.smh.com.au/news/environment/buried-gases-may-escape-scientists/2006/07/04/1151778936655.html.

[124] Vajjhala, S et al., 2007, pg 5

[125] Azar et al., 2006

[126] Benson et al., 2005, pg 264

[127] Abanades, J C et al., 2005, pg 10

[128] National Energy Technology Laboratories (hereafter "NETL"), 2007, ii

[129] Rubin et al., 2005a, pg 40

[130] Ragden, P et al., 2006, pg 18

[131] Heddle, G et al., 2003, pg 17

[132] Abanades, J C et al., 2005, pg 10

[133] Parfomak, P & Folger, P, 2008, pg 5 and 12

[134] Abanades, J C et al., 2005, pg 10

[135] Rubin et al., 2005b, pg 4444

[136] Ragden, P et al., 2006, pg 20

[137] US DOE, FY 2009 Congressional Budget Request, February 2008

[138] Diesendorf, M, 2006, pg 13

[139] NETL, 2007, ii

[140] Rubin et al., 2005a, pg 40

[141] Abanades, J C et al., 2005, pg 15

[142] Van der Zwaan, B & Smekens, K, 2007

[143] Spreng, D et al., 2007, pg 851

[144] Abanades, J C et al., 2005, pg 12

[145] Diesendorf, M, 2006, p. 16

[146] Forbes, S, 2002

[147] Bruant et al., 2002

[148] Wilson, E et al., pg 5945

[149] IEA Clean Coal Centre, http://www.iea-epl.co.uk/content/default.asp?PageId=885

[150] Levinson, Marc 2007, pg 14

[151] The Interstate Oil and gas Compact Commission 2007, pg 11

[152] NETL, 2006, pg 5

[153] von Goerne, G, 2002, pg 2

[154] Wilson et al., 2007, pg 5946

[155] The London Convention has attempted to answer the purity question in regulations governing the disposal of CO_2 sub-seabed geological formations. In ANNEX 4.5 Action List of document LC/SG 29/15, it is written that the composition of the injection stream should be overwhelmingly CO_2. However, this fails to give guidance for proper stream characterisation (www.londonconvention.org). Does "overwhelmingly" mean 51%, 75% or 99%? This lack of clarity only adds to the uncertainty surrounding CO_2 storage. Greenpeace believes that the purity of a CO_2 injection stream should exceed 99.9% and any attempt to define "overwhelmingly" should reflect that.

[156] de Figueiredo, M et al., 2005, pg 6

[157] NETL, 2006

[158] Illinois Department of Commerce and Economic Opportunity, "Gov. Blagojevish Appluads the Passage of Important Legislation to Continue Illinois' Strong Bipartisan Push to Bring FutureGen to Illinois", http://www.ildceo.net/dceo/News/pr07262007-2.htm, retrieved 23.1.08.

[159] Gatehouse News Service, "Mattoon gets FutureGen nod, but hurdles remain", http://www.gatehousenewsservice.com/regional_news/midwest/illinois/x1414531785, retrieved 23.1.08.

[160] Rubin et al., 2005a, pg 43

[161] Ragden, P et al., 2006, pg 15

[162] McFarland, J et al., 2000

[163] Groenenberg, H & de Coninck, H, 2007, pg 9

[164] http://www.pointcarbon.com/

[165] lGroenenberg, H & de Coninck, H, 2007, pg 9

[166] IEA Clean Coal Centre, http://www.iea-epl.co.uk/content/default.asp?PageId=885

[167] Groenenberg, H, de Coninck, H, pg 9

[168] Saddler, H et al., 2004, xi

[169] Futu[r]e Investment: A sustainable investment plan for the power sector. A Greenpeace and European Renewable Energy Council (EREC), July 2007 - http://www.greenpeace.org/international/press/reports/future-investment

[170] Energy [R]evolution: A Sustainable World Energy Outlook, Greenpeace and EREC, Jan 2007 – http://www.greenpeace.org/energyrevolution

[171] REN21, 2007, pg 2

[172] Renewable Energy Access, New Zealand Commits to 90% Renewable Electricity by 2025, September 26 2007, http://www.renewableenergyaccess.com/rea/news/story?id=50075

[173] Franz Alt, For German Homeowners, Renewable Energy is No Longer a Choice, 2007, http://www.sonnenseite.com/index.php?pageID=60&article:oid=a9008&template=article_detail.html&flash=true

[174] AWEA, US Wind Energy Power Surges 45%, Again Shatters Record, Wind Energy Weekly, vol 27, issue 1273, January 18 2007, http://www.awea.org/windenergyweekly/WEW1273.html#Article1

image Several large wind turbines in the Shangyi Manjing Wind Farm. China has huge wind resources, which could be easily and profitably exploited by switching investment from climate destroying fossil fuels into harvesting this clean, abundant energy resource.

©GREENPEACE / H WEI

GREENPEACE

Greenpeace is an independent global campaigning organisation that acts to change attitudes and behaviour, to protect and conserve the environment and to promote peace.

Greenpeace International
Ottho Heldringstraat 5
1066 AZ Amsterdam
The Netherlands
Tel: +31 20 7182000
Fax: +31 20 5148151

greenpeace.org