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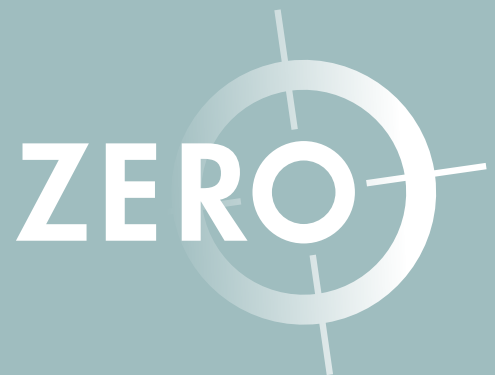
# CARBON CAPTURE AND STORAGE

## About ZERO

Zero Emission Resource Organization is an environmental organization dedicated to reducing climate change by demonstrating and gaining acceptance for zero emission energy solutions. We believe a zero emission solution exists for all energy use. Our mission is to work consistently for these solutions.

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*Cover: CO<sub>2</sub> injection in Weyburn, USA. (Photo: KEMA)*



# Preface

This booklet explains what carbon capture and storage (CCS) is. It presents the major CCS technologies available and some future technologies, as well as the main security issues of CO<sub>2</sub> storage.

We have focused on the technical aspects of CCS against the backdrop of much-needed climate solutions: the reality of escalating climate change, the consequences of this and the overall need for energy efficiency, a transfer to renewable energy *and* CCS.

We have not focused on the political, financial and legal aspects of CCS. This does not mean that these issues are not important. In many ways it is here that the challenges of carbon capture and storage lie.

The technology described in the booklet is mature, has been used for decades and will, in the long term, be cheaper and less energy intensive. The barriers and challenges are, in most cases, funding, juridical issues or a lack of political will, or a mix of these factors.

The challenge for today's humanity is to develop new ways of producing and using energy so that it can be done without creating harmful and devastating carbon dioxide emissions. Because our present societies are so dependent on fossil fuels, the transmission to renewable energy is challenging. To fulfil such profound changes, we rely on huge investments, political courage and knowledge, and public support.

These are decisive times. Within the next few years a global change in our conduct towards the environment must take place on an unprecedented scale. We hope this booklet will contribute to a better understanding of CCS and the role it must play as one of several measures to limit global warming.

Our intended audience is anyone who takes an active interest in the subject, whatever their background or purpose. For more information, we recommend visiting our web portal at [www.zeroco2.no](http://www.zeroco2.no).

Zero Emissions Resource Organisation (ZERO) is a Norwegian non-profit environmental NGO. It is the only environmental organisation in Norway dedicated solely to limiting the threat posed by climate change. ZERO pursues a constructive role in the fight against climate change: instead of negative campaigning, we prefer to advocate the solutions we support - renewable energy, CCS and CO<sub>2</sub>-free fuels for the transport sector.

## **[www.zeroco2.no](http://www.zeroco2.no)**

On this website you will find answers to common questions about CCS. There are also details of the various CCS projects around the world, and a "wiki-style" section containing all the information you may need about the entire CCS chain.

As far as we know, this is the only website in the world where you can find such detailed information relating to all CCS projects. You can also find out where different countries stand in the development and implementation of carbon capture and storage. There are also useful facts about the power companies, industry and key personnel involved in CCS projects.

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# Summary

In climate change humanity is facing its greatest challenge. Our energy production is dominated by fossil fuels and, if the emissions from using these fuels continue to rise, the results will be dramatic.

Among the consequences will be the melting of polar ice and rising sea levels, flooding and more extreme weather, loss of plant and animal species diversity, deforestation, and adverse effects on food and water supply. Even by limiting global warming to 2°C, we will not mitigate serious effects on ecosystems and regions of the Earth.

Greenhouse gas emissions must be reduced by 85 percent to avoid the most serious consequences of anthropogenic climate change. Important and well-established solutions are a shift from fossil fuel to renewable sources of energy - such as wind, bio-energy and solar power - and efforts to increase energy efficiency and reduce energy demand.

However, this is not sufficient to achieve the necessary emissions cuts within a short enough timeframe. According to the International Energy Agency's (IEA) World Energy Outlook (WEO 2011), the most optimistic picture - the 450ppm scenario - puts the share of fossil fuels in the energy mix as declining from 81 percent to still as much as 62 percent in 2035.

Of course, prognoses are only predictions made on assumptions. Therefore, it is possible to get more comprehensive climate policies. The question is whether it is possible to cover both the growing demand for energy and to achieve the needed large reduction in emissions of greenhouse gases based on renewable energy and increased energy efficiency alone by 2030.

According to the scenarios in IEA's World Energy Outlook 2011, and to calculations of IEA, the long economic lifetimes of much of the world's energy-related capital stock mean that there is little scope for delaying action if we are to reach the 2°C target. This leaves very little additional room for emitting greenhouse gases from additional sources.

Wind power is the fastest growing renewable energy source, besides hydropower and bio-energy. In Europe - the leading region in wind power development - about 9.3GW of new wind power was established in 2010, reaching a total installed effect of 84GW. In a normal year, this would produce around 180TWh of electricity (European Wind Energy Association, EWEA 2011). To cover the expected growth in energy consumption, this capacity would have to be installed 145 times over. To replace all fossil energy with wind power, that multiplier is 6200.

Even given a massive change in energy policy, it is technically highly unlikely that the necessary increases in renewable energy production and energy efficiency can be achieved. Therefore, large amounts of fossil fuels will continue to be used for decades to come. This makes rapid development of large-scale carbon capture and storage essential if we are to cut greenhouse gas emissions fast enough.

## CO<sub>2</sub> capture

CO<sub>2</sub> can be captured from large emission sources, such as power generation and industry. The technology can also contribute to reducing emissions from transport, by powering vehicles with electricity and hydrogen produced by facilities deploying CCS.

The technology to separate CO<sub>2</sub> from other gases has been in industrial use for more than 80 years, and there are large-scale CCS projects already in operation worldwide. There are also several new projects under construction. In fact, there are now at least 15 projects operating and/or soon to be finalised. The total CO<sub>2</sub> storage capacity of all these projects is more than 33 million tonnes a year. This is broadly equiv-



alent to preventing the emissions from more than six million cars from entering the atmosphere every year.

The most mature CO<sub>2</sub> capture technology separates CO<sub>2</sub> from the exhaust gas after combustion, known as post-combustion separation. A chemical is used to bind CO<sub>2</sub> and separate it from the other flue gases. Several plants use post-combustion technology to capture CO<sub>2</sub> for industrial use. A major advantage of this technology is that it can be retrofitted to the many emission sources that already exist.

There are two other main groups of capture technologies - pre-combustion separation and combustion with pure oxygen, or oxy-fuel.

## Transporting CO<sub>2</sub>

Extensive experience exists in carrying CO<sub>2</sub> by pipeline to sites where it can be used in other processes. For example, in the USA tens of millions of tonnes of CO<sub>2</sub> are transported to oilfields every year for enhanced oil recovery (EOR) projects. Pipeline is the most economical method of transporting CO<sub>2</sub> for distances of up to 1000-1500km, depending on specific conditions and the volume transported. Beyond this distance, transport by ship can be more economical (Zero Emission Platform, ZEP, 2011).

The transport of CO<sub>2</sub> is similar to and no more challenging than the transport of hydrocarbons such as natural gas, petroleum gas and condensates, which are routinely transported by all carriers under a wide variety of conditions.

## Safe storage

The final phase of CCS is safely storing the captured CO<sub>2</sub> underground. Large geological formations exist that have stored CO<sub>2</sub> and natural gas for millions of years.

The IPCC special report on CCS (2005) suggested that the technical potential for storing CO<sub>2</sub> in different geological formations could be at least 2000 billion tonnes, and may even be considerably higher.

Captured CO<sub>2</sub> can be stored in a variety of geological settings - in sedimentary basins, in depleted oil and gas fields, saline aquifers (underground rock formations containing fluids), and deep unmineable coal seams. These can occur within both on and offshore sedimentary basins.

Storage safety is a fundamental aspect of carbon capture and storage. The stored CO<sub>2</sub> must not leak and cause harm. So, before a site is chosen, the geological setting must be studied to ensure the overlying cap rock will provide an effective seal and that there is sufficient capacity and a permeable structure. Techniques developed by the oil and gas exploration industry are suitable for this characterisation of potential CO<sub>2</sub> storage sites.

Monitoring is also an important part of the overall risk management strategy for geological storage projects.

# Background

Many years have passed since the Rio conference of 1992, when world leaders agreed to take action to prevent dangerous man-made climate change. In 2012, the first Kyoto commitment period comes to an end, 15 years after the Kyoto Protocol to tackle global warming was established.

The facts for increased emissions in this period, both since Rio and Kyoto are depressing. Without much more effective mitigation efforts, the world is heading towards a 4°C temperature rise – nearly the double of the maximum 2°C target, which the world leaders have agreed upon.

## Global warming

In climate change, humanity is facing one of its greatest challenges. Despite the increasing awareness of the severe consequences of climate change, global CO<sub>2</sub> emissions from fossil fuels in 2008 were nearly 40 percent higher than those in 1990 (Copenhagen Diagnosis 2009).

The United Nations established the Intergovernmental Panel on Climate Change (IPCC) in 1988. IPCC does not carry out research on its own, its main activity being the evaluation of available research on climate change. Its first report was presented in 1990 and warned about the consequences of global warming. IPCC's fourth assessment report, published in 2007, stated that *"most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."*

The IPCC predicts that in the period 1990–2100 the global average temperature will increase by between 1.4°C and 5.8°C due to human activity. Global warming and rising of sea levels will continue for decades, even if the concentration of greenhouse gases is stabilised immediately (IPCC 2007d).

All research and observations which have been published after the fourth assessment report show that global climate change is continuing at a pace even faster than expected, i.e. the observations lie in the upper scores of IPCC's projections in the third and fourth assessment reports from 2001 and 2007.

Figure 1 shows that the projections for sea level rise have been adjusted to be three times higher than the IPCC (2007) projections.

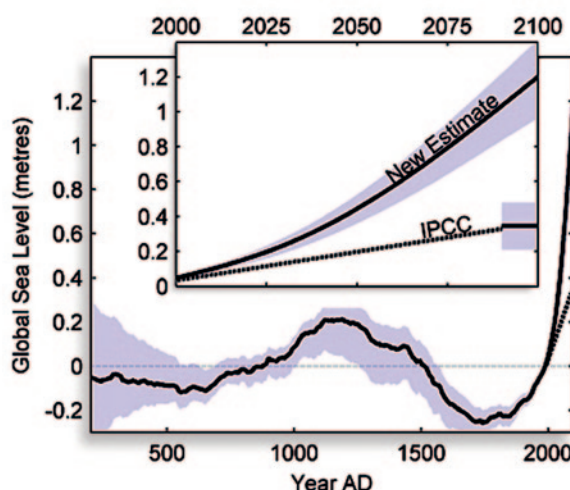


Figure 1: Global sea level from 200 A.D. to 2100 A.D. Source: Dahl-Jensen, 2009

## Consequences

During the UN's international climate change negotiations in Cancun in 2010, most countries agreed upon the target to limit the global average temperature to 2°C above pre-industrial levels.

The higher the global temperature, the more dramatic are the consequences and fewer the possibilities of adaptation. A 2°C rise in the global average temperature means significantly *higher* increases in certain regions: the Arctic will experience an increase of about 5°C to 7°C degrees due to accelerating

heating mechanisms. With a temperature rise of 3°C, the melting of the ice cap on Greenland will cause a two-metre global sea level rising.

From 1979 to 2005, the world has seen a 20 percent reduction of sea ice in the Arctic, and the melting is accelerating. The area of Arctic sea-ice melt during 2007-2009 was about 40 percent greater than the average prediction from IPCC AR4 climate models. Figure 2 shows the area of surface melting across the Greenland Ice Sheet from 1978 to 2008.

Within this century the quantity of water stored in glaciers and snow will be reduced. This will dramatically reduce access to water in regions with mountainous water supplies. One out of six people on Earth live in such regions. Around 75-250 million people in Africa will experience a similar loss in access to drinking water because of the changing climate.

The Himalayas will be exposed to frequent floods, and fresh water quality and access will be adversely affected within the next two or three decades. Central and south-eastern parts of Asia will experience reduced availability to drinking water and parallel rapid population growth, causing a billion people to be severely affected.

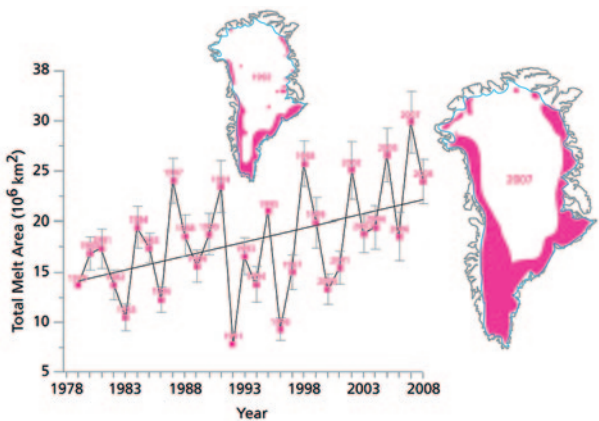


Figure 2: Area of surface melting across the Greenland Ice Sheet, as inferred from satellite observations of the surface temperature. Source: Copenhagen Synthesis Report, 2009.

Around 20-30 percent of all plant and animal species will be exposed to greater risk of extinction with a rise in temperatures of 1.5°C to 2.5°C. Such an increase in temperatures will lead to immense changes in the structure and functions of ecosystems, with a negative impact on biological diversity and food and water supplies. A rise in temperatures will convert tropical rainforests to savannah in the eastern parts of the Amazon.

The impact on food production will vary strongly from region to region. Africa will experience a decrease in areas suitable for agriculture and the growth season will be compressed. This continent is also one of the most exposed to degradation of food security, since the increase in water temperatures in the great lakes will cause damage to fisheries.

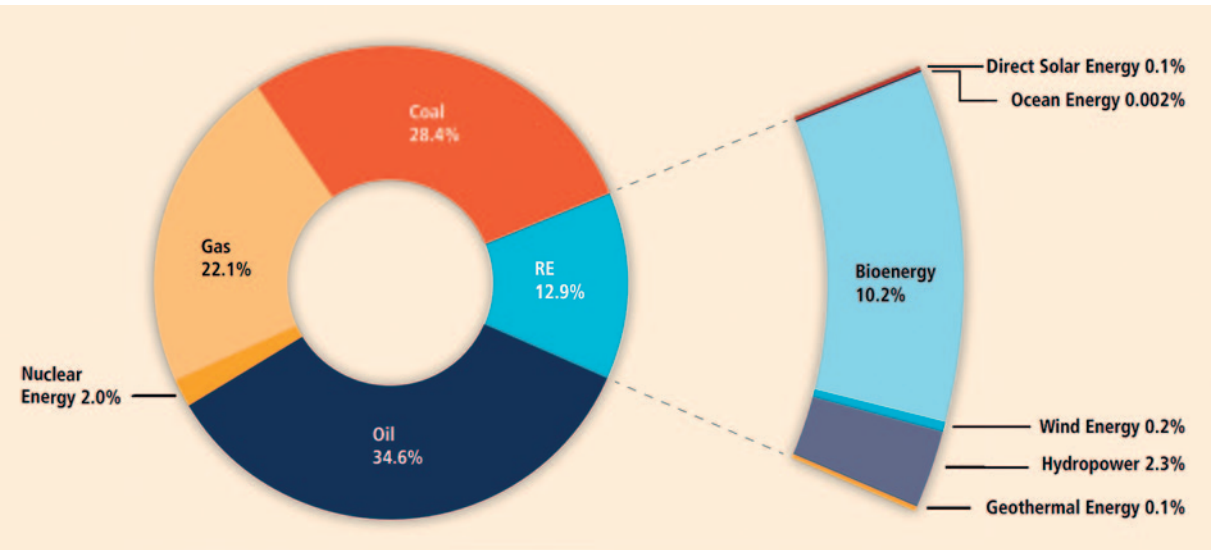


Figure 3: Shares of energy sources in total global primary energy supply in 2008 (Total: 492 EJ). Source: IPCC 2011



Coastal areas are at risk of erosion and rising sea levels. Adaptations to climate change are particularly challenging in coastal regions in developing countries, where a lack of resources reduces the number of practical options.

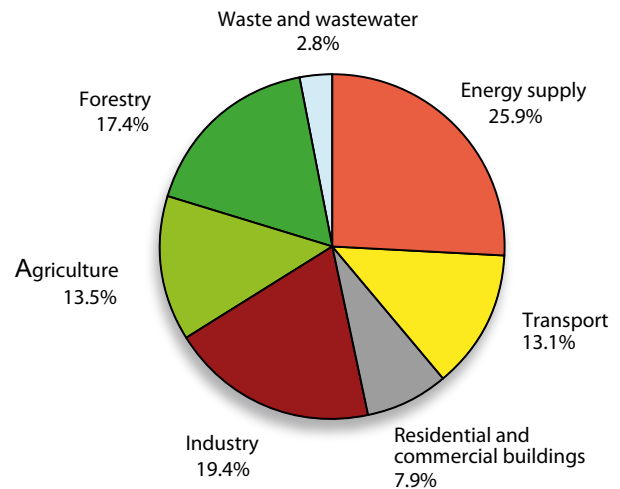
The health of millions of people will be affected by climate change through increased malnutrition, mortality rates and illnesses caused by heat waves, floods, storms, fires and droughts, and also through a possible increase in the spread of certain diseases.

## Where do the Greenhouse gas emissions come from?

From 1970 to 2004, emissions of greenhouse gases (including all gases regulated by the Kyoto Protocol, namely CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFC, PFC and SF<sub>6</sub>) increased from 28.7 gigatonnes to 49Gt CO<sub>2</sub> equivalents (CAIT 2009).

The energy sector had the largest growth in global emissions: 145 percent since 1970. Within the same period the emissions from the transport sector increased by 120 percent and industrial emissions by 65 percent (IPCC 2007a). In 2010, global CO<sub>2</sub> emissions from energy consumption were more than 30 billion tonnes (IEA, WEO 2011). This is an increase by more than 40 percent compared to 1990 (EIA 2011).

On a global basis fossil fuels accounted for 81 percent of the world's primary energy supply in 2008, while the share of renewable energy sources was only 13 percent, as illustrated in figure 3. At the same time, renewable energy contributed approximately 19 percent of global electricity supply, of which 16 percent was hydropower and 3 percent other renewable sources (IPCC 2011).



*Figure 4: Share of different sectors in total GHG emissions in 2004 in terms of CO<sub>2</sub>-eq. (IPCC 2007a)*

## Prognoses

The next decades will see a continuing rise in emissions of greenhouse gases if no significant policy changes are adopted. The IEA predicts that world primary demand for energy will increase by one third between 2010 and 2035 if recent government policy commitments are implemented in a cautious manner. In the same period, energy-related CO<sub>2</sub> emissions will increase by 20 percent, following a trajectory consistent with a long-term rise in the average global temperature in excess of 3.5°C.

The expanding economies of developing countries are an important source of the expected increase of energy requirements and emissions. Around 90 percent of the projected growth in global energy demand will take place in developing countries (non-OECD economies); China alone accounts for more than 30 percent of this projected growth (IEA, WEO 2011). Also the IPCC expects considerable increase in greenhouse gas emissions in developing countries.

Between two thirds and three quarters of increased emissions will take place in undeveloped and newly industrialised countries. However, emissions per capita in industrialised countries (10-15 tonnes CO<sub>2</sub>/capita) will remain considerably higher than in undeveloped and newly industrialised countries (3-5 tonnes) in 2030 (IPCC 2007a, IPCC 2007c).

The IPCC published in 2011 a special report on renewable energy. This report presents over 160 existing

scientific scenarios, which have been reviewed on the possible penetration of renewables by 2050, with four scenarios analysed in-depth. These four were chosen in order to represent the full range.

The most optimistic of the four foresees that renewable energy could account for as much as 77 percent of the world's energy demand by 2050, amounting to about 87,000 TWh of an annual global energy consumption of 113,000 TWh. This scenario implies remarkable efforts within energy efficiency: in 2008, global energy supply amounted to 137,000 TWh. Such a development thus depends on a consistent climate and energy policy among the world's policy makers (IPCC 2011).

While the scenarios arrive at a range of estimates, the overall conclusions are that renewables will take an increasing slice of the energy market. The IPCC further states that the rising penetration of renewable energy could lead to cumulative greenhouse gas savings equivalent to 220 to 560Gt CO<sub>2</sub>eq between 2010 and 2050 (IPCC 2011).

Wind and solar (photovoltaic) energy are the fastest growing renewables with respectively 32 percent and 53 percent yearly increases in 2009, but the basis for this growth is low (IPCC 2011). The IEA is more moderate in its renewable prognoses for development in its New Policies Scenario (which assumes that recent government policy commitments are implemented in a cautious manner).

The IEA assumes that the share of non-hydro renewables in power generation will increase from 3 percent in 2009 to 15 percent in 2035. Figure 5 shows the IEA's estimates for world primary energy demand until 2035 with rising shares of renewables, gas and nuclear energy (IEA 2011).

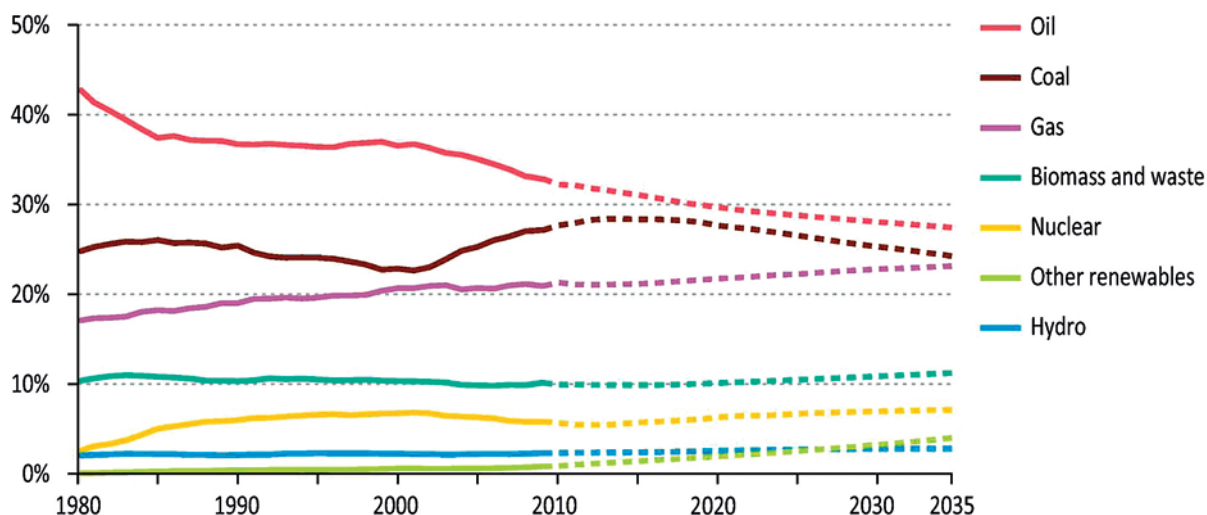


Figure 5: Shares of energy sources in world primary energy demand in the New Policies Scenario, IEA (2011)

## How large reductions are needed?

At the COP15 in Copenhagen and COP16 in Mexico, the attending countries (with minor exceptions) agreed upon 2°C as an overall target for a new international climate agreement, after the first commitment period of the Kyoto Protocol expires in 2012.

To achieve the 2°C target, the concentration of all greenhouse gases must be stabilised at between 400-450 parts per million (ppm) CO<sub>2</sub>e, according to IPCC's fourth assessment report. In order to remain below 2°C with 75 percent probability, global greenhouse gas gases should be stabilised at 400ppm. In 2011, the concentration of CO<sub>2</sub> in the atmosphere was already 394 ppm, more than 100 ppm above pre-industrial level.

The 2°C target also implies that the global emissions must be reduced by 50-85 percent by 2050, compared to 1990 levels, and peak in 2020 at the latest.

Figure 6 shows the trade-off between emission reductions in Annex I (developed) countries and non-Annex I (developing) countries for the years 2020 and 2050. In (b), it becomes clear that if the Annex I countries reduce their emissions by 80-95 percent compared to 1990, the non-Annex I countries will still have to reduce their emissions by 70-75 percent compared to their baseline in order to remain on the 450ppm path. The baseline is the expected emission development, which is calculated based on the different countries' population growth, economic growth etc.

## How to achieve necessary reductions

These challenges may seem insurmountable, but an often ignored fact is that many emission sources of the future have yet to be built. This means that we have a choice, and if we focus on building emission-free sites, emissions will eventually be reduced. Zero-emission solutions are no longer an alternative but an obligation if the worst climate changes are to be avoided.

Prognoses show significant increases in the emissions of CO<sub>2</sub>. Of course, prognoses are only predictions made on assumptions. Therefore, it is possible to get more comprehensive climate policies. The question is whether it is possible to cover both the growing demand for energy and to achieve the needed large reduction in emissions of greenhouse gases based on renewable energy and increased energy efficiency alone by 2030.

According to the scenarios in IEA's World Energy Outlook 2011, the long economic lifetimes of much of the world's energy-related capital stock mean that there is little scope for delaying action if we are to reach the 2°C target. The IEA calculates that four-fifths of the total energy-related CO<sub>2</sub> emissions permissible by 2035 in the 2°C scenario are already "locked-in" by capital stock (power plants, buildings, factories, etc.) that either exists now or is under construction and will still be operational by 2035. This leaves very little additional room for emitting greenhouse gases from additional sources.

If internationally co-ordinated action is not taken by 2017, the IEA projects that all permissible emissions in a 2°C scenario would come from the infrastructure then existing, so that all new infrastructure from then until 2035 would need to be zero-carbon, unless emitting infrastructure is retired before the end of its economic lifetime to make headroom for new investment (IEA 2011).

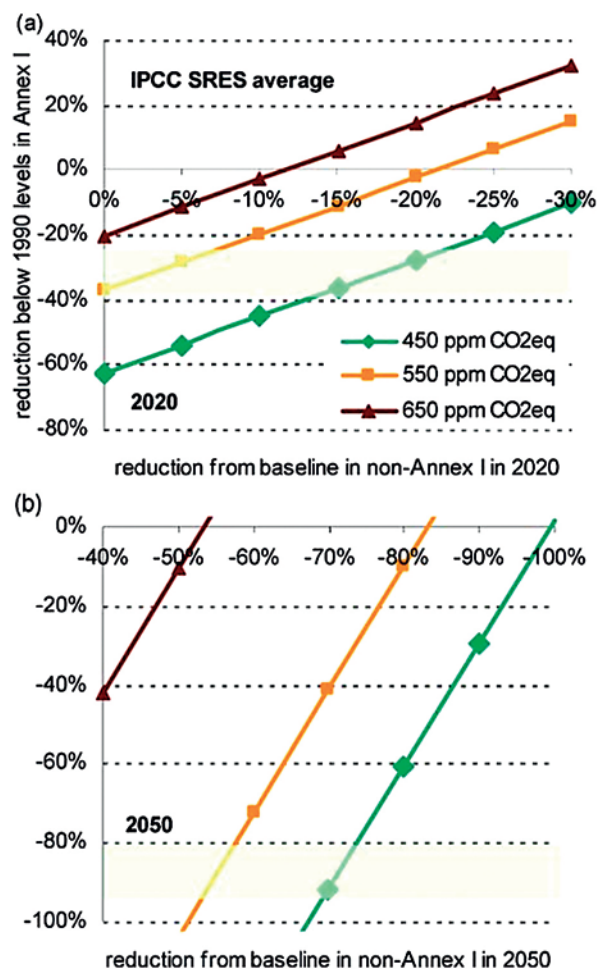


Figure 6: The trade-off in reductions in 2020 (a) and 2050 (b) in Annex 1 and non-Annex 1 countries as a group for three concentration stabilisation levels. The numbers represent the averaged outcome over separate calculations for each of the six IPCC SRES baselines (IPCC SRES average). (Den Elzen and Höhne 2008)

Delaying action is a false economy: for every \$1 of investment avoided in the power sector before 2020, an additional \$4.3 would need to be spent after 2020 to compensate for the increased emissions (IEA 2011).

## Large emission sources from industry

Carbon capture and storage from fossil fuel power plants and industry will enable reduction of greenhouse gas emissions that would otherwise go straight into the atmosphere. It will serve as a decisive addition to the use of renewable energy and increased energy efficiency in cutting emissions fast and efficiently.

The IEA perceives CCS as a key abatement option, accounting for 18 percent of emissions savings in the 2°C scenario (i.e. 450ppm scenario) relative to the New Policies Scenario (IEA 2011).

Carbon capture is possible at large emission sources, such as fossil power plants and industry. The IPCC special report on CCS from 2005 identifies near 8000 large emission sources worldwide (IPCC 2005a).

These sources are dispersed over the entire globe, but four regions stand out: North America, north western Europe, the east coast of South-East Asia, and the Indian subcontinent. In the coming century the number of large emission sources is assumed to rise, especially in south and south-eastern parts of Asia. The number of sources for CCS in Europe will, however, decrease slightly (IPCC2005b).

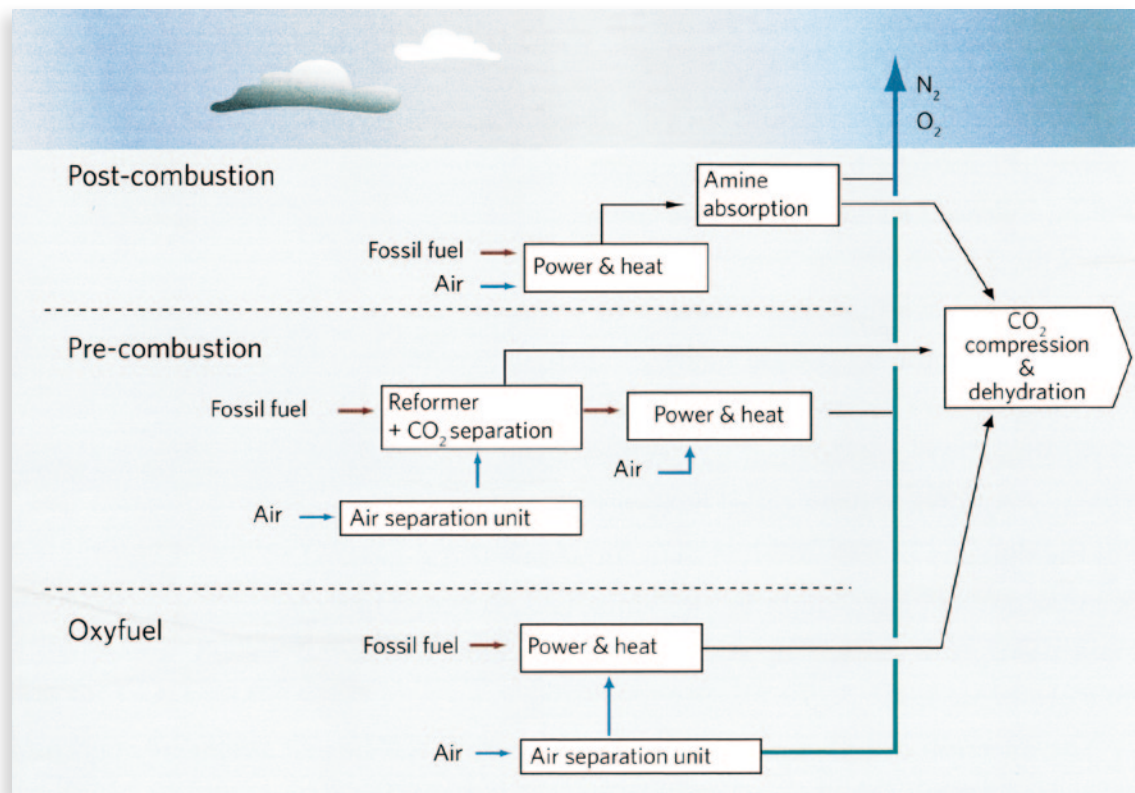
In the longer term, carbon capture can reduce emissions in the transport sector by changing from petroleum fuels to electric and/or hydrogen fuels for vehicles (IPCC 2005a).

IPCC emphasises CCS as a key technology to enable cuts in the emissions from energy production and the industry. The most ambitious scenarios have CCS in addition to increased focus on non-fossil energy sources, to achieve necessary emissions reductions (2007a).

# Capture technologies

CO<sub>2</sub> has been captured from industrial process streams for more than 80 years. It is also captured in relatively large amounts for commercial uses in, for example, urea and ammonia production, for the production of food grade CO<sub>2</sub> used in the brewery industry and in greenhouses to maintain optimal CO<sub>2</sub> concentrations. In Lubbock, Texas CO<sub>2</sub> was captured from a gas fired power plant and used for enhanced oil recovery (EOR) as early as 1980. Extensive experiences from these processes and other CO<sub>2</sub> uses can be utilised to realise full-scale carbon capture plants.

Capture technologies can be distinguished as three main categories, depending on what stage of the process the CO<sub>2</sub> is removed.



Figur 7: Simplified diagram illustrating the three main approaches to carbon capture.  
(Source: Freund & Kårstad 2007)



When separating CO<sub>2</sub> from the exhaust gases after combustion (post-combustion separation), a chemical is utilised to bind CO<sub>2</sub> and separate it from the other flue gases. This is a technology that has been in use for decades. It is well developed commercially and suitable for both new projects and post-fitting onto existing point sources.

Separating CO<sub>2</sub> from fuel before combustion (pre-combustion separation) is another solution. Under high temperatures it is possible to split hydrocarbons into hydrogen and CO<sub>2</sub>. The CO<sub>2</sub> can then be removed before combustion and the reactor is fuelled with hydrogen, which emits only water when combusted. The process to split hydrocarbons, by gasification of coal or reforming of natural gas, is being used in many industrial processes, such as ammonia production. This also applies for combustion and power production using gases with high hydrogen content.

Combustion with pure oxygen (oxy-fuel combustion) is the third major approach to CO<sub>2</sub> capture. In oxy-fuel combustion oxygen is extracted from the air and the fuel is combusted in pure oxygen. When fuels are burned with pure oxygen, the exhaust gas consists of CO<sub>2</sub> and water vapour. The separation of CO<sub>2</sub> is done by decreasing the temperature so that vapour condenses out as water. Large-scale air separation units producing pure oxygen are in commercial use for different kinds of industrial processes.



*The world's first gas power plant with CO<sub>2</sub> capture, in Lubbock, Texas (1980).*

# Post-combustion capture

Today, capturing (or separating  $\text{CO}_2$  from flue gases)  $\text{CO}_2$  using amines is the most widespread method for post-combustion capture.

Amine technology has already been used for decades to capture  $\text{CO}_2$  from both flue gas and natural gas. Several installations exist, of which several are operative. The first gas power plant using this technology was built in 1980 in Lubbock, Texas. Today, companies like Fluor Daniel from UK/USA, Mitsubishi Heavy Industries from Japan, Aker Clean Carbon from Norway and CanSolv from Canada can deliver full-scale, amine based post-combustion separation equipment.

Among the different separation methods post-combustion separation is the most versatile; it can be fitted to many different types of emitters – both power plants and industrial plants – and separation equipment can be post-fitted on existing emission sources. However, such separation equipment requires an available space close to the emission source.

The composition of the flue gas stream will differ depending on the emission source. While exhaust gas from a conventional gas power plant contains 3-4 percent  $\text{CO}_2$ , the equivalent figure for coal power plants is 12-14 percent, and cement industry approximately 20 percent. Differences in flue gas composition,  $\text{CO}_2$  concentration and flue gas pressure affect the choice of chemicals.

How much of the  $\text{CO}_2$  that can be separated is largely a matter of cost. It is possible to separate practically all  $\text{CO}_2$  from a flue stream, but getting at the last few percents requires considerably more energy and is therefore expensive. Typical  $\text{CO}_2$  recoveries from flue gas with amines are about 85 percent, but it is possible to have a higher capture rate.

Other chemicals, such as ammonia, can also be used to bind  $\text{CO}_2$ . Ammonia has been extensively tested in laboratories as a  $\text{CO}_2$  solvent and large demonstration plants have been built.

## Removing $\text{CO}_2$ using amines

In this process the flue gas flows through a large tower called an absorber or scrubber. In this so-called absorption process, the gas comes into contact with the absorption fluid (amines mixed with water) fixing the  $\text{CO}_2$  in a relatively weak chemical bonding. The bound  $\text{CO}_2$  is transported to another tower, called a stripper, where the solvent is heated. This separates the  $\text{CO}_2$  from the amines in a process called regeneration. The amines are then reused to absorb more  $\text{CO}_2$ .

Flue gas from gas power plants has a temperature of about 80 – 100°C. The flue gas should usually be cooled to about 40°C before absorption.

A 400MW gas power plant produces a flue gas stream of approximately 2.5 mil-

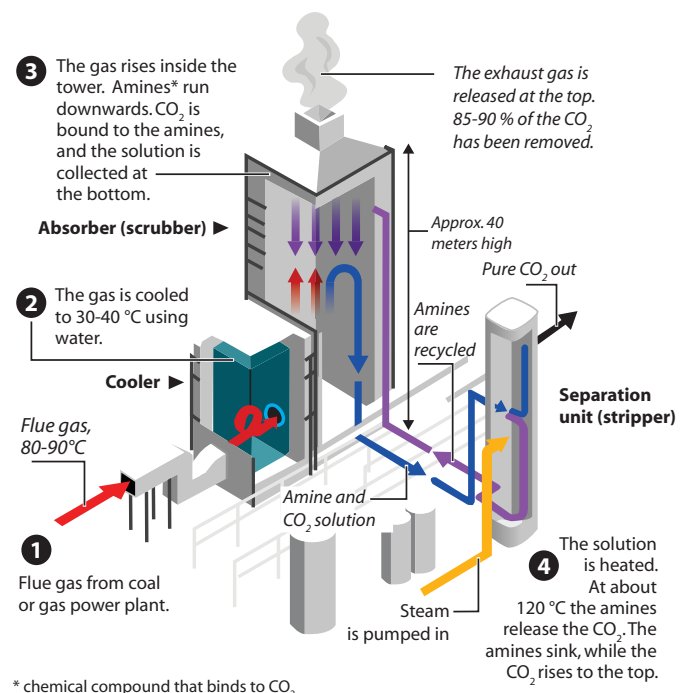


Figure 8: Illustration of a  $\text{CO}_2$  capture facility using amine absorption (Source: ZERO and Mitsubishi)



lion Nm<sup>3</sup>/hour. To treat this amount of gas, an absorption tower with a diameter of 20-30metres and a height of 30-40 metres is required. This will be the largest single unit in the separation facility. The tower is filled with packing to provide the largest possible surface for contact between the upward-rising gas and downward-running amine solution. At the top, a washing tower removes any amine residue that has followed the flue gas stream before the CO<sub>2</sub>-free flue gas is released into the atmosphere.

## The capture plant's energy consumption

The most energy consuming part of the capture process is the heating required to separate CO<sub>2</sub> from the amine solution. This heat is provided by steam holding 120-140°C. The energy can be provided from different sources e.g. excess energy from an industrial process. However, in the case of capturing CO<sub>2</sub> from a gas or coal-fired power plant, the most convenient alternative is to use steam from a steam generator/turbine.

There is also electricity consumption in the process. Fans and pumps are used to compensate for loss in pressure in the absorption tower, to pump amine solution and the cooling water around and to compress or cool CO<sub>2</sub> before transporting. The energy demands of this kind of CO<sub>2</sub> removal process reduces the electricity generating efficiency of a typical new gas power plant from about 58 percent to 51 percent. For coal, the efficiency loss is somewhat bigger - because of larger amounts of CO<sub>2</sub> - from about 45 percent to about 38 percent.

Choosing the right amine for separating CO<sub>2</sub> depends on several conditions. The most used amine compound for flue gas CO<sub>2</sub> removal at atmospheric pressure is *monoethanolamine* (MEA). To remove CO<sub>2</sub> at higher pressures *methyldiethanolamine* (MDEA) is often used. Many suppliers of amine separation plants supply their own mixture of amines and additives, adapted to the intended use. Best known is KS-1 from Mitsubishi Heavy Industries. Considerable improvements in energy efficiency have been achieved over the decades of commercial application of amine technology. More efficient system designs and heat integration in the process plants are two areas where further development is taking place.

## Efficiency

Plant efficiency is often termed as the percentage of fuel energy actually utilised in a given facility.

In gas-fired plants the gas turbine converts almost 40 percent of the energy in the fuel to electricity. The hot exhaust gas is then used to produce steam which in turn drives a steam turbine converting another 20 percent of input fuel energy into electrical power. The added amount of electricity generated is called the *electrical generation efficiency* of the plant. The surplus energy now exists as heat, and when not used this is called waste heat. A power plant may also deliver heat to industrial processes or district heating. If high temperatures are required, steam will be tapped from the generation cycle, somewhat reducing electrical output. The amount of energy utilised either as electrical power or heat compared to the energy input is called *total plant efficiency*.

When CO<sub>2</sub> from a power plant is captured, transported and stored it is generally said that efficiency decreases by some percentage points. This is not quite correct, as energy does not cease to exist. If capture equipment is integrated within the power plant, some of the heat that would otherwise have been wasted can be used in the capture process. The energy required for CCS in a power plant is mostly distributed as seven percentage points of electricity and 14 percentage points of heat. In conventional gas power plants 58 percent of the supplied fuel is converted into power, the rest wasted as heat unless used for district heating; in fact, the total energy utilisation for a plant with CCS would be 72 percent. If we acknowledge that CCS is at least as legitimate a use of power as any other use, a plant with integrated CCS is therefore more efficient than a conventional plant.

From an environmental point of view the emission level, not the efficiency, is of paramount concern. The problem is not that there is a limited supply of fossil fuels in the world, but that there is too much.

## Removing CO<sub>2</sub> using ammonia

Removing CO<sub>2</sub> using ammonia is a similar process to using amines, but has the advantage that the re-generation process requires less energy.

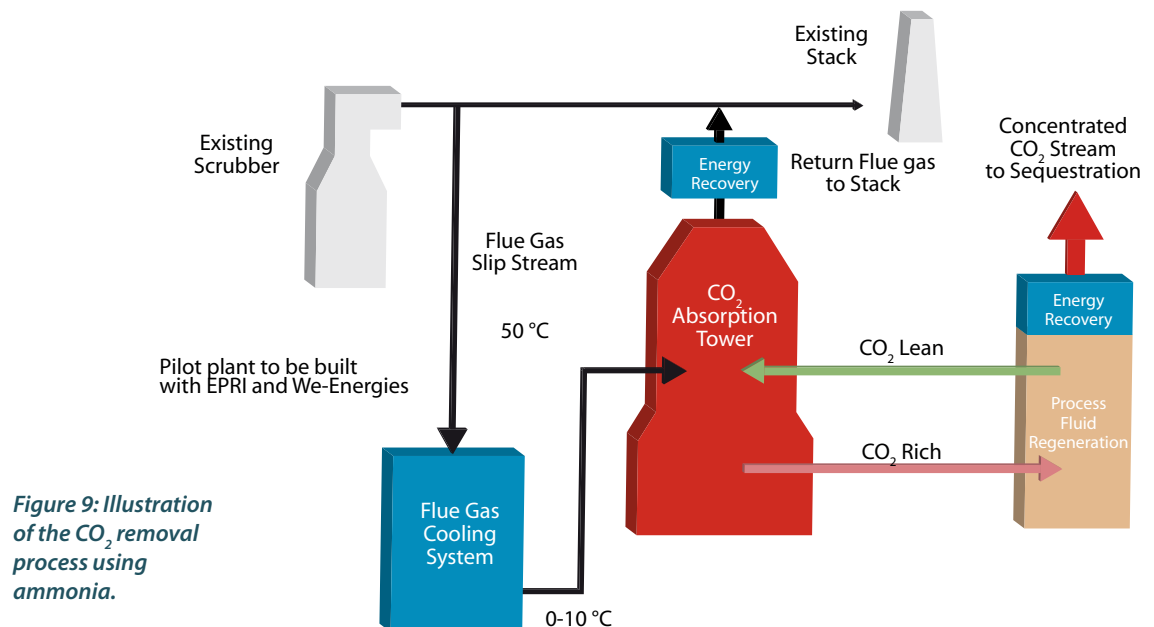
The challenge is that ammonia is highly volatile and vaporises easily. In CO<sub>2</sub> separation this can be solved by using energy to cool the flue gas before separation. This will slow down the reaction speed and increase the size of the required absorber.

The chilled ammonia process has been extensively tested in several projects. The We Energies Field Pilot, designed to capture over 15,000 tonnes per annum of CO<sub>2</sub>, was operated during October 2009. This project demonstrated that chilled ammonia CO<sub>2</sub> capture could be applied to coal-fired applications.

American Electric Power (AEP) has built a demonstration plant for 100,000 t/y at the Mountaineer Plant power plant in New Haven, West Virginia. The plant started in 2009 and the validation programme has now been successfully completed. The full-scale plant, set to be operational by 2015, was postponed in 2011. This was due to lack of financial incentives. When operational, the facility will test Alstom's chilled ammonia technology for CO<sub>2</sub> capture from flue gases – which is of specific use at natural gas combined cycle power plants. The project will capture at least 90 percent of CO<sub>2</sub> from 235MW of Mountaineer's 1300 MW capacity, or about 1.5 million tonnes per year.

The ammonia technology is approved for flue gas with high levels of CO<sub>2</sub> such as from coal. The flue gas is cooled, reaching a temperature between 0 and 10°C, and is transported to the absorber where it meets ammonia in aqueous solution. The reaction with CO<sub>2</sub> produces ammonium carbonate and ammonium bicarbonate. The remaining flue gas is led through a washing process to remove any remaining ammonia. The solution is heated in a separate reactor – a desorber – so that CO<sub>2</sub> is released, and remaining ammonia is reused to capture more CO<sub>2</sub>.

Alstom are building a demo plant for the chilled ammonia process at Technology Centre Mongstad (TCM) in Norway. This will be in operation in the first half of 2012. This testing is expected to give answers on how well this technology is suited to capturing CO<sub>2</sub> from gas streams with lower CO<sub>2</sub> concentrations, such as gas-fired power plants.



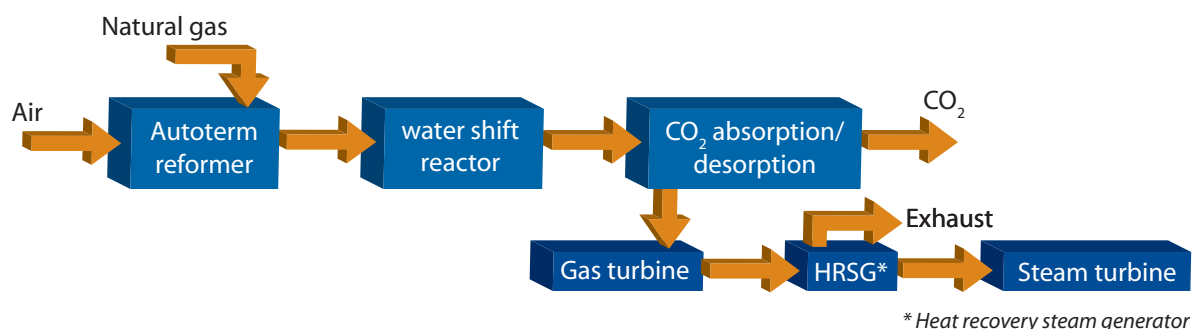


# Pre-combustion capture

When separating CO<sub>2</sub> before combustion the fuel is converted into a mixture of hydrogen and CO<sub>2</sub>, which can be separated relatively easily.

The same technological principles are applicable for power production using coal and gas, but the gasification process in the first stage of the plant will vary.

Figure 10 shows a simple flowchart of the main processes in a hydrogen fuelled power plant with natural gas reformation. Fuel, water vapour and air are mixed in a reactor for chemical reforming of the fuel into carbon monoxide (CO) and hydrogen (H<sub>2</sub>). Reforming takes place at a high temperature and pressure and requires a supply of energy. The synthesis gas is then further converted to additional hydrogen in a so-called water shift reactor after being cooled to about 300°C. In this process CO reacts with water (H<sub>2</sub>O) to form CO<sub>2</sub> and H<sub>2</sub>. CO<sub>2</sub> is removed using amine absorption and hydrogen is used to fuel a gas turbine. Combustion of hydrogen emits no CO<sub>2</sub>, only water vapour.



Figur 10: Illustration of natural gas reformation.

Reforming of natural gas takes place at high temperatures and requires large amounts of energy. This reduces the electrical generation efficiency by 11 to 14 percentage points compared to conventional natural gas power plants. With the current technological level of gas turbines the generation efficiency of a plant of this type would be 44-47 percent.

To improve efficiency, research is exploring ways to reform the natural gas at lower temperatures and/or using less steam. Another possibility is to have the CO<sub>2</sub> separation and the feeding of hydrogen to the turbine happen at higher temperatures. To achieve this, the equilibrium for the reactions must be shifted by removing hydrogen or CO<sub>2</sub> in the process.

A gas power plant using natural gas reforming has yet to be built, but both natural gas reforming and gas turbines using high concentrations of hydrogen are technologies currently in use. This means the technology is considered to be mature and available and that such plants can be built as fast as conventional gas power plants. An advantage for this technology is its potential combination with the production of hydrogen for other purposes, such as hydrogen fuel. Compared to post-combustion separation less energy is required to pressurise CO<sub>2</sub> for transport using this technology. The equipment is also smaller and can be built on a smaller site.

Technological development is needed to achieve hydrogen combustion with low NO<sub>x</sub> emissions combined with high efficiency. Hydrogen burns at a very high temperature. Current combustion chamber technology cannot burn pure hydrogen, which has to be mixed with nitrogen and/or water vapour to reduce temperature and NO<sub>x</sub> emissions. The NO<sub>x</sub> problem can be solved by developing better combustion technology or by removing NO<sub>x</sub> using a process such as selective catalytic reduction (SCR); this is already required in conventional gas power plants to meet NO<sub>x</sub> emission limits.

# Oxy-fuel combustion

In the so-called oxy-fuel process the combustion takes place using pure oxygen rather than air. The exhaust gas consists of water vapour and  $\text{CO}_2$ , which is separated by cooling the flue gas so that the water vapour condenses into liquid.

This method requires large quantities of oxygen that usually is extracted from air. Air consists of 78 percent nitrogen, 21 percent oxygen and smaller quantities of other gases, such as Argon and  $\text{CO}_2$ . Figure 11 is a simplified illustration on Vattenfall's oxyfuel process where a separation unit delivers oxygen to the combustion chamber.

## Oxyfuel ( $\text{O}_2/\text{CO}_2$ recycle) combustion capture

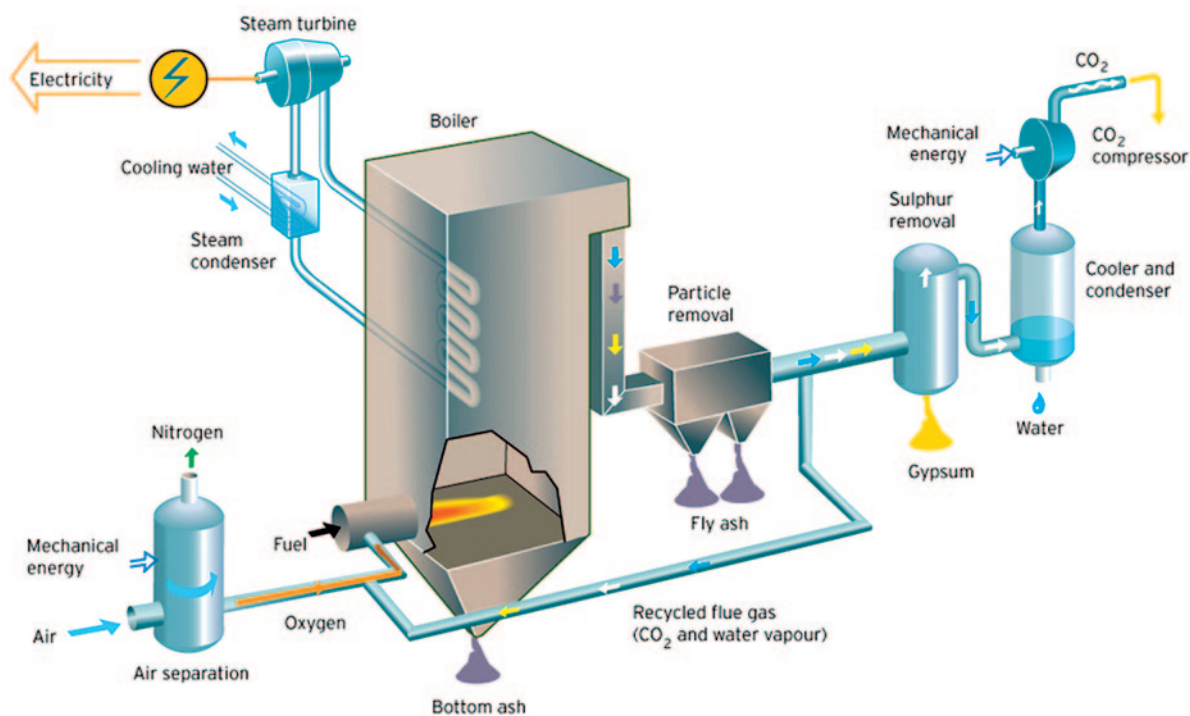


Figure 11: Simplified flowchart for an oxy-fuel power plant. (Source: Kjell-design / Vattenfall)

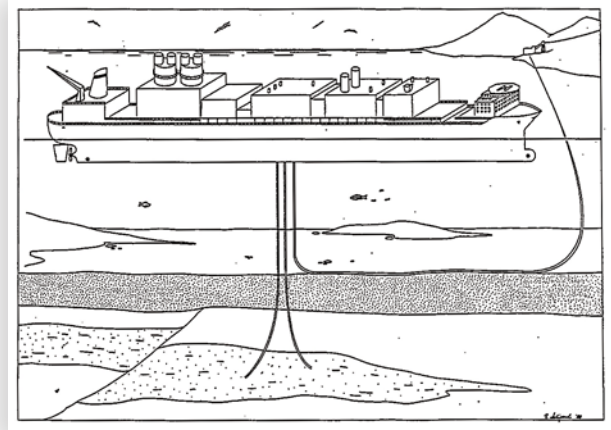
Combustion with pure oxygen generates very high temperatures. Combustion chamber technology must therefore be changed to allow for recycled  $\text{CO}_2$  or water vapour to be used as inert gas in oxy-fuel projects.

Combustion with pure oxygen emits virtually no  $\text{NO}_x$  as there is no nitrogen from the air from which  $\text{NO}_x$  could form; only small quantities of nitrogen in the fuel may lead to the forming of some  $\text{NO}_x$ . The exhaust gas consists almost exclusively of  $\text{CO}_2$  and water vapour. The water vapour is removed by cooling the flue gas so that the water vapour condensates into liquid, leaving almost pure concentrated  $\text{CO}_2$  in the exhaust gas.

Electrical generation efficiency in oxy-fuel plants may be higher than in conventional plants using combustion with air. But air separation and  $\text{CO}_2$  compression requires energy, leading to an overall loss in effi-

ciency of about 12 percent. The power generation efficiency of a combined cycle gas power plant with oxygen combustion and CO<sub>2</sub> compression is therefore 43-48 percent.

The advantages of oxy-fuel technology are that it provides a relatively simple way to capture nearly all CO<sub>2</sub> with virtually no emissions. It can be realised technically by using conventional steam turbine technology, and air separation is a well-known and mature technology with many existing installations and suppliers. Oxy-fuel technology is equally suited for gas and coal power plants and can be an alternative for post-fitting when existing plants are modernised or rebuilt.



*Figure 12: Offshore gas power plant with CO<sub>2</sub> capture, from 1988 (Source: Holt & Lindberg).*

Plans for an offshore gas power plant with oxy-fuel CO<sub>2</sub> capture was made public as early as 1987. In many ways this marked the beginning of efforts to provide an alternative energy supply to Norwegian petroleum activity. In 1988 a report to Statoil contained a study of the concept, called "Environmentally friendly gas power combined with EOR" (Holt & Lindeberg 1988). The concept is illustrated in figure 12.

## Vattenfall builds oxy-fuel pilot

In 2008 Vattenfall opened a 30MW oxy-fuel pilot plant, located near the existing lignite fired 1600 MW power plant in Schwarze Pumpe, Germany. The plant has the capacity to capture 9 tonnes of CO<sub>2</sub> per hour, which translates into 75,000 t/y at full load.

The purpose of the pilot plant is to validate and improve CO<sub>2</sub> capture technology.

Originally, the separated and liquefied CO<sub>2</sub> produced by the pilot plant should have been transported by truck to the storage site in Altmark 350km away (see below). Public protests together with a lack of federal storage legislation have brought the Altmark project to a halt. However, in May 2011, the first tonnes of CO<sub>2</sub> captured at Schwarze Pumpe were stored geologically in onshore saline aquifers transported by truck to the storage project in Ketzin.

## Altmark

With a storage potential of 508Mt, the reservoir currently has the largest storage volume available in depleted gas fields in Europe and is the only nearly exhausted gas field capable of storing the CO<sub>2</sub> from a power plant over its entire lifespan. Being already investigated, explored and developed, this gas field therefore provides very favourable conditions for developing the entire CO<sub>2</sub> value chain. Vattenfall planned to inject up to 10,000 tonnes of CO<sub>2</sub> in the 3000m deep gas storage site.

The project is accompanied by the research project CLEAN (Geotechnologien), which will provide support for the development of technologies and methods for CO<sub>2</sub> storage and enhanced gas recovery (EGR). Seventeen research institutions and companies are involved. From 2008 to 2010, injection technologies, the characterisation the geological formations and process monitoring were investigated.

# Future technologies

Many technologies require considerably more research and development to be considered mature for full-scale implementation. The following technologies present a number of possibilities for the future.

## Chemical looping combustion

In this process pure oxygen for combustion is supplied by circulating metals that bind oxygen from the air.

Two separate reactors are used. In the first one the metal reacts with oxygen under pressure and a temperature of 400-500°C. The oxygen is bound to the metal, which oxidises to form a metal oxide. This in turn is transported to the next reactor, where the oxygen is released at 500-900°C in a reaction with natural gas. The metal is then recycled and transported back to the first reactor. Instead of moving large volumes of metal from one reactor to another, it is possible to have each reactor play a dual role, alternating between supplying air and fuel to each reactor.

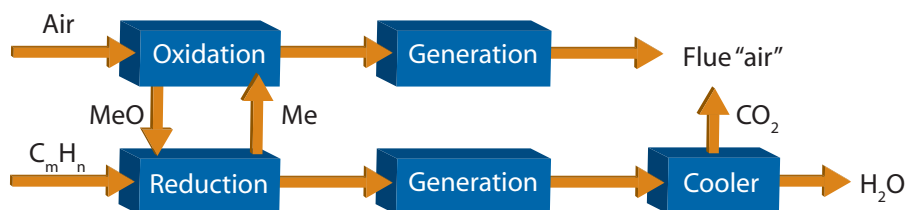


Figure 13: Chemical looping combustion.

From the reactor the exhaust gas is led through a turbine to generate power. As in any other oxy-fuel process  $CO_2$  is separated, by cooling the exhaust gas and condensing the water. In addition, some power may be generated in a turbine from the warm oxygen-lean air from the oxidation process. Research on this technology is being carried out at the Norwegian University of Science and Technology and Chalmers in Sweden, among other places.

## Solid Oxide Fuel Cells (SOFC)

Solid oxide fuel cells operate at very high temperatures. They are made of ceramic materials requiring temperatures as high as 1000°C to acquire the necessary conductivity in the cell.

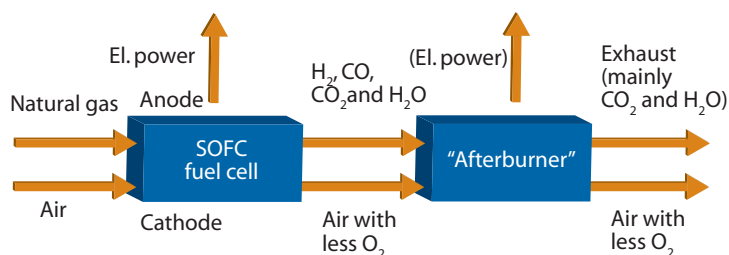


Figure 14: Solide oxide fuel cell

Fuel cells offer the possibility for more efficient power production than with combustion. In general, fuel cells feature the electrochemical oxidation of gaseous fuels directly producing electricity.

Power generation efficiency using SOFC technology is about 48-50 percent. The fuel cell will leave an excess stream of around 15 percent that does not react. This could be used to fuel an afterburner to provide extra power generation in a turbine. Such a hybrid solution may yield 60-70 percent generation efficiency.

These systems make use of the internal reforming capabilities of the high temperature fuel cells. By running natural gas through a reforming process with water at 600-800 C° the natural gas can decompose to a mixture of hydrogen and CO<sub>2</sub>. The hydrogen can be used in a gas turbine or a fuel cell, which then produces electricity.

## ZEG

The Norwegian Institute for Energy Technology (IFE) is developing a process for CO<sub>2</sub> capture using calcium carbonate at high temperatures integrated with a SOFC. In a joint venture with Christian Michelsen Research (CMR) and Prototech, IFE is conducting lab tests on combined power and hydrogen production with carbon capture, called ZEG (Zero Emission Gas Power Project).

Here, natural gas is reformed to hydrogen and CO<sub>2</sub> in a reactor at high temperature. Calcium oxide is supplied, reacting with the CO<sub>2</sub> to form calcium carbonate. Heat from the fuel cell is used to separate CO<sub>2</sub> from the carbonate. Regenerated calcium oxide is recycled and used to capture more CO<sub>2</sub>. The process produces both electricity and hydrogen.

## Hydrogen membrane reactor

In hydrogen membrane reactors hydrogen is produced using a membrane that separates hydrogen from a given gas mixture. This reaction is therefore more complete than in conventional reactors, and the technology can improve efficiency of pre-combustion carbon capture.

With this membrane natural gas and steam is transported through a pipe filled with small spheres of catalytic material. CO and H<sub>2</sub> are formed in the reforming process, through which hydrogen is continuously tapped through the pipe wall. The reaction is more complete and can take place at a lower temperature with lower steam surplus and at a higher pressure – all in all reducing the energy loss. However, acquiring adequate materials and a practical design for integrated high temperature membranes is very difficult.



# CO<sub>2</sub> capture from industrial sites

Large amount of the CO<sub>2</sub> emitted around the world comes from production of industrial products like cement, ammonia, urea, pulp and petrochemical industry. Capture from most industrial sites can undergo the same capture technologies used for power plants.

Within industry, iron and steel manufacturing now contributes the largest proportion (30 percent) of CO<sub>2</sub> emissions, followed by cement (26 percent) and chemical production (17 percent) (IEA, 2009a). But this picture is changing rapidly. As late as 2005 the IPCC said the production of iron and steel was the third largest contributor of CO<sub>2</sub> after cement production and refining. Most current applications of CCS are in industry.

In the context of enabling CCS in general, industrial applications are important because they can provide valuable experience with regards to capture techniques, transport infrastructure, suitability of storage sites and the behaviour of stored CO<sub>2</sub>. This knowledge can then be transferred to larger-scale and more complex CCS deployment in both industry and power generation (IEA, 2009c). As a whole, industry is a major contributor to global CO<sub>2</sub> emissions, although the extent may vary depending on each country and region. Therefore, the application of CCS in industry could become a catalyst for more widespread use of CCS in other areas as well.

## Cement production

Production of cement, involving the calcination of limestone, is the largest industrial source of CO<sub>2</sub> emissions globally apart from the power sector, accounting for about 1000Mt/y of CO<sub>2</sub>. In addition, large quantities of heat energy are needed to drive the process and this energy is usually taken from fossil fuels.

### Industrial use of CO<sub>2</sub>

For decades a number of countries have captured, transported and used CO<sub>2</sub> in the food industry, in the chemical industry and for EOR. CO<sub>2</sub> is captured from natural gas, industrial processes, and coal or gas power plants.

CO<sub>2</sub> is used in the production of soft drinks and beers, for keeping optimal CO<sub>2</sub> concentrations in greenhouses, in fire extinguishers, in fertilisers and in the production of chemical products such as methanol. It can also be used for cooling and wrapping in food production.

The production of CO<sub>2</sub> for commercial purposes is a well-established industry, and the gas is an important commodity in the food industry. The European market is continually growing, and in 2004 sales were at almost 3 million tonnes, of which 70 percent was used as additives in beverage production.

However, most of the current industrial uses do not reduce CO<sub>2</sub> emissions. In days, weeks or months the CO<sub>2</sub> that has been captured is emitted back into the atmosphere.

The concentration of CO<sub>2</sub> in the flue gases from cement production is 15-30 percent by volume. With this high CO<sub>2</sub> concentration, post-combustion capture technologies are well suited to cement production plants. It is possible to utilise waste heat from the cement kilns in the capture facility, but capture of a high percentage of the emitted CO<sub>2</sub> would require additional generation of steam for the regeneration process.

## Oil and gas processing

Emissions from the processing of natural gas and from oil refineries account for about 850 Mt/y of CO<sub>2</sub>. The majority of these emissions come from oil refineries. Emissions from the generation of electric energy, heat energy and steam used in the various processes on the plant, and emissions from the production of hydrogen, would be most viable for capture. In principle, most capture methods suitable for power plants could be integrated into a refinery. Limitations in the area available and specific needs in modes of energy delivery may limit the options.

The processing of natural gas from sources with high CO<sub>2</sub> content involves removing CO<sub>2</sub> from the gas stream. This process produces an almost pure stream of CO<sub>2</sub>. Gas captured from natural gas processing is used in several EOR projects in the USA.

The Sleipner plant in the North Sea, the Snøhvit plant at Melkøya in northern Norway and the In Salah plant in Algeria are three operating natural gas plants that currently capture and store CO<sub>2</sub> from natural gas processing.

## Steel Production

The iron and steel industry is a major industrial emission sector, accounting for about 650 Mt/y of CO<sub>2</sub>. The integrated steel plants are used predominantly to produce steel from iron ore in a blast furnace, using coal as the primary fuel.

In many blast furnace operations, CO<sub>2</sub> removal is already integrated in the process. The blast furnace process involves reacting iron ore with CO to remove carbon from the ore, producing CO<sub>2</sub>. The top gas in these furnaces is a mixture of CO, CO<sub>2</sub> and H<sub>2</sub>O, where the CO can be recycled to the bottom of the furnace to improve steel production. This requires the CO<sub>2</sub> and water to be removed. Water can then be removed from this stream, using condensation, leaving a pure CO<sub>2</sub> stream, ready for capture, compression and storage.

In mini-mills, the direct reduction of iron ore is an opportunity for CO<sub>2</sub> capture. This involves reacting high oxygen content iron ore with H<sub>2</sub> and CO to form reduced iron and H<sub>2</sub>O and CO<sub>2</sub>. Around 90-95 percent of the CO<sub>2</sub> may be captured from this process. In addition, CO<sub>2</sub> can be captured from the production of H<sub>2</sub>, in a process similar to pre-combustion capture in power plants.

Capture from steel production has been studied extensively in the ULCOS (Ultra-Low Carbon dioxide Steelmaking) project. It is a consortium that consists of all major European Union steel companies from 15 European countries supported by the European Commission. The aim of the programme is to reduce the CO<sub>2</sub> emissions of today's best routes by at least 50 percent.

## Ammonia production

Ammonia production is one of several petrochemical processes that produce CO<sub>2</sub> as a part of the industrial process. Ammonia is produced through reformation of hydrocarbons. The CO<sub>2</sub> must be removed from the reformer as part of the process. This is done using amine technology in most existing plants.

In many cases ammonia plants are set up so as to use the produced CO<sub>2</sub> in other processes. Some CO<sub>2</sub> captured from ammonia plants is currently used in EOR and in food grade industry.

## Other processes

Other petrochemical processes, such as the production of ethylene, hydrogen and methanol, are also viable for CO<sub>2</sub> capture and storage. The petrochemical industry combined accounts for nearly 300Mt/y of CO<sub>2</sub>.

CO<sub>2</sub> can also be captured from processes involving biomass, such as the fermentation of sugar to produce bio ethanol. One full-scale capture plant of this type is planned by Archer Daniels Midland Company in Illinois, USA

# Bio CCS

Bio CCS is a concept that consists of capturing, transporting and storing CO<sub>2</sub> from biomass- fermentation and/or combustion processes. This CO<sub>2</sub> is considered climate neutral since plants and trees absorb CO<sub>2</sub> from the atmosphere for their growth via photosynthesis. It is then emitted back to the atmosphere during biomass transformation. Under specific conditions, Bio CCS can even create artificial carbon sinks.

As an example, Bio CCS can be applied to a biomass power plant, a pulp and paper factory or to a biofuel production unit. Capturing and storing emissions from biomass combustion has the effect of reducing the net concentration of CO<sub>2</sub> in the atmosphere, making it a potentially powerful global warming mitigation measure.

Current biomass energy production plants are much smaller than fossil fuel plants. A typical plant has a capacity of 30MW, with yearly CO<sub>2</sub> emissions of less than 0.2 MtCO<sub>2</sub>, which needs to be located near to other large emission sources to be practical for CCS. Biomass is used in increasing scale in a number of countries as co-firing with fossil fuels, as in large coal fired power plants. Biomass is a limited resource which also limits potential for Bio CCS in power generation. However, alternative biomass sources, like algae production, may increase the availability of biomass in the future.

# Carbon Capture and Utilisation (CCU)

CO<sub>2</sub> has been in use in a wide range of industries for decades. Most of them have no climate mitigation effect, but some can have a good GHG impact. It is also an important learning process for industry, which plays a role in scaling up CCS processes for large-scale use.

Perhaps the most common operations from which commercially-produced CO<sub>2</sub> is recovered are industrial plants that produce hydrogen or ammonia. In Norway, Yara produces more than 200,000 tonnes of CO<sub>2</sub> for use in the food-grade industry from their ammonia production.

The following table is taken from a report produced by the Global CCS Institute (GCCSI) and gives a very good overview of existing uses for CO<sub>2</sub>.

## Uses of CO<sub>2</sub> for industrial applications

Uses of CO <sub>2</sub>	Description
EOR (EOR)	CO <sub>2</sub> is injected into depleted oil fields. The CO <sub>2</sub> acts as a solvent that reduces the viscosity of the oil, enabling it to flow to the production well. The CO <sub>2</sub> can potentially be permanently stored in the reservoir.
Urea yield boosting (non-captive use only) <sup>2</sup>	Urea production usually gives surplus ammonia as a bi-product. CO <sub>2</sub> can be compressed and combined with the surplus ammonia to produce additional urea.
Other oil and gas industry applications	CO <sub>2</sub> as a fluid for the stimulation/fracturing of oil and gas wells. It is injected as liquid carrying propping agents
Beverage carbonation	Carbonation of beverages with high-purity CO <sub>2</sub> .
Wine making	Seal gas to prevent oxidation of the wine during maturation. CO <sub>2</sub> is produced during the fermentation process, and is already captured on-site for reuse for its inert gas properties.
Food processing, preservation and packaging	Cooling while grinding powders such as spices. Maintaining of inert atmospheres Packaging applications, CO <sub>2</sub> is used in modified atmosphere packaging (Carbon dioxide is commonly used because of its ability to inhibit growth of bacteria that cause spoilage.
Coffee decaffeination	Supercritical CO <sub>2</sub> is used as the solvent for decaffeinating coffee.
Pharmaceutical processes	Inserting, chemical synthesis, supercritical fluid extraction, product transportation at low temperature, and acidification of wastewater.

## Clustering

There will be an advantage in including CO<sub>2</sub> emitting industry into plans for CCS in industrial areas. Some projects are starting to look at industrial synergies in several heavily industrialised areas of Europe, such as Rotterdam and the Skagerrak/Kattegat region. These regions have cement, pulp and petrochemical companies that, together with the power generating sector, the EU and local authorities aim to find a common strategy for contributing to a more climate neutral industry.

# Transporting CO<sub>2</sub>

Captured CO<sub>2</sub> can be transported in a number of different ways, including by road tankers and railway, but for the volumes involved in CCS, pipeline and ship are the most practical and economical options.

Extensive experience exists in the transport of CO<sub>2</sub> by pipeline, while the use of ships and other carriers is still in its infancy and is so far only applied to small quantities of food grade CO<sub>2</sub>. However, natural gas, petroleum gas and condensates are routinely transported by all of the mentioned carriers under a wide variety of conditions - including across deserts, mountain ranges, heavily populated areas, arctic areas and in deep sea. Therefore, the transport of CO<sub>2</sub> is similar to, and no more challenging than, the transport of hydrocarbon gases.

Pipeline is the most economical method for distances up to 1000-1500 km, depending on specific conditions and the volume transported. Beyond this distance, transport by ship may be more economical (IPCC, 2005). At present, no planned CCS projects are based on marine transport of CO<sub>2</sub> from the capture site to the storage site, but future projects may require it, particularly if no suitable storage site is found within the vicinity of a large emission source or a cluster of large emission sources.

## Ship transport

The key elements in ship transport are liquefaction, intermediate storage, loading, unloading (onshore or offshore) and heating. These are illustrated in figure 15. When unloading offshore, a pumping station is needed. Here, the liquid is pumped to injection pressure and heated to ambient temperature, at least 15°C, to avoid hydrate formation before injecting.

Offshore processing is considered costly and can be avoided by unloading the CO<sub>2</sub> from the ship to an onshore hub located close to the offshore storage site. This requires an additional onshore intermediate storage tank, compression and an offshore pipeline.

Until the ship reaches its destination, the CO<sub>2</sub> is stored in semi-pressurised intermediate storage tanks, which keep it in a liquid state, with a pressure higher than atmospheric pressure and a temperature lower than the surroundings. The intermediate storage capacity should match the amount of CO<sub>2</sub> produced between the ship calls. Transport of CO<sub>2</sub> by ship requires intermediate storage since the gas is in most cases captured continuously.

A loading system on the quay transfers the liquid CO<sub>2</sub> to the ship. The CO<sub>2</sub> then arrives at the storage site or at an onshore hub in a ship at around 7-9 bar and -50°C. The slight increase in pressure is because the tanks holding the liquid CO<sub>2</sub> will heat up slightly during transport. This increase will be dependent on transport duration.

A hub is defined as intermediate storage and can either be in a ship transport solution, where the CO<sub>2</sub> continuously captured is stored until the next ship call, or a collection point for CO<sub>2</sub> from different sources.

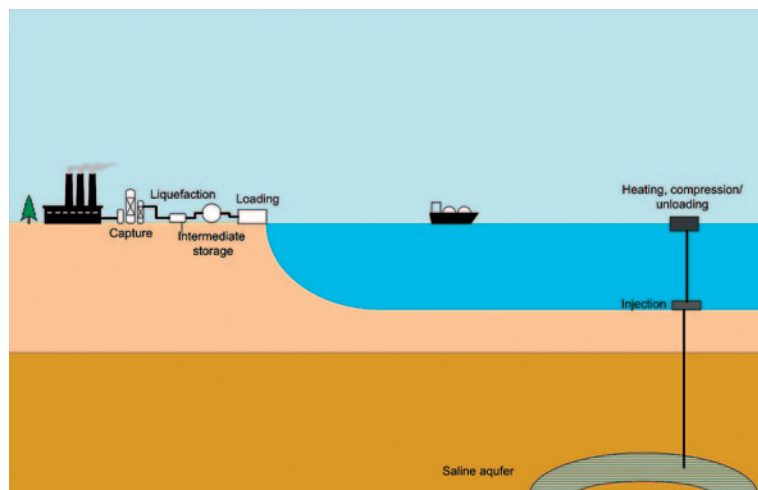


Figure 15: Illustration of ship transport with key elements.





*Transport of CO<sub>2</sub> by ship. For almost 20 years Yara has transported liquid CO<sub>2</sub> on ships, being both the European and world leader in the field. Each year, the company delivers about 850-900,000 tonnes of CO<sub>2</sub>, or around 30 percent of the European market.*

## Pipeline transport

Transport of CO<sub>2</sub> by pipeline is most effective when the gas is in liquid or supercritical state (dense phase). The reason for this is that the friction loss along the pipeline per mass unit of CO<sub>2</sub> is lower compared with its transport as a gas or a two-phase (liquid and gas).

The pressure in the pipeline decreases due to friction and the temperature drops due to heat transfer with the outside medium along the length of the pipeline. The CO<sub>2</sub> will gradually move from a supercritical fluid into a liquid, but will still be in single phase. The pressure at the end of the pipeline must be above ~ 74 bar (critical pressure of CO<sub>2</sub>) to ensure that the gas is kept in liquid dense phase.

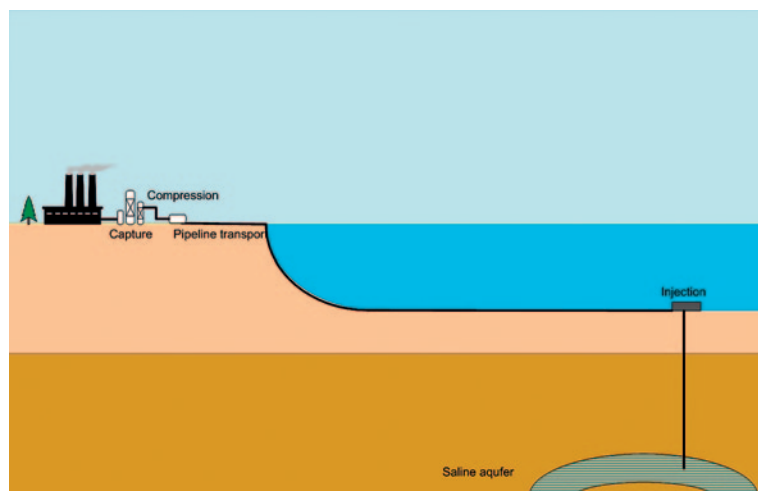


Figure 16: Illustration of pipeline transport.

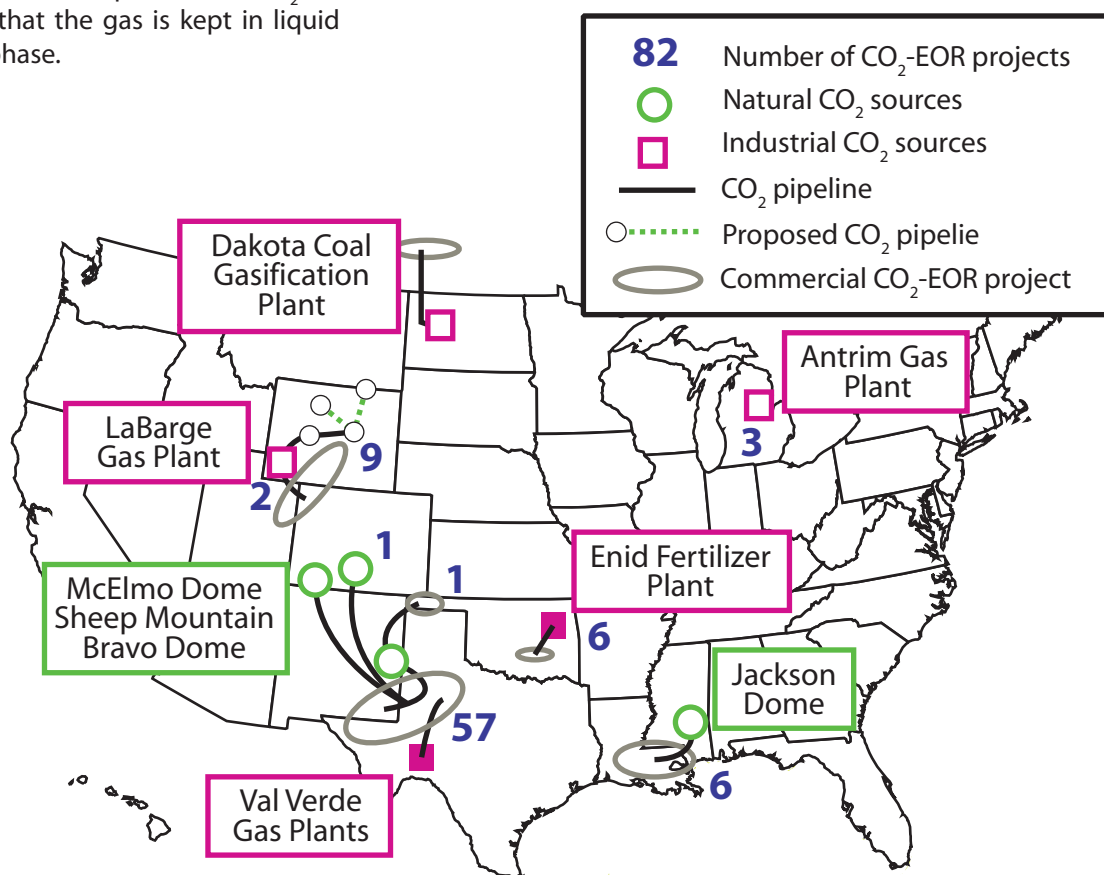


Figure 17: Pipeline infrastructure for CO<sub>2</sub> transportation in USA (Source: Advanced Resources International).

The initial pressure at the beginning of the pipeline depends on the associated pressure drop over the pipeline length. The pressure drop in the pipeline depends on the flow rate, pipe geometry, pipeline route, and other factors. An illustration of pipeline transport is given in figure 16.

Pipelines have been used for CO<sub>2</sub> transport in the USA for a relatively long time, transporting large volumes to oilfields for EOR. Pipeline infrastructure there has the capacity to carry 50 million tonnes of CO<sub>2</sub> a year, and according to experiences, pipeline transport is safe and reliable. Valuable lessons have been learned. For example, gas must be dried before transported through steel pipes to avoid corrosion, and the sulphur level (in the form of hydrogen sulphide, H<sub>2</sub>S) must be low in case of leakages, particularly when pipelines go through inhabited areas. Pipelines must be constructed to shut down automatically in case of leakage.

Large compressors are in current use, for example, at the Dakota Coal Gasification plant in North Dakota, where one compresses and delivers 1.2 million tonnes a year to the Weyburn oilfield in Canada (Freund & Kårstad 2007).

## Risks and safety

Land pipelines are built according to defined standards and are subject to regulatory approval to assure a high level of safety, particularly in densely populated areas. Pipelines in operation are monitored internally by pigs (piston-like inspection devices that are driven through the pipeline by gas pressure) and externally by corrosion monitoring and leak detection systems. In the case of a leak, transport of CO<sub>2</sub> is shut down automatically.

The risk involved in transport by ship is low. New tankers are generally well designed to avoid loss of cargo in the case of a collision, stranding or fire. There have been no accidental losses of cargo from liquefied natural gas (LNG) tankers. Should an accident happen to a liquid CO<sub>2</sub> tanker, liquefied CO<sub>2</sub> might be released onto the surface of the sea. The environmental effects of such an event are not fully known and require further study. However, the long-term effects are anticipated not to have the long-term environmental impacts of crude oil spills.

## Challenges

There are few technical challenges in large scale CO<sub>2</sub> transport. Extensive experience in pipeline transport has been gained in connection with use of CO<sub>2</sub> in EOR in the USA and Canada, as mentioned above. Further, experiences derived from natural gas pipelines are of relevance to the transport of CO<sub>2</sub>.

There is less experience with large-scale transport of CO<sub>2</sub> by ship. Some further development of large transport vessels is needed but, as with pipeline transport, comparison with the transport of LNG provides very useful knowledge and experience.

There are also some legal matters to be dealt with, such as the ratification of a prohibition on the export of CO<sub>2</sub> under the London Dumping Protocol and the fact that ship transport is not currently accepted within the EU's Emission Trading Scheme.

## CO<sub>2</sub> infrastructure and transport in the North Sea

Situated on each side of the North Sea, the UK and Norway are both struggling to fulfil their commitments to reduce greenhouse gas emissions. Both countries are looking for solutions to cut CO<sub>2</sub> emissions on short and long term through clean energy initiatives. Governments in both countries see CCS as an important instrument to combine fossil energy production with measures which efficiently reduce emissions.

The One North Sea study, which concluded with a final report titled “A study into North Sea CO<sub>2</sub> cross-border transport and storage” (One North Sea, 2010), was carried out for the Norwegian and UK governments on behalf of the North Sea Basin Task Force. The aim was to investigate and plan for the possible joint regulation of CCS in the North Sea. This taskforce includes the Netherlands and Germany in addition to the two aforementioned countries.

A main driver for the One North Sea study was the fact that there is both an abundant storage capacity and a large cluster of CO<sub>2</sub> sources in and around the North Sea basin. Combined with the presence of world-class research institutes and commercial stakeholders, this suggested that the North Sea countries could be natural leaders of the development and deployment of CCS technology in Europe.

About 50 percent of the European storage potential for CO<sub>2</sub> is located under the North Sea. The clustering of sources and possible storage sites provides opportunities to develop efficient transportation and storage networks. It is concluded in the One North Sea study that in the initial period no cross-border transport is necessary. Several countries are possibly involved, and at a later stage, i.e., beyond 2020, cross-border transportation of CO<sub>2</sub> could become increasingly important, and eventually account for up to 25 percent of the CO<sub>2</sub> stored.

The North Sea Basin Task Force analysis concludes that the rapid deployment of large-scale low cost infrastructure by 2030 is technically achievable and is necessary for full deployment (e.g. the ‘Very High’ scenario described in this report which stores over 270Mt/y of CO<sub>2</sub> in 2030).

However this would require a step change in co-operation in planning by numerous stakeholders, favourable economic conditions and CCS cost reduction. With only modest further intervention, the market is likely to deliver only a few of the most straightforward CCS projects by 2030, storing up to 46Mt/y of CO<sub>2</sub> under the North Sea in a ‘Medium’ scenario. The shortfall between ‘Very High’ and ‘Medium’ scenarios would need to be met by other approaches to CO<sub>2</sub> abatement.

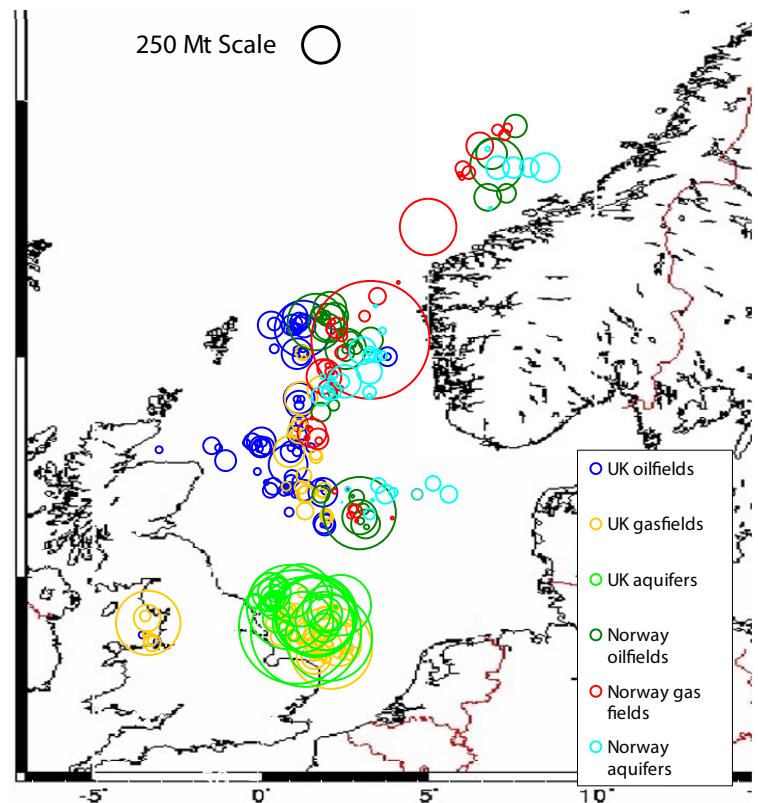


Figure 18: Storage capacity in the Norwegian and UK part of The North Sea (Source: Element Energy).

The CO<sub>2</sub> Storage Atlas (Dec 2011), Norwegian North Sea, prepared by the Norwegian Petroleum Directorate (NPD), shows that this area has a total storage capacity of around 70 billion tonnes - or 70 Gt - of CO<sub>2</sub>. By comparison, the oil refinery at Mongstad, which is the largest single source of CO<sub>2</sub> emissions in Norway, releases about 1.5 Mt/y of CO<sub>2</sub>. The atlas is based on studies and data from more than 40 years of petroleum operations. Twenty-one geological formations have been identified and assessed in terms of reservoir quality and presence of the sealing layer. Reservoirs that are considered suitable are discussed in detail.

The NPD has considered abandoned oil and gas fields in addition to producing fields that are scheduled to be shut down in 2030 and 2050. Reservoirs that may be used in conjunction with EOR are also described.

Making North Sea carbon storage a reality is a longstanding matter of high priority for ZERO. Know-how from Sleipner and the large storage capacity in the Utsira field is of key importance. For Norway and the UK pipeline transport to the North Sea is the most practical solution for offshore carbon sequestration.

Studies indicate that 28 pipelines on the British side of the North Sea would have the capacity to carry between 10 and 50 MtCO<sub>2</sub> a year, but if existing infrastructure is to be used, this needs further clarification. Within a few years, many oil and gas fields in the North Sea will close down and an inter-governmental plan will be necessary to fully exploit the potential of existing closed-down installations for CO<sub>2</sub> storage.



# Carbon storage

The last but not least step in the CCS process is to store it safely underground. This can be achieved by finding deep geological formations that can be monitored and controlled for thousands of years.

Natural accumulations of virtually pure  $\text{CO}_2$  can be found all over the planet in a wide range of geological settings: particularly in sedimentary basins, intra-plate volcanic regions and in faulted areas, or in dormant volcanic structures. Natural gas and oil reservoirs have demonstrated that a great many formations are capable of storing gas for millions of years.

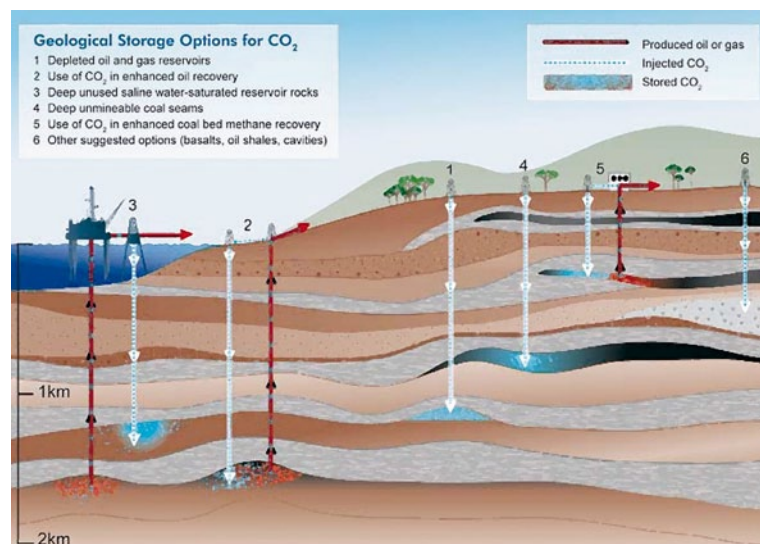


Figure 19: Geological storage options (Source: IPCC 2007)

In  $\text{CO}_2$  sequestration, long term storage safety is paramount. Further geological surveys are necessary to map the global storage potential, but in areas of petroleum activity the geology is already well mapped. Gas and liquid injections for EOR has also provided valuable information on how  $\text{CO}_2$  can be safely stored for global warming mitigation purposes.

$\text{CO}_2$  can be stored in a variety of geological settings, in sedimentary basins, in depleted oil and gas fields, saline formations, and deep unmineable coal seams. Suitable storage formations can occur both in on-shore and offshore sedimentary basins.

## Storage potential in geological formations

Not all sedimentary basins are suitable for  $\text{CO}_2$  storage; some are too shallow and others are dominated by rocks with low permeability or poor confining characteristics. Basins suitable for  $\text{CO}_2$  storage have characteristics such as thick accumulations of sediments, permeable rock formations saturated with saline water (saline formations), extensive covers of low porosity rocks (acting as seals) and structural simplicity (IPCC 2005).

The IPCC special report on CCS (2005) estimates the worldwide technical potential for storage in geological formations to be at least 2,000 Gt  $\text{CO}_2$ . This is only the lower bound, and the IPCC believes the capacity may be many times higher, but the upper limit estimates are uncertain due to insufficient charting and disagreements on methodology. The capacity for storing  $\text{CO}_2$  in depleted petroleum reservoirs is known with larger certainty. In most cases this kind of storage is considered as safe, since the formations have already proven themselves capable of storing gas for millions of years, and since the geology of the formations has been extensively surveyed.

Estimated capacity for some storage options

Storage option	Global capacity, lowest estimate (Gt CO <sub>2</sub> )	Global capacity, highest estimate (Gt CO <sub>2</sub> )
Depleted oil and gas reservoirs	675*	900*
Deep saline aquifers	1000	Uncertain, but possibly 10,000
Deep unmineable coal seams	3-15	200

\* These estimates may increase by 25 percent, when undiscovered oil and gas fields are included (IPCC 2005b).

Potential storage sites are likely to be broadly distributed in many of the world’s sedimentary basins, located in the same regions as many of the world’s greatest emission sources.

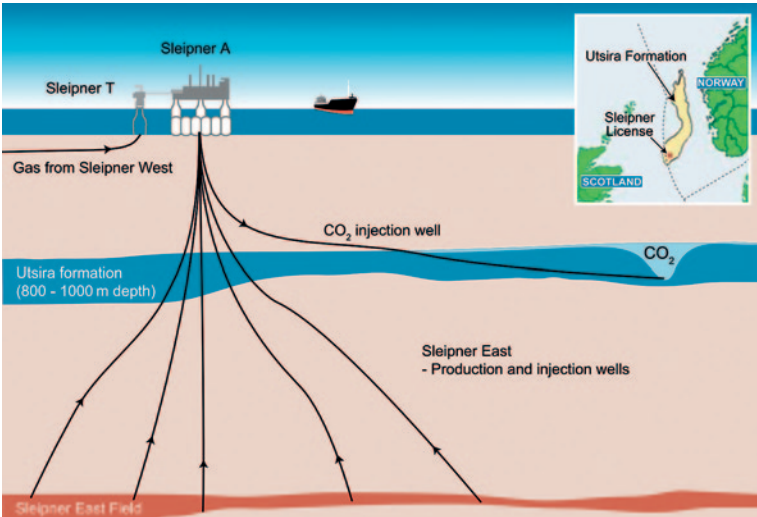
Experiences in CO<sub>2</sub> storage

The engineered injection of CO<sub>2</sub> into subsurface geological formations was first undertaken in Texas, USA, in the early 1970s, as part of EOR projects.

There are four industrial-scale storage projects in operation today: the Sleipner project and the Snøhvit project in Norway, the In Salah project in Algeria, and the Weyburn EOR project in Canada. Annually, about 4 MtCO<sub>2</sub> that would otherwise have been released into the atmosphere, are captured and stored in geological formations.

Sleipner: 10 million tonnes stored since 1996

At the Sleipner field in the North Sea, situated about 250 km off the coast of Norway and operated by Statoil. This was the first large scale geological CO<sub>2</sub> storage project, started in 1996. Approximately 1 Mt CO<sub>2</sub> is stored each year. The produced natural gas in the Sleipner field contains up to 9 percent CO<sub>2</sub>. To meet commercial specification this concentration must be reduced to 2.5 percent. When a tax on CO<sub>2</sub> emissions was introduced in Norway in 1991, this was a sufficient economic incentive for Statoil to start the Sleipner storage project for the CO<sub>2</sub> they were already removing from their natural gas.



Figur 20: Sleipner CO<sub>2</sub> Storage Project (Source: IPCC 2007)

The CO<sub>2</sub> from Sleipner is injected into the Utsira formation – a brine saturated unconsolidated sandstone about 800-1000m below the sea floor. At its widest, this saline formation is 50 km wide and it stretches for 500 km in length. The Utsira formation has a very large storage capacity, in the order of 1-10 GtCO<sub>2</sub>.

## The In Salah Gas Project (Algeria)

The In Salah Gas Project, located in the central Saharan region of Algeria and operated by BP, is the world's first large-scale CO<sub>2</sub> storage project in a gas reservoir. The Krechba Field at In Salah produces natural gas containing up to 10 percent CO<sub>2</sub> from several geological reservoirs and delivers to markets in Europe after processing and stripping the CO<sub>2</sub> to meet commercial specifications.

The CO<sub>2</sub> is re-injected into a sandstone reservoir at a depth of 1800m. The top seal is a thick succession of mudstones up to 950m thick. CO<sub>2</sub> is injected in the water-filled parts of the reservoir, below the gas-bearing part. The injected CO<sub>2</sub> is expected to eventually migrate into the area of the current gas field after depletion of the gas zone.

Injection started in April 2004 and up to 1.2 MtCO<sub>2</sub> are stored annually. Over the life of the project, it is estimated that 17 MtCO<sub>2</sub> will be stored.

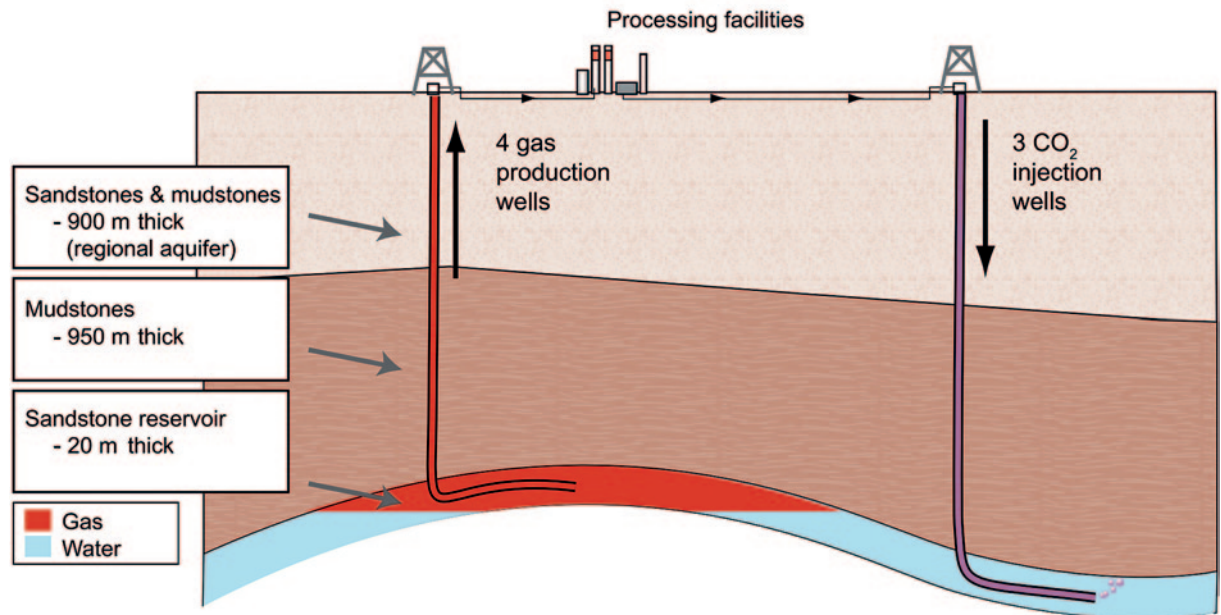


Figure 21: Schematic of the In Salah Gas Project, Algeria (Source: IPCC 2007)

## Ketzin onshore storage (Germany)

The Ketzin (former: CO<sub>2</sub>SINK) project started in 2004, with the aim of demonstrating long-term geological storage of CO<sub>2</sub> in a saline aquifer. Eighteen industrial partners and research institutions from nine European countries are involved in the project, coordinated by the GFZ German Research Centre for Geosciences.

In summer 2008, the asset went into operation. Over a period of three years, around 60,000 tonnes of highly pure (>99 percent) CO<sub>2</sub> has been stored at a depth of between 600 and 800m.

The storage site is near a small town, Ketzin, west of Berlin. As the test site is close to a metropolitan area, it provides a unique opportunity to develop a European showcase for onshore CO<sub>2</sub> storage. The site is therefore equipped with an information centre which is open to the public.

The project has developed an in-situ laboratory for CO<sub>2</sub> storage to fill the gap between the numerous conceptual engineering and scientific studies on geological storage and a fully-fledged onshore storage demonstration.

## Storage of natural gas

Underground natural gas storage projects have operated successfully for almost a century in many parts of the world, and provide know-how relevant to CO<sub>2</sub> storage. These projects provide for peak loads and balance seasonal fluctuations in gas supply and demand. The majority of gas storage projects are in depleted oil and gas reservoirs and saline formations, although caverns in salt have also been used extensively.

A total of 634 geological deposits for produced natural gas have been established in 25 countries. The total volume of gas stored in this way is 340 billion m<sup>3</sup>, equivalent to 270 GtCO<sub>2</sub> (Freund & Kårstad 2007).

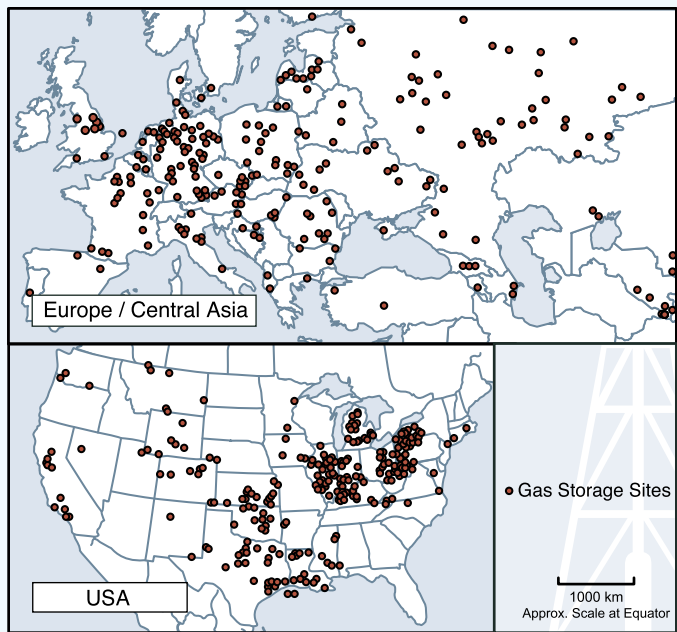


Figure 22: Natural gas storage in Europe, Central Asia and USA  
(Source: IPCC)

To characterise the underground environment and understand the processes which happen there, detailed analysis are being made of samples of rocks, fluids and micro-organisms gathered there. The project involves intensive monitoring of the injected CO<sub>2</sub> using a broad range of geophysical and geochemical techniques, the development and benchmarking of numerical models, and the definition of risk-assessment strategies.

Post-injection measurements, including time-lapse vertical seismic profiling transects along selected azimuths, cross-well seismic topography, and saturation logs, show that CO<sub>2</sub> migration under gravity slowed greatly two months after injection, matching model predictions that significant CO<sub>2</sub> is trapped as relative permeability decreases. As expected, CO<sub>2</sub> dissolved rapidly into brine, causing pH to fall and calcite and metals to be dissolved.

## Storage safety

Storage safety is a fundamental aspect of CCS. It is of utmost importance that the stored CO<sub>2</sub> does not leak and cause harm. For climate purposes, the CO<sub>2</sub> has to remain in the storage reservoir as long as required in a climate perspective. The IPCC estimates the probability for the CO<sub>2</sub> to remain in the storage reservoir in a long-term scenario as high.

For large-scale CO<sub>2</sub> storage projects, assuming that the sites are well selected, designed, operated and appropriately monitored, it is likely that the fraction of stored CO<sub>2</sub> retained is more than 99 percent over the first 1000 years. Similar fractions retained are likely for longer periods of time (IPCC 2005).

Before selecting a site the geological setting must be characterised to determine if the overlying cap rock will provide an effective seal and if there is a sufficiently voluminous and permeable storage formation. Techniques developed for the exploration of oil and gas reservoirs, natural gas storage sites and liquid waste disposal sites are suitable for characterising geological storage sites for CO<sub>2</sub>.





*Many natural gas deposits are situated in populated areas. The 1085 million m<sup>3</sup> deposit underneath the Berlin Olympic Stadium is a good example. (Source: GASAG)*



When geological storage formations are properly selected and operated, leakage is highly unlikely. But there are scenarios in which CO<sub>2</sub> can escape its storage reservoir, either as abrupt leakage through injection well failure, or up an abandoned well, or as gradual leakage through undetected faults, fractures or wells.

Several techniques are available to remedy a leakage situation. In many cases standard well repair techniques would suffice. In more serious cases, the injected CO<sub>2</sub> can be produced back from the storage reservoir and reinjected into a more suitable storage structure. These are nevertheless extreme cases. The main assumption is that properly stored CO<sub>2</sub> will not leak.

Even if there should be a leakage in a worst case scenario, there can be no catastrophic failure. CO<sub>2</sub> cannot explode, and if accidents did occur in the injection phase, the emissions would be small and only dangerous in the immediate vicinity of the injection well where the accident happened.

A report on the best practice for the storage of CO<sub>2</sub> in saline aquifers has been developed by the EU projects SACS and CO<sub>2</sub>STORE. The report aims at providing technically robust guidelines for effective and safe storage.

## What happens when CO<sub>2</sub> is geologically stored?

Storage of CO<sub>2</sub> will differ according to what type of storage reservoir you choose. The two options that are in use today are depleted oil and gas field and saline aquifers.

After injection of CO<sub>2</sub>, there are various physical and geochemical trapping mechanisms that prevent the injected gas from migrating to the surface from a suitable saline formation or oil or gas field: an impermeable cap rock, the sponge-like property of the reservoir, dissolution and eventually mineralisation of the CO<sub>2</sub> (CO<sub>2</sub>GeoNet, 2009).

The storage reservoirs consist of porous rock, mainly sandstone. The billions of microscopic pores in the sedimentary rock allow CO<sub>2</sub> to be stored in much the same way as water is contained in a sponge. CO<sub>2</sub> is injected at depths of below 800-1000m, where the pressure and temperature keeps it in a natural supercritical form. Supercritical CO<sub>2</sub> has properties midway between a gas and a liquid, expanding to fill its containment space like a gas but with a density like that of a liquid. This is the ideal state for efficient utilisation of the storage space in the pores of sedimentary rocks.

The residual trapping mechanism can most easily be compared with that of filling a sponge with water - the liquid is contained in many individual chambers within it.

A thick layer of shale and clay rock above the storage formation blocks upward migration of CO<sub>2</sub>. This impermeable layer is known as the cap rock. Capillary forces also retain the CO<sub>2</sub> in the pore spaces of the formation, providing additional physical trapping. In gas reservoirs CO<sub>2</sub> will eventually migrate downwards, because it is denser than natural gas.

In the long term, geochemical trapping mechanisms like dissolution and mineralisation increase storage safety. The CO<sub>2</sub> reacts with the host rock and the water inside it. Water saturated with CO<sub>2</sub> is slightly denser than the original formation water, and therefore sinks down into the formation rather than rising toward the surface. Some of the dissolved CO<sub>2</sub> reacts chemically with the rock minerals, and is converted to solid carbonate minerals. The multiple trapping mechanisms make the risk of leakage lower over time, as most of the gas eventually settles deep in the formation in a diluted or mineralised form.

## Side effects of CO<sub>2</sub> storage

There are objections against storage of CO<sub>2</sub>, pointing at still unknown risks for humans and the environment. These are risks aspects which have to be included in investigations of potential storage sites.

### Drinking water

In depleted oil and gas reservoirs, there used to be oil and gas in the tiny pores of the stone. For saline aquifers, the sandstone is already filled with brine (very salty water). When CO<sub>2</sub> is stored in the aquifer, some of the CO<sub>2</sub> is dissolved in the brine, and the rest of the brine is replaced and pushed sideward towards the fringes of the reservoir. The major increase in reservoir pressure will occur directly around the injection site. The pressure then drops rapidly the further one moves away from the injection site/bore hole. At the fringes of the reservoir, there will hence only be a smaller increase in pressure.

The amount of CO<sub>2</sub> which dissolves in the water varies according to in situ temperature, pressure and water salinity and composition. Rates of solution can be estimated from published datasets and site specific laboratory measurements. (Cooper et al., 2009)

The pressure inside the reservoir increases with the CO<sub>2</sub> injection, in the same way as it decline when producing natural gas and oil. One fear is whether increase in pressure could lead to upward movement of brine through a sequence of layers into shallow groundwater bodies.

Various studies (Bergman and Winter, 1995, Birkholzer et al, 2009) nevertheless claim that such brine migration is very unlikely. Firstly, examination of storage sites will be done along the fringes of the reservoir and make sure that there are no potential leakage paths for brine to migrate along. Secondly, the brine will only migrate as much as the overpressure allows it to. With one bar pressure increase, water can migrate 10m upwards. For water to reach potable ground water layers, the pressure in the fringe areas of the reservoirs will have to increase by more than 80 bars, and this can be prevented through careful and continuous monitoring of the reservoir pressure.

### Cap rock breakage

Another risk concerns the resistance and strength of the cap rock. If the pressure in the reservoir becomes too high, the cap rock could eventually break, leading to migration of CO<sub>2</sub> and brine into shallower layers. The risk can be handled by making tests of the cap rock before starting injections. Based on such tests, the resistance values and strength of the cap rock are calculated. During injection, the operators make sure that these values are not exceeded. Based on experiences from the oil and gas sector, there are well known methods for monitoring the pressure in the reservoir and in the wells.

One example for the value of pressure monitoring is the CO<sub>2</sub> storage project at Snøhvit in north Norway. Here, the CO<sub>2</sub> injection has been more difficult than expected. The capacity in the storage reservoir Tubåen turned out to be lower than originally calculated. As a result, the CO<sub>2</sub> did not migrate as expected

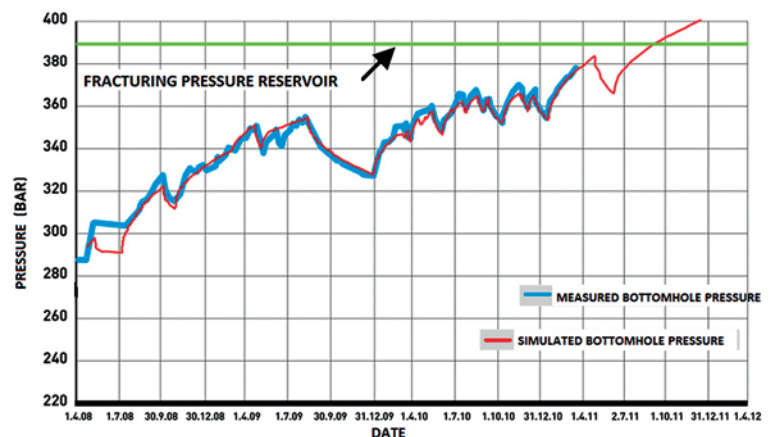


Figure 23: The pressure development in Tubåen reservoir at Snøhvit. (Source: Teknisk Ukeblad, 2011)

## Lacq, Total (France)

In January 2010, Total launched Europe's first industrial-scale CCS chain demonstration project at its gas processing plant at Lacq in south-west France.

The €60 million project uses oxyfuel combustion technology developed by Air Liquide. The project aims to capture around 120,000 tonnes of CO<sub>2</sub> over a two year period. Alstom supplied the retrofit of a 30MW conventional boiler for oxy-firing combustion for the pilot plant. The captured gas is transported by pipeline and injected into a depleted natural gas reservoir 4500m below ground at Rousse, 27 kilometres from Lacq.

The Rousse gas field was chosen as a suitable CO<sub>2</sub> storage site following studies in 2006 of depleted gas fields operated by Total in the region. Its geological structure is well known and is generally considered suitable for safe, long-term storage of CO<sub>2</sub> from the Lacq pilot.

This reservoir is made of porous rock which becomes impregnated with CO<sub>2</sub> and the gas is then trapped there just as the natural gas (also containing CO<sub>2</sub>) was for thousands of years. The quantity of CO<sub>2</sub> to be injected during the demonstration project is much smaller than the volume of natural gas originally contained in the reservoir.

Above the Rousse reservoir is a gastight "lid" of marl and clay 2000m thick. This formation is more than 35 million years old and remained intact when the Pyrenees were formed. Rousse is geologically isolated from other reservoirs in the region and is not connected to any active aquifer (i.e. porous underground rock impregnated with water). Therefore, Rousse offers optimum conditions for long-term safety.

## Mountaineer (USA)

American Electric Power (AEP) and Alstom began operating a small-scale test of the technology at the coal power plant Mountaineer in New Haven, West Virginia, in September 2009, capturing up to 90 percent of CO<sub>2</sub> from 20MW of generating capacity. The captured gas – at a rate of more than 100,000 t/y – has been compressed and injected for permanent storage about 1609m below ground. The project ended, as planned, in spring 2011.

through the storage formation and the reservoir pressure rose quickly. After only three years of injection, the reservoir was full. Figure 23 shows the development of the reservoir pressure during the injection period from 2008 to 2011.

The experiences from Snøhvit clearly show that it is feasible to measure the pressure in a reservoir and hence avoid exceeding the maximum pressure limit.

## Earthquakes

Even an earthquake is unlikely to release large amounts of CO<sub>2</sub> that is properly stored. Firstly, CO<sub>2</sub> will not be stored in areas where high magnitude earthquakes or other geological events are likely to occur. Secondly, earthquakes happen regularly in areas where water, oil or gas is stored in the ground the same way CO<sub>2</sub> will be stored. As yet, there are no known occurrences of massive eruptions of water or petroleum from the ground during such events. The trapping mechanisms are too strong for more than small amounts of the CO<sub>2</sub> to be released even under such dramatic circumstances.

## Monitoring

In order to be sure that the CO<sub>2</sub> is behaving as expected in the reservoir, the storage site has to be carefully monitored throughout the storage process and after injection has ended. Before injections starts, geoscientists carry out a site characterisation. After injection has started, they will observe the injection performance and on-going reservoir properties.

Monitoring includes different technologies, of which the most important are seismic data, gravity and direct measurements of the CO<sub>2</sub> concentrations, pressure or fluid composition in the injected storage reservoir (Cooper et al, 2009). The choice of monitoring methods depends on the storage site and factors as depth, temperature and compositional properties of the geological layers. The characteristics of the surface play a role in the selection process.

Direct measurement normally means that different properties are measured via access into the storage reservoir via the well-bores. Measuring emissions at the surface above the injection site is another form of direct measurement.

The indirect monitoring tools – seismic, gravity and electromagnetic – are the most important way to depict the properties of the underground geological formations. The results are fed into 3D computer models that can describe reality with high degree of precision.

Seismic imaging is carried out by sending out energy waves into geological formations. Because the underground consists of different layers of stone, they will reflect this energy back in the form of different sound waves. The reflected signals are stored and seismic profiles or images created.

Seismic imaging is an extremely powerful tool. However, it also has some restrictions, such as limited vertical resolution for features less than 10m thick and unreliable images for formations below some rock types which to a certain degree inhibit the seismic waves. It is more challenging to carry out seismic monitoring on than offshore. On land, surface properties can have implications for seismic acquisitions, and it is more expensive to carry out.

Gravity measures reveal changes in density for a vertical rock column. Such measurements are for instance suitable in order to detect where CO<sub>2</sub> displaces saline brine in a subsurface reservoir as displacement causes lower density.

Finally, electrical resistivity tomography (ERT), or electrical resistivity imaging (ERI), is a geophysical technique for imaging sub-surface structures from electrical measurements made at the surface, or by electrodes in one or more boreholes.

At Ketzin, outside Berlin, one of the main research tasks is to develop and test a reliable and complete monitoring process. Here, they combine seismic surveys, ERT and the continual monitoring of the pressure and temperature in the reservoir. With their so-called multi-disciplinary monitoring concept, they are able to detect even small quantities of CO<sub>2</sub>.

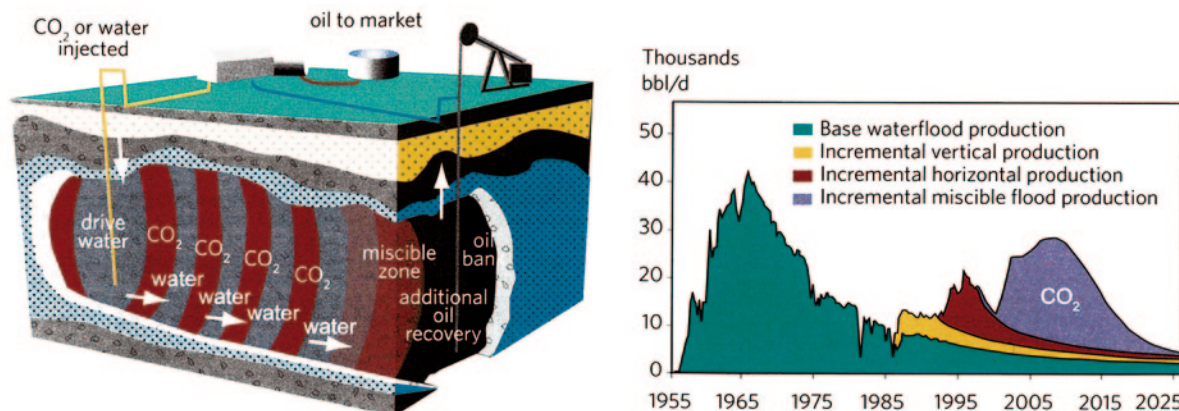
The most important result from the research at Ketzin is that the actual observations correspond with the modelling of the CO<sub>2</sub>. This shows that it is possible to model the reservoir and the behaviour of the CO<sub>2</sub> with high degree of precision before injection begins. Further results from Ketzin are that there is no leakage detected and that the geological system has attained a dynamic equilibrium.

## CO<sub>2</sub> in enhanced oil recovery

EOR is mainly achieved by injecting different substances into the oil reservoir, i.e. gas injection, chemical injection or microbial injection. The most commonly used option for EOR is the injection of gas.

Oil displacement by CO<sub>2</sub> injection relies on the phase behaviour of the mixtures of the gas and the crude oil, which depends on reservoir temperature, pressure and the composition of the crude oil.

In these applications, more than half and up to two thirds of the injected CO<sub>2</sub> returns with the produced oil and is usually re-injected into the reservoir to minimise operating costs. The remainder is trapped in the oil reservoir by various means.



*Figure 24: CO<sub>2</sub> can be used to improve oil recovery. CO<sub>2</sub> is usually pumped into the reservoir for one month, and then water injected for one month, in a continuing cycle. The diagram shows how tertiary recovery increases oil production at the Weyburn oil field in Canada (Source: Freund & Kårstad 2007).*

In the USA, 30Mt of CO<sub>2</sub> are injected into 82 different oilfields every year. Initially, CO<sub>2</sub> separated in industrial processes was used, but this has gradually been replaced by cheaper gas from natural CO<sub>2</sub> reservoirs in geological formations. Only 10 percent of the CO<sub>2</sub> used in EOR today comes from industrial sources. In these projects there has been no environmental motivation for injecting CO<sub>2</sub> into the oil reservoirs. Therefore, little is known about the storage safety of the reservoirs in Northern America, with the exception of the Weyburn project in Canada (IPCC 2005b).

In the early stages of CCS development, EOR projects may prove useful to CO<sub>2</sub> capture technology. Using CO<sub>2</sub> in EOR would also contribute to the deployment of necessary and costly infrastructure. The extra revenue from EOR can finance CO<sub>2</sub> pipelines, injection installations and power plants with CO<sub>2</sub> capture, which will enable CO<sub>2</sub> injections for a long time after oil production has been closed down.

The EOR projects should nevertheless be carefully planned and designed. It should also be made sure that as large a share of CO<sub>2</sub> as possible is permanently stored. In this context, it is especially important that all the CO<sub>2</sub> that returns with the produced oil is re-injected into the reservoir.

### Weyburn & Great Plains Synfuels Plant

The Weyburn oilfield is situated in Canada, close to the USA border. In October 2000 EnCana started injection of CO<sub>2</sub> into the field to improve oil recovery. The CO<sub>2</sub> is transported through a 325 km pipeline from Dakota Gasification Company's coal gasification plant in North Dakota. Around 20 Mt of CO<sub>2</sub> will be injected, extending the expected life span of the field by 25 years.



Great Plains Synfuels Plant (GPSP) produces syngas from lignite, which is manufactured into many different products, such as natural gas, methanol and fertiliser. This is a commercial project where the company separates and sells CO<sub>2</sub>. The CO<sub>2</sub> is separated in the industrial process, so no separate capture equipment is needed. The plant has been running since 1984, using 6 Mt of lignite a year. It is the first gasification plant in the world to sell CO<sub>2</sub> for EOR.

The geological conditions around Weyburn are well suited for long-term CO<sub>2</sub> storage. The Petroleum Technology Research Center has conducted a four-year cross-field study of the storage conditions, in cooperation with field operator EnCana. Seismic surveys have charted the distribution of CO<sub>2</sub> in the geological formations, and a model to calculate storage capacity has been developed. A risk evaluation concluded that most of the injected CO<sub>2</sub> will remain in the reservoir for more than 5000 years.

# Carbon capture and storage is safe, accessible and necessary

There is a great deal we can do to prevent global warming. We need to replace as much fossil fuel energy as possible with renewable alternatives, and we need to replace fossil fuels in our cars with alternative fuels. We have to end deforestation of the rainforests, and we need to conserve energy. In addition to this, we need to capture and store CO<sub>2</sub>. These are the most important reasons why:

- We use so much fossil fuel energy that it will take many decades to replace it all with renewable alternatives. In fact, world energy consumption is likely to increase in the next decades because world population is growing and more people are moving from poverty to demand the same commodities as those enjoyed in developed nations such as Europe and the USA.
- A relatively small number of emission sources are responsible for a very large portion of the total global emissions. That means a relatively small number of CCS plants can cut global emissions by a very large amount.
- Some emissions cannot be removed in any other way. Certain industrial processes, such as the manufacturing of cement and steel, emit massive amounts of CO<sub>2</sub>. In fact, a fifth of all CO<sub>2</sub> emitted comes from industrial processes and, while some of these can be improved or replaced to reduce their impact, these emissions cannot be completely eliminated as long as we need the products they produce.
- We have no time to lose. CCS means we can start removing CO<sub>2</sub> right now from power plants and industrial facilities that already exist and that we know will continue emitting CO<sub>2</sub> for decades to come. Opportunities like this cannot be ignored when climate action is so urgently needed to save the planet.

## Fossil fuel energy

More than half of the global emissions of greenhouse gases come from the use of oil, coal and natural gas. There is no way we can stop climate change unless we drastically reduce these emissions. The obvious solution is to stop using fossil fuels, and in long term we should. This will require a massive change of energy policy and markets globally.

In 2009, we used about 115,000 TWh of fossil energy. If we were to build enough wind turbines to replace all this fossil energy, it would take approximately 50 million new turbines. If construction began now - one new turbine every minute - it would take almost 100 years to finish. We do not have that much time to play with.

Until enough wind turbines, hydro-power plants, solar panels and other renewable alternatives have been built, we will continue using fossil fuels. And as the global population grows, and poorer countries develop, energy demand will increase, making the quick replacement of fossil fuels even harder to achieve.

## Large emission sources

The 2000 largest CO<sub>2</sub> point sources in the world account for 40 percent of the total global emissions. That makes CCS a potentially very effective way of achieving considerable cuts in emissions. Some of these emission sources literally emit as much CO<sub>2</sub> as a small country.



Figure 25: Large emission sources in the world (Source: IPCC).

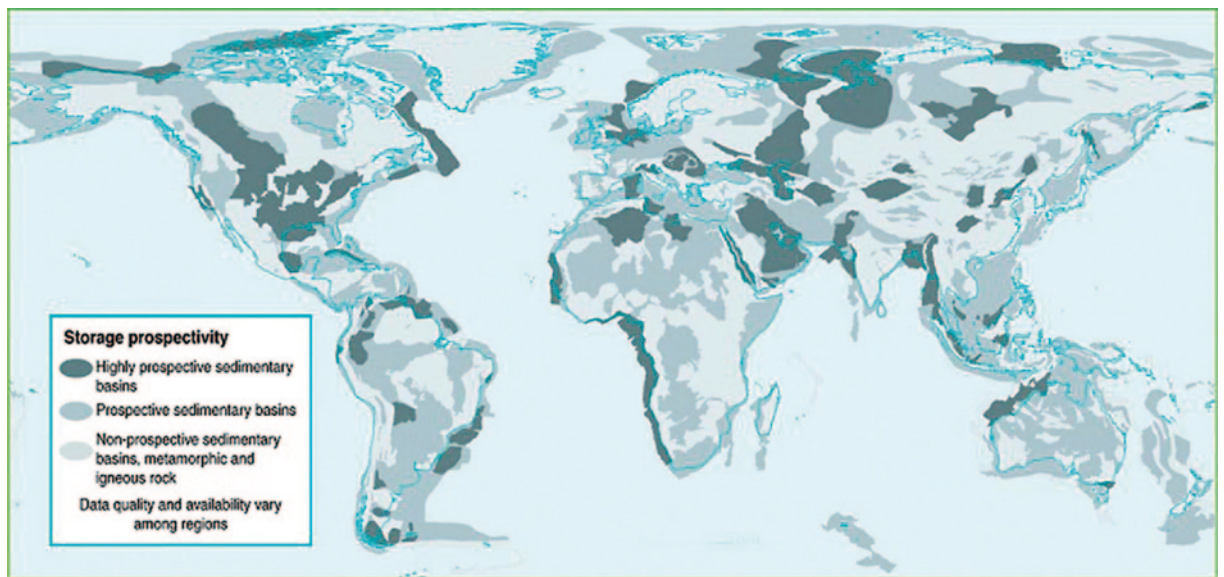


Figure 26: Global storage capacity (Source: IPCC).



Figure 27: Global oil and gas fields. According to the IPCC the world's oil and gas regions are very well surveyed. Many empty petroleum fields can hold huge amounts of CO<sub>2</sub> (Source: Freund & Kårstad 2007).

Also, quite often large sources of CO<sub>2</sub> are clustered together within a small geographical area, making them even better suited for CCS, as they can share some of the infrastructure, such as using the same pipelines to transport the captured gas and sharing storage locations.

## Industrial emissions

Most people are unaware of concrete as a source of pollution. But production of cement is actually one of the greatest industrial sources of CO<sub>2</sub> in the world.

Cement is made from limestone or chalk - natural minerals that contain carbon, calcium and oxygen. To make cement, you remove some of the oxygen and most of the carbon in a process that involves heating the limestone until the carbon is released as CO<sub>2</sub>. At present there are no practical alternatives to this process.

Production of steel is another huge emitter of CO<sub>2</sub>, as is the production of important chemicals, such as ammonia and methanol.

## We have no time to lose

Cutting greenhouse gases is becoming increasingly urgent, as it becomes ever clearer how dramatic the consequences will be if we don't. The longer it takes for the first large-scale facilities to be realised, the longer it will take for the next hundred to be built. To be able to reduce emissions fast enough, it is imperative to have the first ten full-scale CCS plants operating now.

We cannot afford not to use the solutions available to us. CCS alone will not remove all emissions but it can take a large share. And in combination with renewable energy, energy conservation and other climate change mitigation solutions, it can make a very big difference. For all these reasons, we need carbon capture and storage.

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