Future large-scale use of fossil energy will require CO_2 sequestering and disposal.

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1. Summary

Despite increased use of renewable energy sources, it is very likely that all or the most of the worlds fossil fuels might be exploited within the next 500 years to meet the increased demand for energy especially in the development countries. The corresponding CO_2 emission will increase the atmospheric concentration to a level that might be unacceptable due to possible global climate change. An undesired CO_2 accumulation in atmosphere can, however, be avoided if the conversion of fuel to energy is performed so that the resulting CO_2 comes out from the process in a separate and concentrated stream and can be safely deposited for a long period of time. This scheme relays on that sufficiently large and safe deposits are available. At the present, underground CO_2 disposal in geological formations seems to be the most feasible disposal option.

The presentation emphasises on a discussion of the need for CO_2 sequestering and an analysis of the possibilities dispose CO_2 underground both with respect to capacity and safety.

2. Background

The uncertainty about the anthropogenic climate change has been used as an argument to defer far-reaching measures to reduce emissions of greenhouse gases. The possible threat is however so large that a precautionary principle has been the guidance for action instead of waiting for more evidence on the climate relations. The precautionary principle is also the official policy for the work UN (IPCC) is doing to meet the future. It may take decades to improve the predictions of anthropogenic climate change.

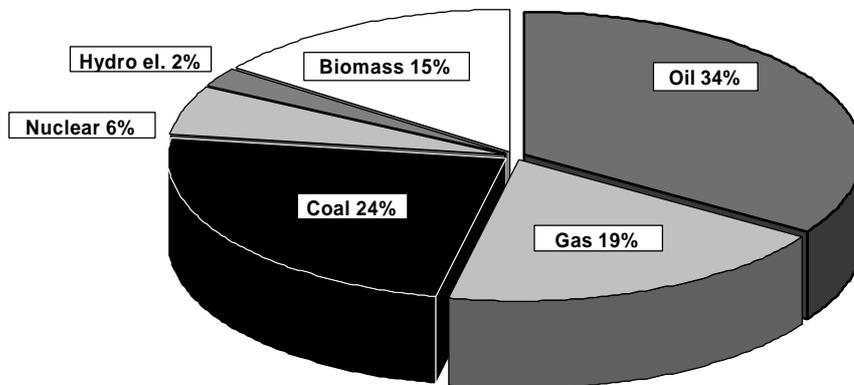## 3. The dependence of fossil fuels will remain

Figure 3.1   World energy distribution 1999

Approximately 80% of the energy used to day are based on the fossil resources oil, coal and gas as illustrated in Figure 3.1. The corresponding CO_2 emissions are is also the major sources for the anthropogenic CO_2 illustrated in Figure 3.2. Large-scale development of hydroelectric and nuclear power is possible, but it is also limited by ecological and political constraints. The use of bio fuels can be increased especially in the counties in the temperate climate zone, but in many places this will compete with food production. Solar energy in various forms has a large potential, but for power production solar energy is only applied in small scale due to high cost. Even with an intensive research effort on these and other renewable energy sources, it will be difficult to reduce the dependence of fossil energy in a world with strongly increasing energy demand. The future increase in energy consumption will mostly occur in the development countries. India and China are increasing their energy consumption in large scale based on coal resources.
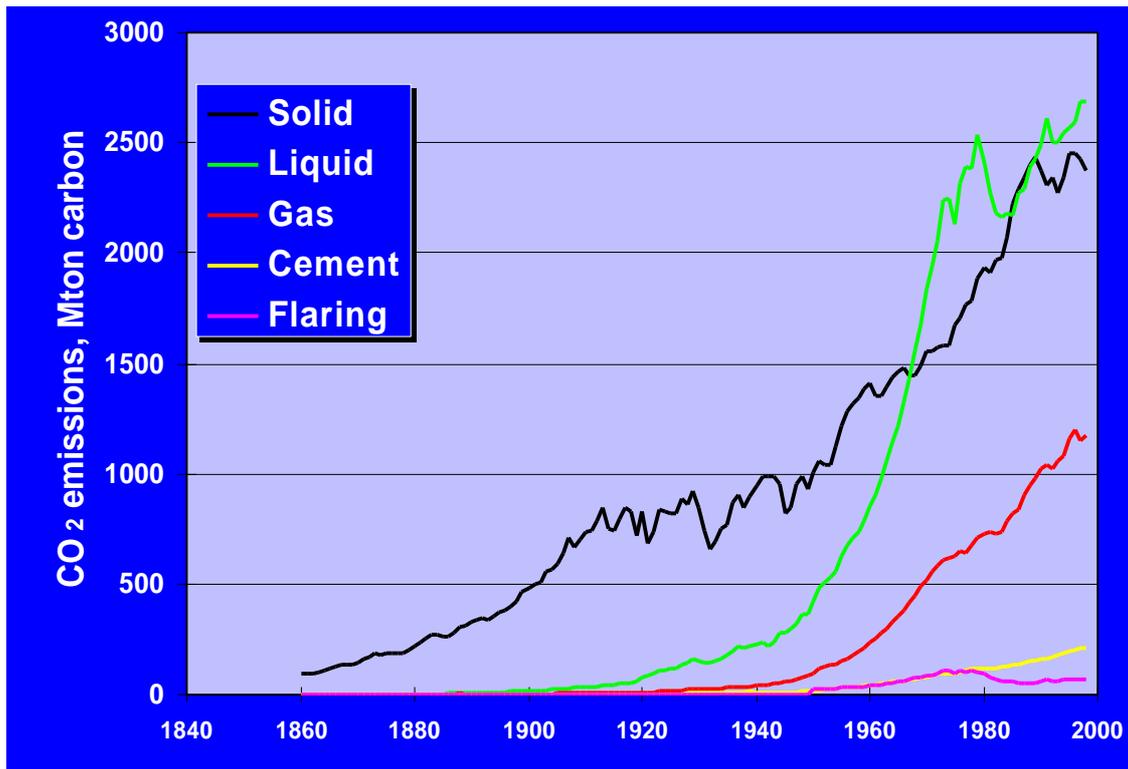
Figure 3.2   CO₂ emission from the five largest anthropogenic fossil sources

4. The length of the fossil fuel era

A simple model, based on a few parameters, can be used to quantify the future carbon dioxide load and to estimate the time span of the fossil fuel era. The model is based on a gamma distribution (Lindeberg and Holloway 1998) which is easy to normalise to the total amount of fossil fuels available. It is skewed and can therefore both describe the exponential increase in fossil energy use corresponding to the present exponential growth and the more extended tail that is characteristic of the decay due to exhaustion of a non-renewable resource. Its shape and size is described by only three parameters and is therefore easy to fit to the key data and assumptions. This limits its ability to describe complex patterns, but given the great uncertainties in the future energy demand, it is probably more than adequate.

The gamma distribution function of time, t, is given as

$$f(t) = \frac{A}{b^a \cdot \Gamma(a)} \cdot t^{a-1} \cdot e^{-t/b}$$

where, A, is the total amount of CO_2 from fossil fuels and a and b are related to profile shape. The parameters A, a and b are fitted to the following data:
1. The historical fossil energy use over the last five decades.
2. A total available reserve of fossil fuels corresponding to 6000 Pg of carbon. This is an average of to two estimates based on different approaches (Bolin et al 1986, Bolin 1998).

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3. The world population will cease to grow in year 2100 at a level of 11 200 million (Chamie 1998) and the peak of energy use coincides with the end of growth in population in 2100.
4. The world average use of fossil fuel per capita at the peak will be equal to half of the per capita energy use of fossil energy in the OECD countries today.

This is a model for the exploitation of a non-renewable resource until its final exhaustion during a period of increasing demand. There are no restrictions other than the abundance of fossil fuels and accordingly no restriction due to the possible environmental problem of emitting 6000 Pg of carbon in the form of CO_2 into the atmosphere. This will correspond to an atmospheric CO_2 concentration on 1400 ppm in year 2150, which is more than five times the pre-industrial level. The result is shown in Figure 4.1.
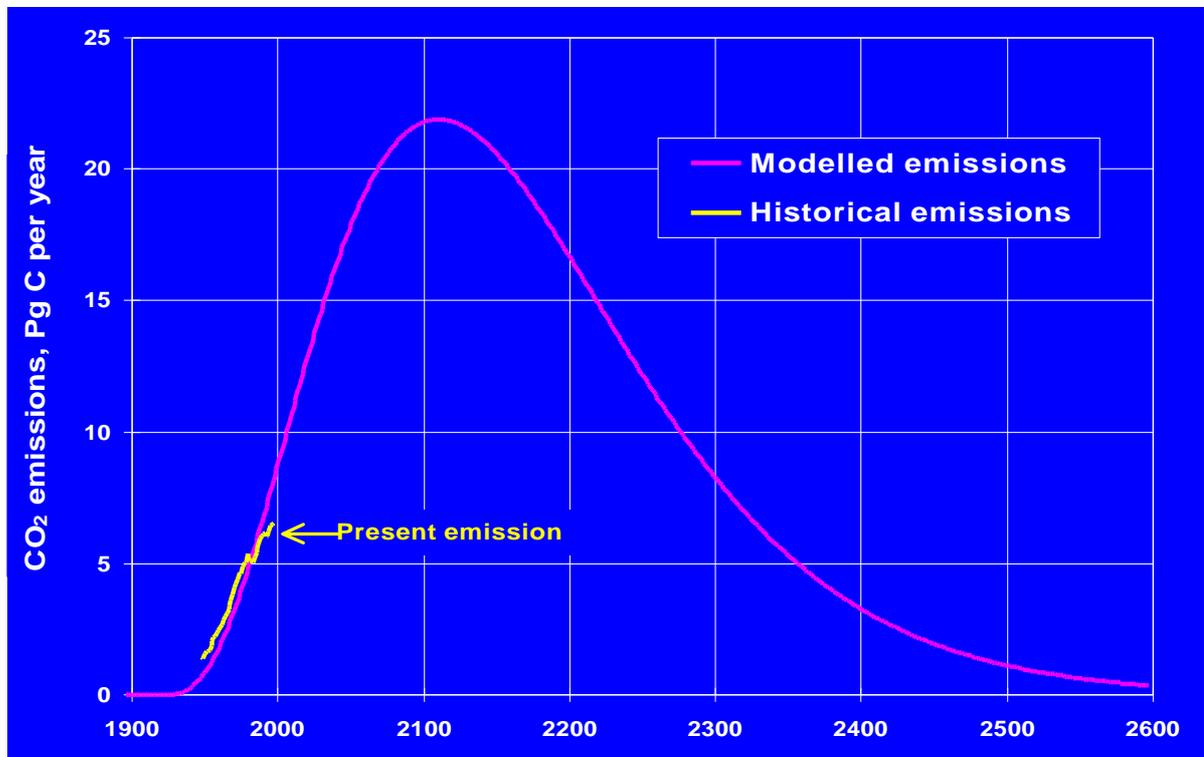

Figure 4.1   The CO_2 emission profile for a "business as usual" scenario only based on the increasing demand for fossil fuel and the depletion of the resources

The result suggests that, under this "business as usual" scenario, the fossil fuel era could continue for another 500 years. Despite the uncertainty about the theory on anthropogenic climate change, there will be significant concern about a CO_2 emissions corresponding to the model above. If the current concerns regarding anthropogenic climate change due to greenhouse gas emissions remain, we can see that technical measures to reduce the problem have to be implemented very soon and that these measures will have to remain in place for a very long period of time. The capacity of the measures must be in the order of thousands of million tonnes per year if they are to make a significant contribution.

5. Is it possible to change direction?

It may be difficult to sufficiently reduce the emissions by means of technological measures only. It is therefore necessary change the way of life to some extent so that the energy use per capita is reduced. This will include both limitation of individual choices and social organisation of transport, housing, industrial development etc. In many fields technological measures can contribute to reduce emissions. In Figure 5.1 a number of selected alternatives to meet this challenge is schematically presented. Many of these alternatives might be less attractive because they represent other risks or because the full consequences of the measure is not fully understood (e.g. large-scale increase of nuclear power, climate engineering, *e.g.* dusting the atmosphere with aerosol). Other measures might have limited capacity on the long time scale that the challenge persists. *E.g.* fuel switching from coal to gas can reduce the CO_2 emission per unit energy to the half. In Figure 5.2 the fossil CO_2 emissions from Figure 4.1 is broken down into the contribution form coal, oil and gas respectively. From this analysis it follows that large-scale substitution of coal with gas is an alternative, but only to small extent and only on relative short time scale can contribute to reduce global CO_2 emissions. After this period our descendants will have one alternative less to reduce their emissions because their dependence of coal will have increased, if it is assumed that the dependence on fossil fuels remains.

By applying measures with sufficiently large capacity it will be easier to avoid the least attractive alternatives for meeting the challenge of possible anthropogenic climate change. One answer to this challenge is to sequester the CO_2 that is associated with the use of fossil fuels. This will be a method to exploit the large fossil reserves without risking anthropogenic climate change.

Only underground storage (geo-storage) and ocean disposal of CO_2 can possibly meet a demand of this size in the future. At present only underground storage is feasible.

The fossil energy resources are large, but still finite. When they are exhausted we have to expect to rely on other energy sources. Considering the large dependence of fossil fuels it is is not likely that we will refrain from the use of all or most of the available fossil energy. The problem is how to go from the present situation with relatively low emissions (but still too high according to the recommendations from IPCC) to a situation in a few hundred years based on other energy sources without risking a major climate change in between.
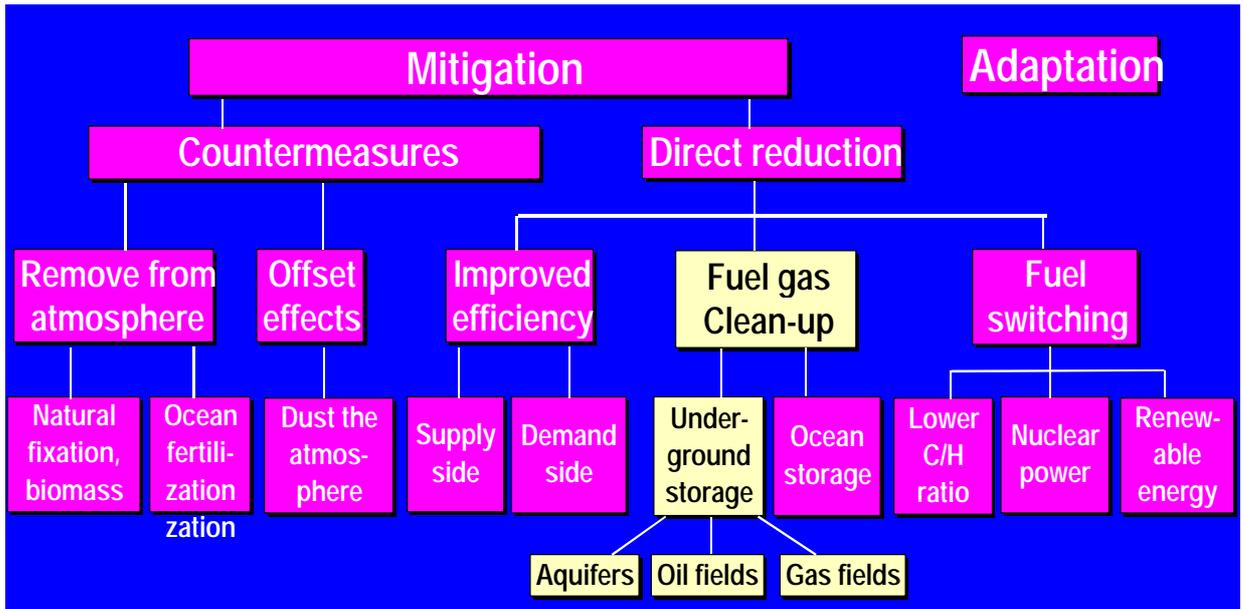
Figure 5.1   There are several choices and methods to meet the challenge of greenhouse warming. Underground storage is one of the few methods that can contribute to reduction in really large scale. The light boxes represent the area that is focused on in this work.

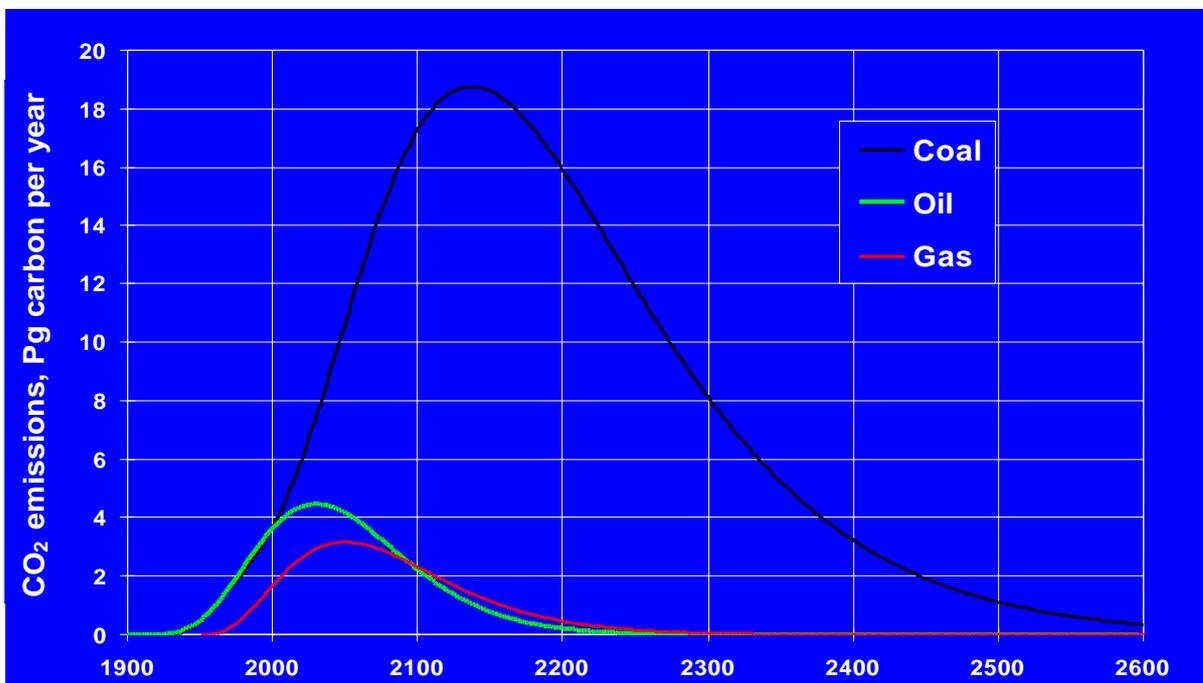*Figure 5.2 CO_2 emissions distributed on the three fossil energy sources coal, oil and gas. Substituting coal with gas will contribute to reduce the problems on a relatively short time horizon because coal is much more abundant than gas.*

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6. Is CO_2 sequestration a feasible option?

As late as 1987 the UN Commission on Environment and Development concluded that the only way to reduce the emission of carbon dioxide was to reduce the consumption of fossil fuels despite that scientists already prior to this report had shown that CO_2 sequestering was a feasible option. In Amsterdam 1992 the first conference on this special topic was organised and it has been followed by a number conferences and seminars for scientists within a growing field of research on this topic. Most interest has been related to CO_2 removal from point sources as power plants where CO_2 is emitted in large quantities. Also other point sources like ammonia, cement or gas processing plants are interesting point sources for CO_2 sequestering because CO_2 is available in relatively concentrated from. Some of the separation methods also rely on heat that partially can be recovered as excess heat from the power or process plant.

Emissions from large point sources account today for approximately one third of the total anthropogenic CO_2 emissions. If CO_2 sequestering will be applied in really large scale, it also is possible to turn distributed CO_2 sources into point sources. In the transport sector vehicles can be run on hydrogen or electricity and house heating from oil fired heaters can be replaced with district heating or heat pumps. In all these cases the energy (heat, electricity or hydrogen) can be produced in large central fossil-fuelled units where it is easy to handle CO_2.

The present schemes for CO_2 sequestering will substantially increase the energy production cost, typically with 50 to 100%. This might still not be a surmounting cost considering previous increase in energy in the recent time. In the early seventies the oil price increased with more than fourfold and the oil price is still more than double as high as in 1973 measured in money of the day as illustrated in Figure 6.1, (BP-Amoco 1999). At the same time the increase in oil price was accompanied by a retrofitting of coal power plants in many industrialised countries, so that the sulphur form the exhaust gas could be removed. This also increased the power cost significantly. This did have an effect on world economy, with a reduced yearly increase of gross national product, but the result was far from catastrophic. This could be an indication that a similar increase in energy today can be handled without large economical and social penalties, in particular when the alternatives are considered: to desist from most of the existing fossil fuel resources or to meet the climatic consequences of an uncontrolled accumulation of CO_2 in the atmosphere.

To include the CO_2 sequestering cost by use of fossil fuels, can be considered as a way to end subsidies to a sector that at the present are not debited the cost corresponding to its effect on climate change. Other energy sources that do not emit CO_2 will then compete on equal basis.
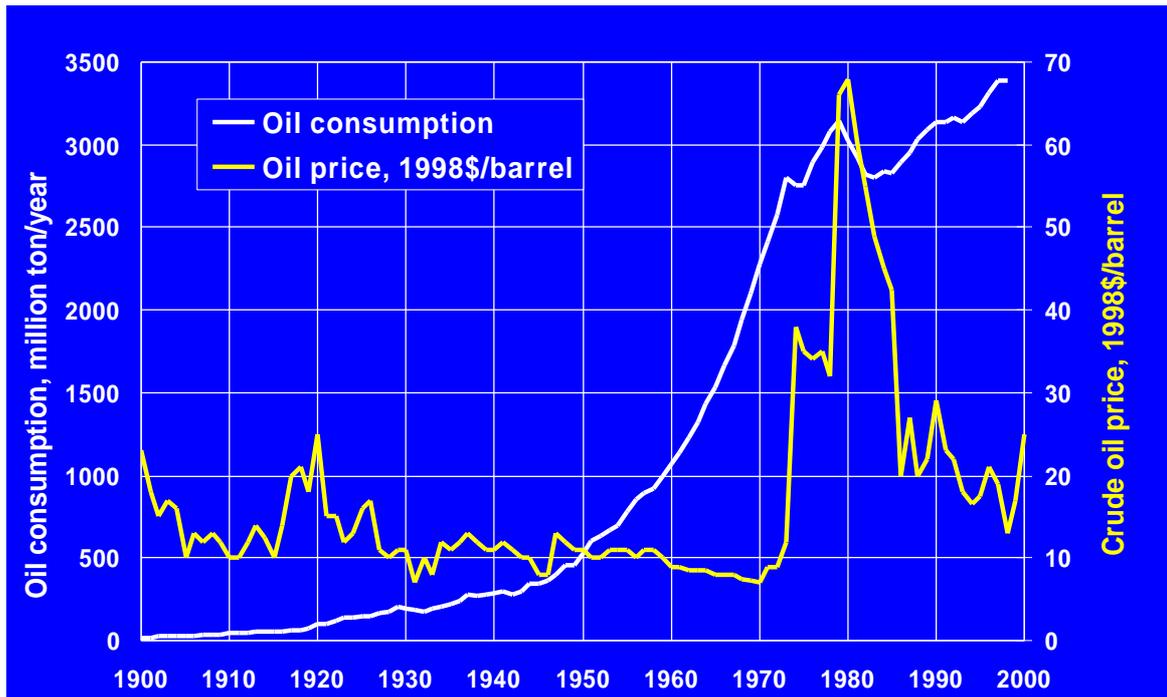
Figure 6.1   *Oil price compared to oil consumption in last century. At the present the oil price has more than doubled since 1973 measured in 1998-$.*

6.1   CO$_2$ separation methods

There are several methods to produce power from fossil fuels that allow the resulting CO$_2$ to come out from the process in a separate and concentrated stream. A number of combinations of fuels, combustion processes and separation methods can be combined. Most methods gives a penalty on the over all energy efficiency. In Table 6.1 some methods based on natural gas have been selected.

The separation and combustion are more or less integrated in these methods. Examples of a less integrated methods is found on the top of the table, *e.g.* to remove CO$_2$ from the exhaust gas from e.g. a combined cycle gas power plant by non-solvent transport membranes. This will require a pressure drop across the membrane and this power is directly reducing the power output. In the middle of the table somewhat more integrated process are listed, e.g. to remove the CO$_2$ by a chemical scrubbing process and use some of the excess heat from the power plant to regenerate the solvent.

Several of the listed methods can also be applied for coal, *e.g.* by use of coal gasification, and in some cases in combination with sulphur and particle removal (Hendriks and Block, 1992, Schütz *et al.*, 1992, Goldthorpe *et al.* 1992)

Table 6.1   Selected examples of methods for CO_2 separation based on natural gas. Only for some of the methods the technology is readily available.

Method	CO_2 separation method or other characteristics	Typical CO_2 removed	Over all efficiency [5]
NGCC[1]-PSA [2]	Pressure swing adsorption on exhaust gas after combustion	80-90%	~45%
NGCC-Membrane	Membrane separation of CO_2 from exhaust gas	80-90%	~45%
NGCC CO_2 scrubber	MEA or other amine scrubbing agent	85-90%	~51%
H_2-NGCC auto reforming	H_2 and CO_2 is separated by scrubbing before combustion	85-90%	~51%
NGCC O_2/CO_2 cycle	Near stoichiometric combust. with O_2 from an ASU [3]	~100%	~49%
MeO/Me [4] chemical looping	Generation MeO with air Regenerating Me with gas	~100%	50 - 60%
Solid Oxide Fuel Cell, SOFC	Integrated auto reforming at the anode at 1000°C	~100%	50 - 60%

[1] NGCC   Natural Gas Combined Cycle
[2] PSA   Pressure Swing Adsorption
[3] ASU   Air Separation Unit (typically cryogenic)
[4] Me   Metal, *e.g.* Ni, Co or Fe. MeO is the corresponding oxide, e.g. Fe_2O_3
[5] The basis for the efficiencies is a NGCC with 60% without CO_2 removal

6.2   Ocean disposal

It is theoretically possibly to dispose large amounts of CO_2 in the deep oceans. The ocean is also a sink for anthropogenic CO_2 and one third of the emission is absorbed naturally by the world oceans. If CO_2 is injected at 3000 meters depth or more, the CO_2 will be a liquid denser than water. It will sink to the maximum depth at this location and form a CO_2 lake and partially react with water and form solid hydrates. In this case long residence time of CO_2 can be expected. These depth are, however, not readily available near land on many locations. The possibility to inject CO_2 at more shallow depth, *e.g.* 1500 meter, has therefore been investigated. At these depth CO_2 will dissolve in water or form unstable hydrates if CO_2 is injected with special methods. This is also a potential disposal option, but there some questions remain to resolve. Among these are the possible effects the relatively concentrated CO_2 solution may have on biological life in the sea locally and regionally. The dissolved CO_2 will reduce the pH and this can have a strong effect on pelagic species. Another question is what the residence time of CO_2 will be. Most modelling of CO_2 residence time indicates that the atmospheric concentration of CO_2 will be reduced strongly the first 500 years, but after another 500 years, the concentration will be the same as if the CO_2 had been emitted into the atmosphere directly. This might be considered to be too short. These questions have to be answered by further research.

6.3   Underground disposal

Underground disposal is today the most attractive and mature storage option, at least in parts of the world where there are sedimentary rocks. These are rocks have been created through thick sea floor accumulation of sand, clay and organic material (*e.g.* animals with large content of carbonate) through million of years. During geological period of times these have been transformed into various forms of sandstone and limestone. These are usually porous and the pores are filled with water (aquifers) or in special cases with gas or oil (petroleum reservoirs). These natural underground geological formations can constitute long time storage sites for CO_2 provided they have a cap rock seal and are deeper than 700 meter (Holloway *et al.* 1996). At this depth CO_2 will behave like a fluid with densities of between 700 and 800 kg/m^3. Exhausted oil and gas reservoir can be used in the same way. The advantage of underground disposal compared with other storage options is that it gives minimum of interference with other ecological systems and, depending on the quality of the rock, can provide storage for long very period of time. *E.g.* gas and oil reservoirs have in many cases stored petroleum for millions of years. This storage option will therefore most easily gain public acceptance.

Lindeberg and Holloway (1998) have given an overview of various underground formations and their features in Table 6.1:

Table 6.1   Classification of different underground storage reservoirs. The capacities in the last column refer to EU and Norway.

Type of reservoir	Special features	Residence time Years	Capacity Gtonne CO_2
Petroleum reservoirs and over-pressurised aquifers	Pressure limitation due to geo-mechanical restriction	>1 000 000	50
Hydrostatic aquifers in anticlinal structures	Relies in the integrity of cap rock	100 000	50
Hydrostatic aquifers with monoclinal structures.	Ditto, cap rock topography determines CO_2 migration	2 000 to 100 000	700
Deep aquifers with semi-permeable seal	Relies on CO_2 being dissolved in brine during migration	2 000 to 100 000	Potentially large
Unconsolidated sediments at >1 000m sea depth	Relies on formation of sealing hydrates in the sediments	Not studied	Potentially large

In the last column of the table estimates of the storage capacity in EU and Norway are given. The total capacity in aquifers and petroleum reservoirs is sufficiently large to store all the CO_2 emissions from EU power plants in several hundred years (1 Gigatonne CO_2 per year).

A special case of CO_2 storage is to inject CO_2 in depleted oil reservoirs. Compared to other fluids, CO_2 has a special quality to efficiently displace oil and actually enhance oil recovery (EOR) from depleted reservoirs. CO_2 has been used successfully as injection fluid for several decades, mostly in USA. In this case, CO_2 will actually have a value in contrast to all the other alternatives for disposal that increases the energy production cost.

Initiated in 1972, Pennzoil's SACROC Unit in west Texas, was the world's first large-scale commercial CO_2 injection project. Prior to CO_2 injection, the oil field had been flooded with water for 18 years. The CO_2 came from a gas processing plants and would normally have been emitted into the atmosphere.

Boosted by high oil prices in the early eighties (Figure 6.1) the interest of CO_2 for EOR escalated rapidly. In 1980 two gas power plants were fitted to deliver CO_2 to oilfields in Carlsbad, New Mexico and Lubbock, Texas. The largest of these, in Lubbock, had a capacity of handling 410 000 tonne CO_2 per year (Pauley 1984). The CO_2 was separated from the exhaust gas by a monoethanolamine (MEA) solution. Due to the high oil prices the cost of producing CO_2 from gas power exhaust was economically viable till 1986 when these EOR facilities were closed. In periods of more normal oil prices the value of CO_2 is sufficient to cover about half of the extra cost associated with separation of CO_2 from gas power.

Today most CO_2-EOR projects utilise naturally occurring CO_2, which is produced from high pressure, high-purity underground deposits. For example, Shell's McElmo Dome field in south-west Colorado contains over 520 million tonne CO_2. However, a significant fraction of EOR projects utilise anthropogenic CO_2 such as waste streams from fertiliser or gas processing plants. This amounts to approximately 9 million tonne anthropogenic CO_2 per year. At present the largest CO_2 EOR project based on anthropogenic CO_2 is the Rangely Weber Unit, Colorado, operated by Chevron. Until 1996 40 million tonne CO_2 had been injected and the total amount of CO_2 injected when the project is ended, has been estimated to 70 million tonne. This corresponds approximately to twice the yearly total Norwegian CO_2 emissions.

In the North Sea most oil fields are being produced by water flooding or pressure depletion. When a field is exhausted and it is not economical to continue production still 40 to 65% of the oil may remain. All the oil can not be recovered and it is not easy to mobilise all the oil without injecting a suitable gas. Some of these fields can be interesting candidates for CO_2 injection.

6.4   Industrial aquifer disposal started 1996 in Norway

Several gas fields contain so much CO_2 that it has to be removed before it can be used. Standard engineering practice has been to separate the CO_2 and emit it into the atmosphere except for four locations in USA where the CO_2 is used for enhanced oil recovery. At the Sleipner Vest gas field, CO_2 rich natural gas is being stripped for its CO_2 and in this case the CO_2 is being injected into a saline aquifer at approximately 1000 m depth schematically illustrated in Figure 6.1.
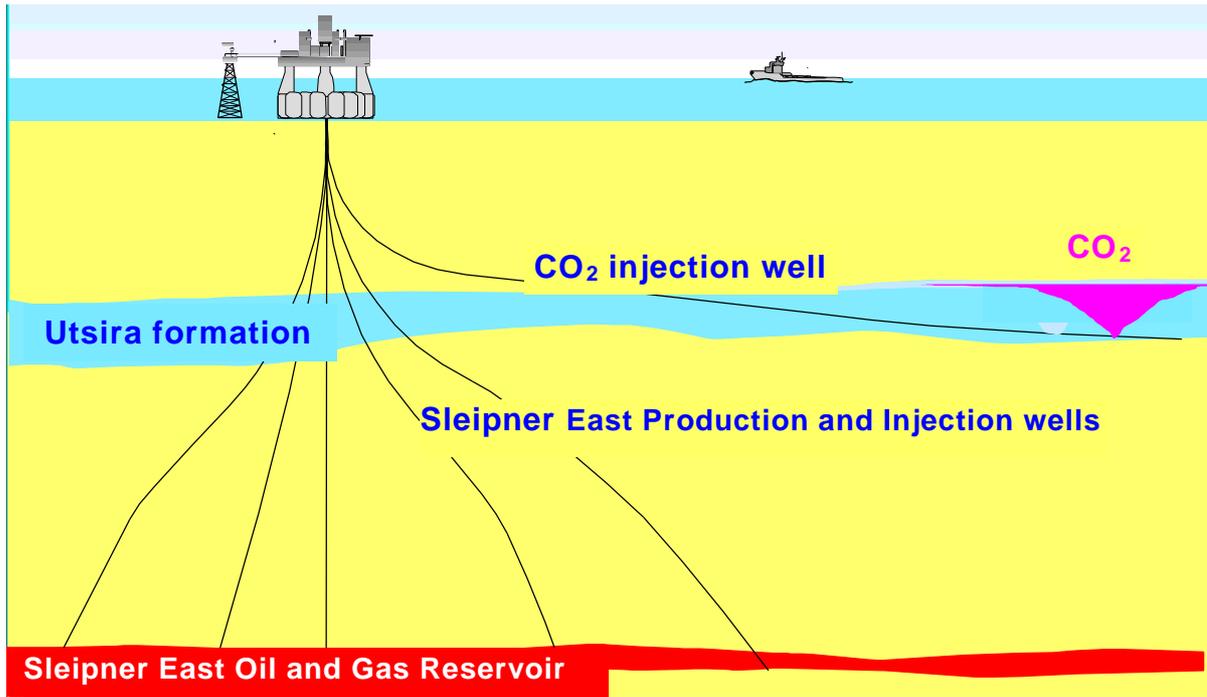
Figure 6.1   The Sleipner CO_2 injection project in the North Sea. Approximately 1 million tonne CO_2 per year is being disposed into a saline aquifer called the Utsira formation. It consists of high-permeable sand.

The 1 million tonne CO_2 per year corresponds to approximately 3% of the total CO_2 emissions in Norway. The extra investments in compressors and injection well were significant, albeit profitable if the Norwegian CO_2 tax is considered (46 USD/tonne CO_2). This project is interesting because it is the first project where CO_2 is being disposed solely to mitigate emissions into the atmosphere. There has been a considerable international interest for the project. A research project to monitor and give the best possible prediction of the short- and long-term fate of the CO_2 has been started. It involves researchers form five countries and one of its key elements is to monitor the CO_2 plume by performing seismic surveys at time-intervals (time-lapse seismic).

The Natuna field 210 km west of the Natuna island outside Borneo is a gigantic gas field containing the same amount of gas as the largest European gas field, Troll. The gas will be exported as LNG. The gas, however, contains 70% CO_2 that has to be removed. Also in this project the CO_2 will be disposed in nearby aquifers. In this project 210 million tonne CO_2 will be handled each year. This corresponds approximately to one forth of the total emissions from EU's power plants.

When CO_2 is injected into petroleum reservoirs there are good reasons to believe that CO_2 will remain underground for a period of time similar to the residence time of petroleum, *i.e.* millions of years. In aquifers there is not similar evidence for the storing quality. The sealing quality must therefor be established for each aquifer based on geological information. Data from core samples, well-logs, seismic surveys, natural

analogies and reservoir simulation must be combined to provide an estimate for the most likely retention time for each reservoir.

Lindeberg and Holloway (1999) have calculated a minimum retention time of CO_2 of 5000 years to reduce the risk of future anthropogenic climate change due to CO_2 escape into the atmosphere. This suggests a design criteria of 5 000 to 10 000 years retention time for selecting CO_2 disposals sites.

An example of simulated prediction of CO_2 escape from a reservoir with an open fault (spill point) allowing CO_2 to escape to the atmosphere when it reaches the fault as illustrated in Figure 6.2. The fault is located 8000 m from the injection point in an aquifer with a flat seal on top of high-permeable sandstone. The escape will depend on the permeability, but it can be seen that after an escape period of about 2000 year the escape rate decreases. After 8000 years 90 to 98% of the injected CO_2 still will remain in the reservoir as CO_2 dissolved in the aquifer brine. Dissolved CO_2 will only escape very slowly.
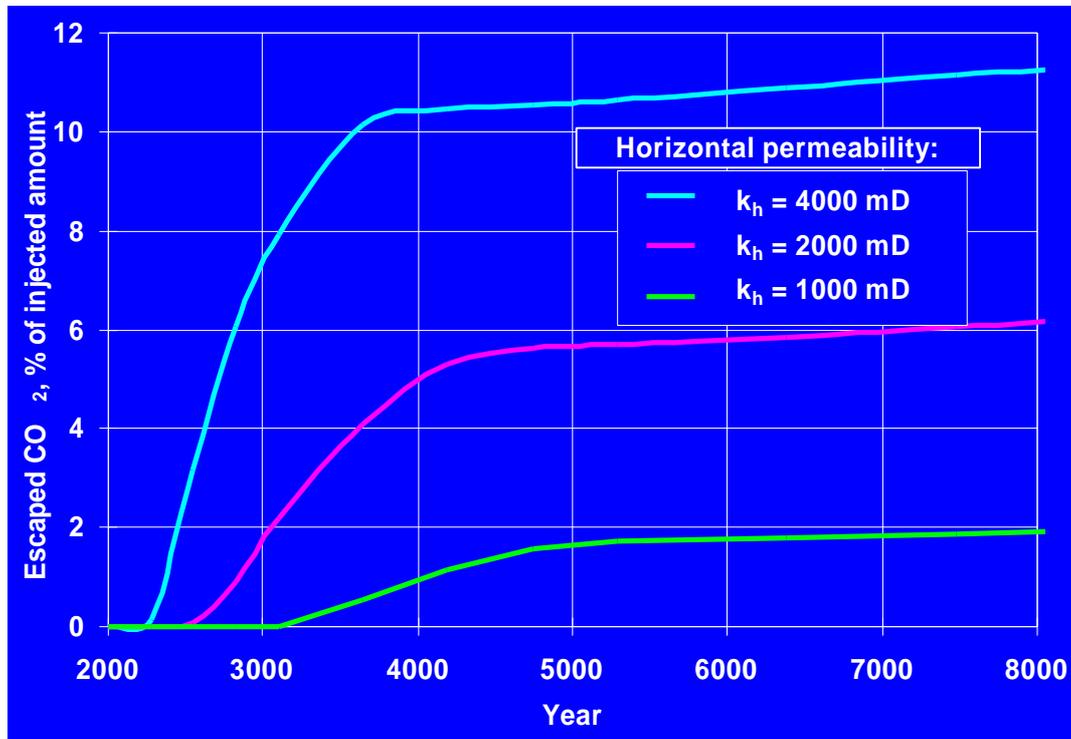

Figure 6.2   Simulated escape of CO_2 from an aquifer with an open fracture 8000 m from injection point

In another scenario the distribution of CO_2 is predicted in a reservoir which is subdivided by semi-permeable horizontal shales which are frequently found in aquifer and petroleum sandstone reservoirs. For a 25-year period 6 million tonne CO_2 per year is injected and a profile of the reservoir (Figure 6.3 and Figure 6.3) illustrates the distribution of CO_2 in 25 respectively 274 years after start of injection. Some of the CO_2 is temporary retained under the shales on its migration to the top seal. Much of the CO_2 will never reach the top to because it will dissolve in the brine during migration.

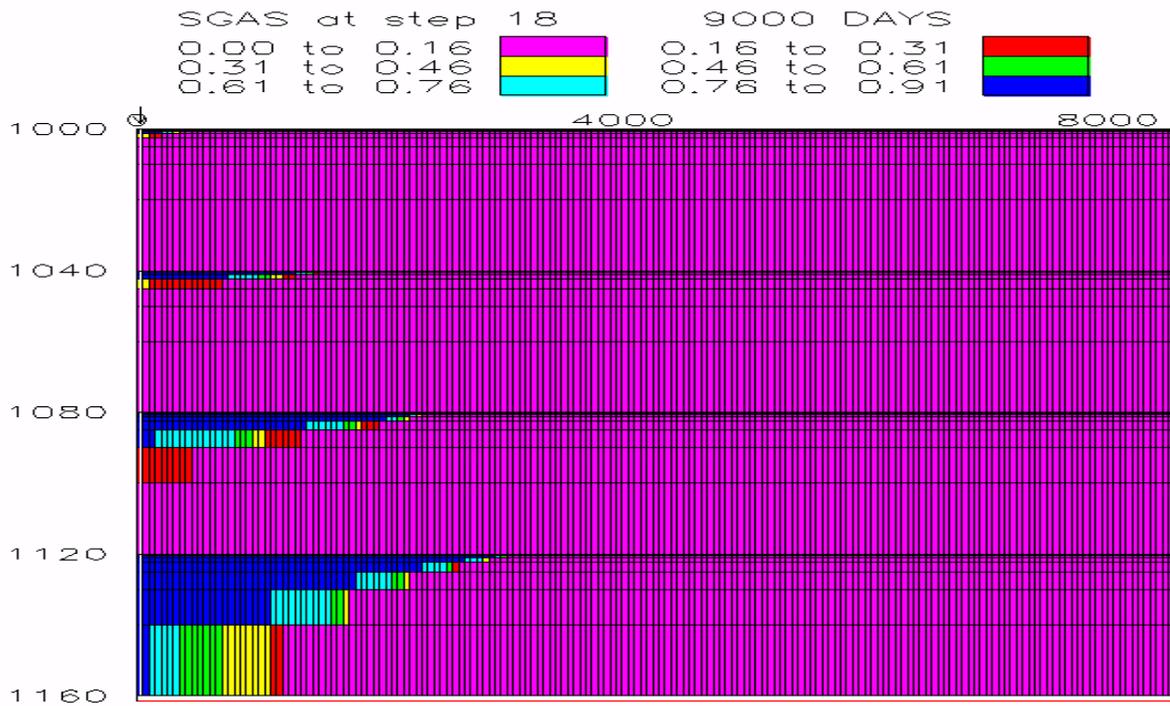Details of the simulations above are given by Lindeberg (1996).

Figure 6.3   *A vertical profile of an aquifer after 25 years of CO_2 injection in the bottom of the reservoir. The vertical axis is depth and the horizontal is distance from injection well. The CO_2 has accumulated under the semi-permeable shales and some CO_2 has just reached top of the reservoir. Pink represents the least brine and the other colours represent a gradually increasing fraction of free CO_2.*
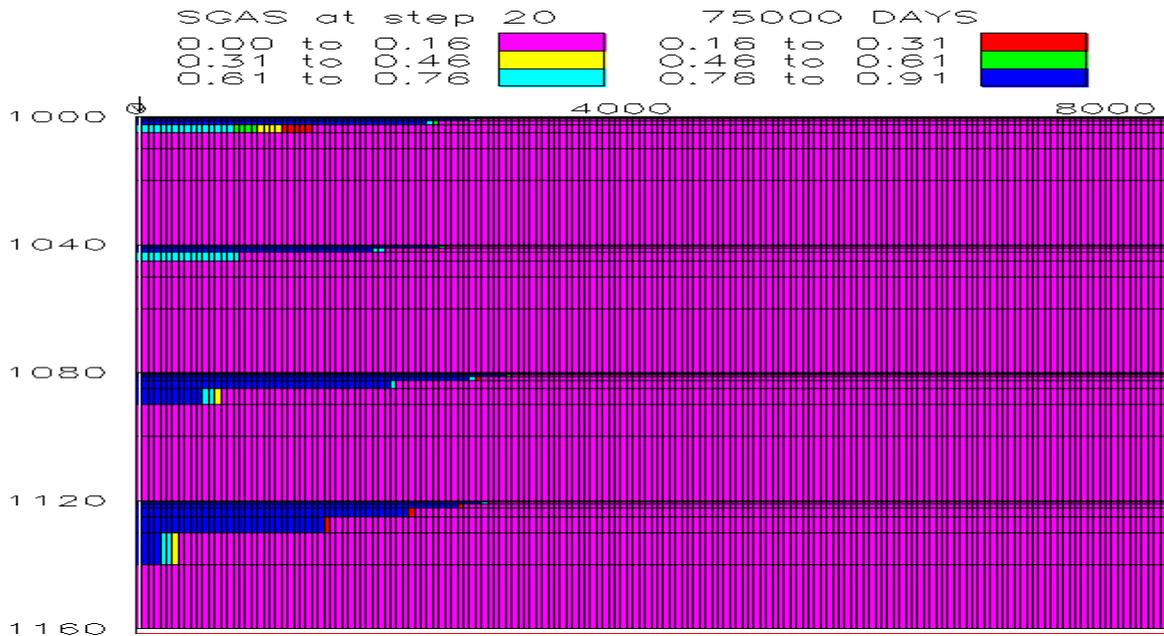

Figure 6.4   *The same aquifer after 274 years. The injection ended after 25 year. More CO_2 has now accumulated under the top seal, but the total volume of free CO_2 has been reduced because some of the CO_2 has dissolved in the aquifer. All CO_2 will eventually dissolve.*

7. Conclusion

To remove CO_2 from the combustion process of fossil fuels and dispose it under ground in petroleum reservoirs or aquifers is a feasible option for reduction of anthropogenic CO_2 emissions provided that the extra cost of energy associated with this scheme is accepted. When CO_2 is disposed into aquifers or other geological formation with unproven sealing capacity, special geological studies of the formation combined with reservoir simulations has to be performed to ensure that minimum sufficient retention time (5 000 to 10 000 years) can be achieved.

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