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An Introduction to CO_2 Capture and Storage

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It has become increasingly clear that reduction of the emissions of carbon dioxide arising from combustion of fossil fuels is needed. Replacement of fossil fuels for other energy sources and measures to reduce the primary energy demand are important paths of achieving this goal. A third path, which is beginning to receive recognition, is the capture and storage of the carbon dioxide formed from the combustion or conversion of fossil fuels. The purpose of this symposium is to give an overview of the status of the technology for capture and storage, and to highlight related work carried out in the Nordic countries.

Below an introduction to the CO_2 problem and to the status of CO_2 sequestration is given.

The CO_2 problem

The latest IPCC evaluation concludes that the temperature increase during the last century was 0.6±0.2ºC (IPCC, 2001), and that it is "likely that, in the Northern Hemisphere, the 1990s was the warmest decade and 1998 the warmest year" during the last 1000 years. (However, "…less is known about annual averages prior to 1,000 years before present and for conditions prevailing in most of the Southern Hemisphere prior to 1861.") The estimated temperatures during the last thousand years are shown in Fig. 1.

Although it would be difficult to prove, it is very likely that the noted temperature increase has been caused by the emission of greenhouse gases, of which CO_2 released from fossil fuel combustion is the primary one.

Today the concentration of CO_2 in the atmosphere is about 370 ppm, which is 30% higher than the pre-industrial level of 280 ppm. The stabilisation of the CO_2 level at twice the pre-industrial level, or 550 ppm, is estimated to require a gradual reduction of the average CO_2 emissions per capita by a factor of two before the year 2100, see Fig. 2. The corresponding reduction in Europe would have to be much greater because of the higher emissions per capita, about 10 ton/year. Even with such measures the climate is expected to be dramatically affected, with an estimated average temperature rise of 1.5-4.5 degrees. These numbers are put in perspective by a comparison: the average world temperature during the last ice age was approximately 4 degrees lower than today. Although many uncertainties remain regarding greenhouse gas effects, it is clear that even a temperature increase of a few degrees would have enormous impacts, for instance displacement of climate zones, and accompanying irreversible impairment of ecological systems.

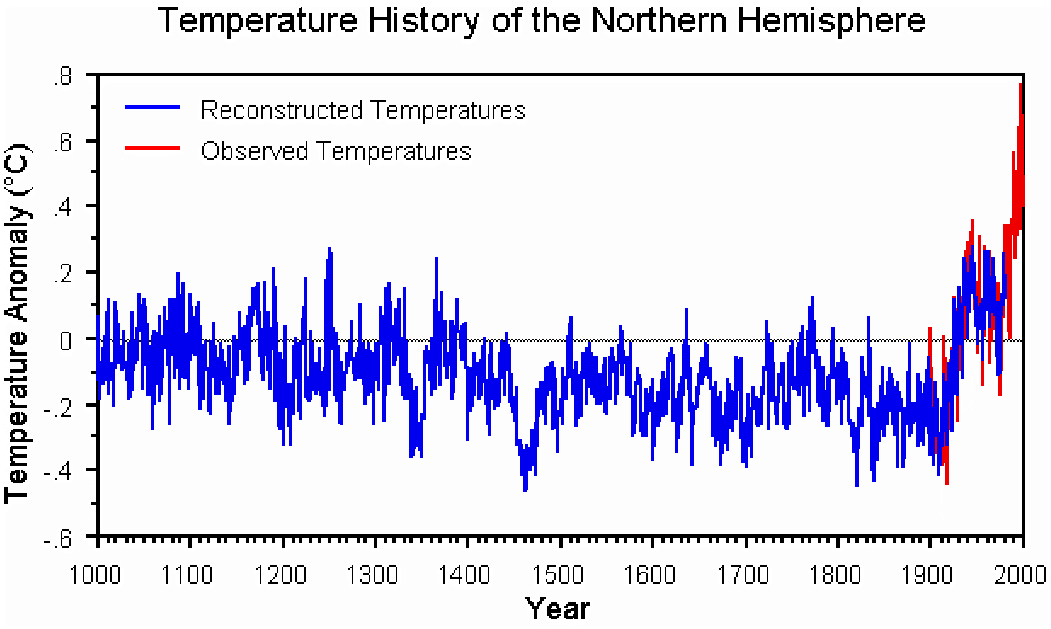

Fig. 1. Estimated temperature history of the Northern Hemisphere (Mann et al., 1999)

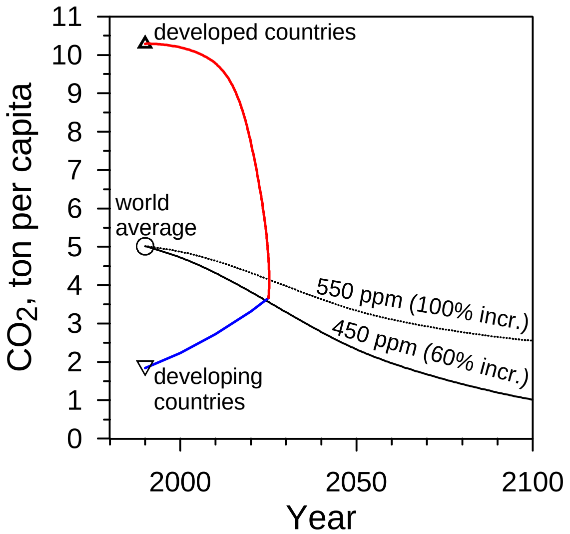

Fig. 2. World average emissions of CO_2 per capita and needed reductions for stabilisation at 550 or 450 ppm. Also shown is the average emissions of the developed and the developing countries. The assumed increase in developing countries is 2% year. In order to stabilise CO_2 emissions, the reduction needed in the developed countries is dramatic.

Thus to reduce the adverse effects, a bolder target for CO_2 levels is advisable. To stabilize the level at a 60% increase, 450 ppm, a per capita reduction by a factor of four would be needed before 2100. Again the decrease in the developed countries would have to be much greater. If it is assumed that the developing countries increase their per capita emissions by two percent per year, they will already reach the stabilization line for 450 ppm within 25 years, see Fig. 2. Preferably, the developed countries should also reach the stabilization line in terms of reductions, within the same time range. This would require decreasing our CO_2 emissions by a factor of three within 25 years.

The task of reducing CO_2 emissions

Fossil fuels constitute approximately 80% of the world's total energy supply, renewable sources 13%, with the remaining 7% coming from nuclear power. There are two general paths for decreasing the CO_2 emissions from the energy sector, Table 1, reducing the use of energy or reducing the CO_2 emissions from energy conversion.

Table 1. Possible ways of reducing CO_2 emissions.

Less use of energy	Less CO_2 from energy conversion
Increased efficiency of conversion/use	Fuel change, i.e. from coal to gas
Decreased demand	Non-fossil energy sources
	CO_2 sequestration

One of the major options is obviously non-fossil energy sources. These include:

Biofuels, which are the most important renewable energy source, contributing 10% or more of the total primary energy. A significant increase in the use of biofuels is to be expected, but the areas needed to produce sufficient quantities of biofuels to replace a substantial part of the fossil fuels would be enormous. Thus, shortage of land is expected to limit the use of biofuels. Here, shortage of land mainly reflects the conflict with other land uses, such as food production, natural habitats, etc.

Hydropower, which is the second most important renewable energy source, with about 2% of the total primary energy. Some increase in hydropower production is expected, but many possible sites are unsuitable because they would entail flooding of populated areas and environmental disturbances.

Wind power, which provides on the order of 0.02% of the total world energy at present, but is rapidly increasing. The future contribution from windpower is likely to be significant, but the availability of suitable sites is expected to set an upper limit to use.

Solar energy has great potential, but unfortunately both thermal and photovoltaic solar energy are still very expensive, compared to fossil fuels. Hopefully, the future will bring dramatic cost reductions.

Nuclear energy contributes 7% of the total primary energy today, but because of the lower efficiency of nuclear power the actual electricity produced is no more than that of hydropower. The availability of nuclear fuel resources is significant. Today, few nuclear power plants are being built, mainly because of the lower costs of fossil fuel power plants. The future of nuclear power depends on the public and political acceptance and is therefore difficult to assess.

Future energy demand

The task of reducing the CO_2 emissions related to the ***present*** energy demand, however, is only the tip of the iceberg. The growth in the world economy will mean rapidly increasing demands for energy. A comparison of countries with different gross domestic products (GDPs) reveals a virtually linear relationship between energy consumption and GDP over a wide range of per capita GDPs, see Fig. 3. This relationship, which corresponds to the slope in the diagram, is called "energy intensity". The energy intensities of most large countries and regions are within a factor of two of the world average.

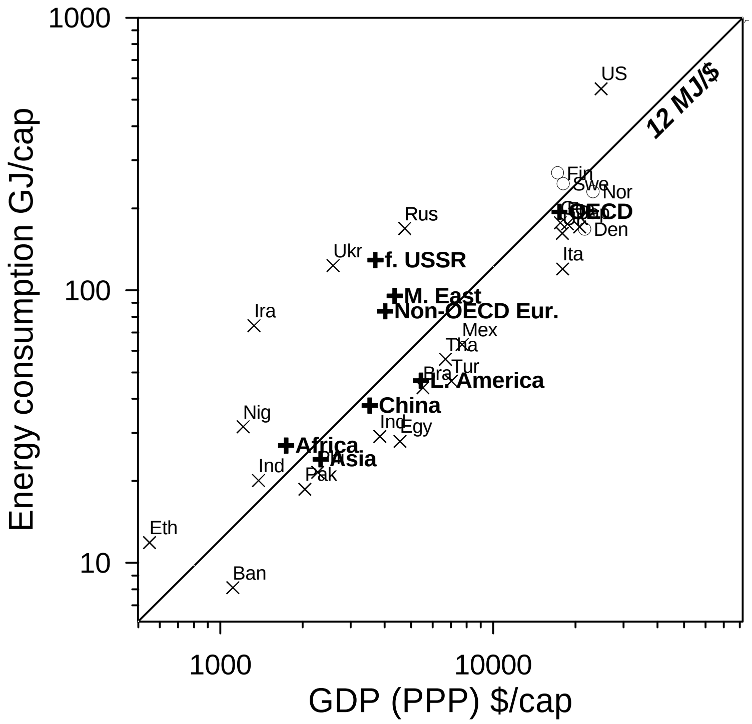

Fig. 3. Per capita energy use versus GDP per capita. The ratio between these two is energy intensity. The world average energy intensity of 12 MJ/$ is indicated by the slope. Based on data from IEA (1999). Regions (+), countries with more than 50 million people (×), Nordic countries (o).

Thus, a significant increase in energy demand can be expected with the growth of the economies of the developing countries. For example, an average annual growth of 3.1% will mean a fivefold higher global GDP by the year 2050. A five-fold increase may appear dramatic, but considering the growth in population it will not be sufficient to increase the average GDP per capita of the world to the level where the developed countries are today, see Fig. 4.

This leads to the question of the future correlation between energy demand and GDP. If energy intensity is constant, a fivefold increase in the GDP would give a fivefold rise in energy demand, but how will energy intensity develop in the future? There are two major factors affecting energy intensity: technical development and energy price.

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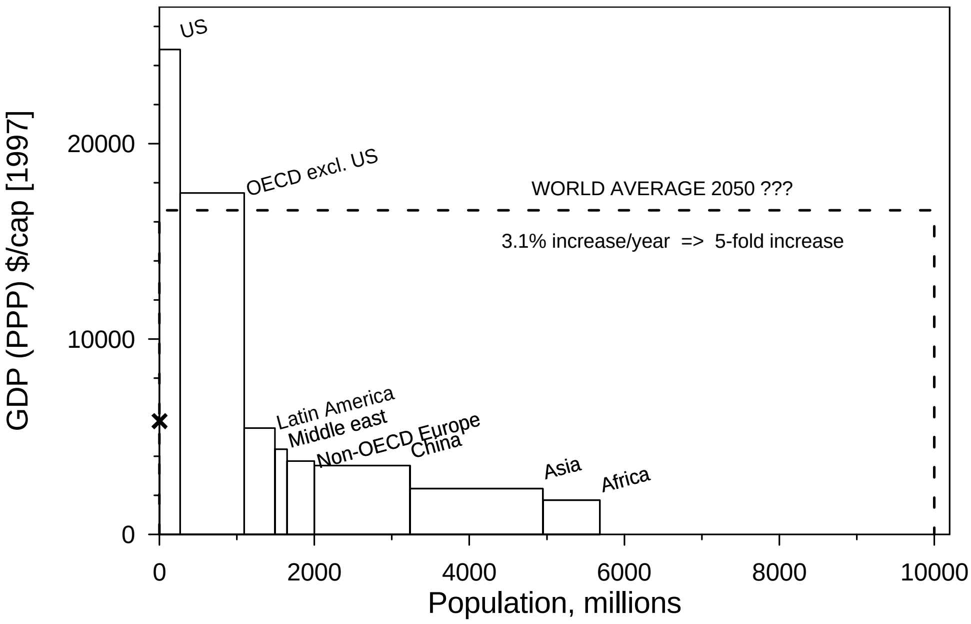

Fig. 4. GDP per capita in different regions versus population. Based on data from IEA (1999)
The cross shows the world average GDP (1997).

Historically, decreasing energy intensity has been noted, e.g. in the US. One example of the role of technical development is the increase in efficiency of thermal power plants, which was more than tenfold (!) in the US over the last century. In 1900, the average efficiency was 3%, and now the highest efficiencies are close to 60%. It is evident that a further tenfold increase in power plant efficiency is not possible as there is a definite upper limit at 100%. Power production is only one of many processes involving conversion or use of energy, and there are many other possibilities for making the conversion or use of energy more efficient. However, the example reveals that we cannot safely assume that improved technology will provide a steady, unceasing decrease in energy intensity, at least not at the low energy prices of today.

The effect of price, on the other hand, is clear, and it is obvious that economies with low energy prices generally have higher energy intensities. (Note, for instance, the countries above the world average in Fig. 3.) Thus, energy price is a powerful tool in determining total energy demand.

The solution

It has often been stated that there is no single path to reducing the CO_2-emissions, and this also applies to CO_2 sequestration. In order to solve the CO_2 problem many paths are needed.

However, there is only one solution that will enable us to effectively obtain the necessary large reductions in CO_2 emissions, and this is to provide strong economic incentives in the form of high costs for CO_2 emissions. This will open all the doors previously discussed, and provide the necessary incentives for reducing energy demand, for replacing fossil fuels with non-fossil energy sources, and for CO_2 sequestration.

CO_2 sequestration

CO_2 sequestration involves the capture, transport and storage of CO_2 from processes in which fossil fuels or biofuels are converted.

Capture of CO_2 from power plants has been practiced commercially since the late 1970s. This CO_2 was used for enhanced oil recovery, and in the chemical and food industries. For instance the Lubbock plant, opened in 1980, had a capacity of 400,000 tonnes of CO_2 per year, used for enhanced oil recovery. Worldwide, approximately 450 million tonnes of CO_2 per year are used for enhanced oil recovery and of these approximately 25 million tonnes come from anthropogenic sources. (By comparison, the CO_2 emissions of the four large Nordic countries range from 34 to 64 million tonnes/year).

In 1998, Norsk Hydro announced plans for building two natural gas power plants of 10-12 TWh with 95% CO_2 capture, where CO_2 was to be disposed of in connection with enhanced oil recovery. The reason was that Norwegian laws had been adopted prohibiting the building of fossil fuel power plants without CO_2 reduction. These plans were later postponed, probably because of the present low prices of electricity in Northern Europe.

A prerequisite for the use of carbon dioxide removal is the possibility of disposal. Several methods are available, such as storage in aquifers, gas fields and the above-mentioned enhanced oil recovery. Mineral carbonation, i.e. reaction of CO_2 with magnesium silicates to form carbonates is another possibility (Zevenhoven, 2001). Storage in aquifers is already practiced by Statoil in the North Sea, where CO_2 is injected into the Utsira aquifer 1000 m below the bottom of the sea. In fact, one million tonnes of CO_2 per year, or 3% of Norway's total CO_2 emissions, are disposed of in this way. This is the first time large-scale storage of CO_2 is being used solely for climatic reasons anywhere in the world. The critical decisions regarding this project were made as early as 1991-92 and the injection of CO_2 began in 1996. The injection is monitored by an international research project - SACS (Lindeberg et al., 2000, 2001).

In 2000 an enhanced oil recovery project was started, involving the injection of 1.8 million tonnes of CO_2 per year in the Weyburn Field, Saskatchewan, Canada. The CO_2 comes from a coal gasification plant in Dakota and is transported via a 330 km long pipeline.

The potential for this geological storage of CO_2 is large; the capacity of the 26,000 km^2 large Utsira aquifer in the North Sea has been estimated to be sufficient to store the emissions from European power plants for many hundreds of years. Exhausted gas fields typically have a storage capacity corresponding to twice the amount of CO_2 obtained from burning the gas extracted from the field (Blok et al., 1997). In the EU-project GESTCO the possible geological disposal of CO_2 is being investigated in Norway, Denmark, Germany, Holland, Belgium, France, England and Greece (Christensen, 2001).

The cost of disposal in aquifers is small, in contrast to the costs of CO_2 separation. Provided that the amount of CO_2 is sufficiently large, disposal costs down to 2-3 $/tonne of CO_2 would be feasible and the costs of transportation could be of a similar magnitude. In the case of enhanced oil recovery, the cost is even negative, as there is an income from the increased oil production. *Thus, it is an important challenge to find cost-effective capture technologies.*

Costs

The non-fossil energy sources are associated with high costs (compared with fossil fuels) and/or a restricted availability/potential. A comparison of costs for electricity production is given in Fig. 5. The future costs of different energy technologies are uncertain, but the use of fossil fuels in combination with CO_2 capture will probably be less expensive than other options for producing CO_2-free power. However, the main point is that the potential of biomass and wind power is limited, and therefore these will be insufficient to accomplish future large reductions in CO_2 emissions.

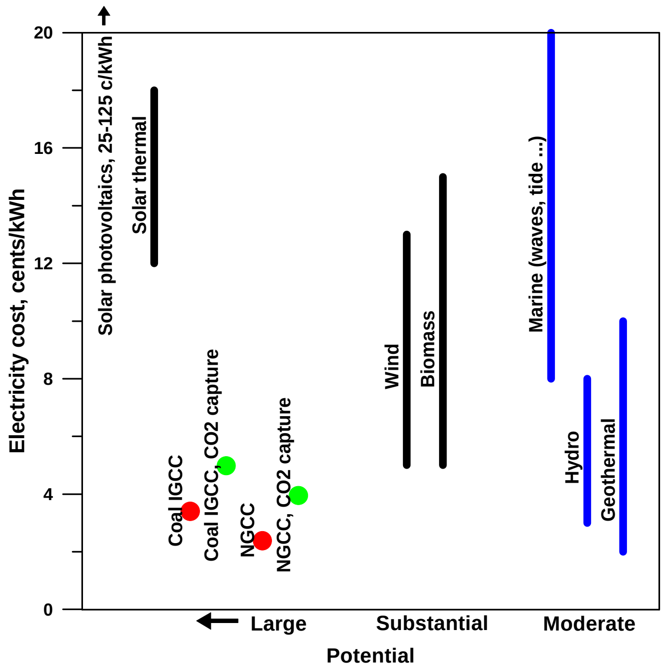

Fig. 5. The cost of electricity versus potential. Here potential is a qualitative measure of the possible contribution to electricity production, e.g. availability of rivers where hydropower plants can be built. Data on costs from UNDP (2000). Fossil fuel plants: IGCC (Integrated Gasification Combined Cycle) and NGCC (Natural Gas Combined Cycle); without CO_2 capture (red dots) and with "conventional" CO_2 capture (green dots).

The costs of CO_2 capture in Fig. 5 correspond to 30 to 50 €/tonne of CO_2. Most estimates of the cost of CO_2 capture are on the order of 50 €/tonne or less. Is this a feasible cost? In order to answer that question we first assume that other measures of CO_2 reduction are associated with similar costs. In other words, we assume that we could obtain large reductions of CO_2 emissions at an average cost of 50 €/tonne. Would it be realistic to reduce the CO_2 emissions significantly at such costs?

The total European CO_2 emissions are 3000 million tonnes/year. If it is assumed that half, 1500 million tonnes/year, were eliminated at a cost of 50 €/tonne the total cost would be 75 000 million €/year. This is certainly a lot of money, and corresponds to an average of 200 €/capita, or about 1% of the European GDP. Another way of putting it, is that it corresponds to a loss of approximately four months of economic growth.

Another comparison is with the cost of oil production. The average production costs of oil decreased from 29 $/barrel to 18 $/barrel between 1981 and 1997. The decreased cost of 11 $/barrel corresponds to 43 $/ton of CO_2!

In conclusion, it will cost a great deal of money to reduce the CO_2 emissions ***but it will certainly not make us significantly poorer or threaten our standard of living.***

It should also be said that the costs of CO_2 reduction may well be lower in the future. Firstly, the incentives needed to make reductions of CO_2 possible, would increase energy prices and therefore reduce the use of energy significantly, which would probably lead to lower total costs for the emission reduction. Secondly, the large-scale development and commercialisation of CO_2-free energy sources will reduce the costs. The many recently started CO_2-capture projects, with a focus in cost reductions are a pertinent example. Some of these are discussed in the papers in this volume.

Emissions of CO_2 and riding a bicycle without brakes - a parable

The climate system is highly complex and we cannot be perfectly certain about the effects of greenhouse gas emissions. However, we can know that it is likely that greenhouse gases will affect the climate, and that the consequences could be catastrophic. Also, we can safely conclude that the problem will not disappear, and that the emissions of CO_2 will continue to increase unless forceful measures are taken.

This situation can be compared to riding a bicycle downhill at high speed towards an intersection with heavy traffic - and finding that the brakes do not work. In such a situation there are two possibilities:

i) remain on the bicycle as it proceeds towards the intersection and hope for the best,

ii) jump off the bicycle at full speed, get hurt, but not risk being hit by a car.

If we reduce the CO_2 emissions significantly this will cost a large amount of money (it will hurt just like jumping off the bicycle) but we will be safe in the knowledge that we have done our best to protect the world we once inherited before we pass it on to our children.

Many years ago I actually experienced that situation on the bicycle and I chose to jump off. It did hurt, but I am happy I did it. Otherwise I might not have been able to write these words.

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