Confining and abating CO_2 from fossil fuel burning – a feasible option? (revised edition)

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Summary

In this study, options have been analysed for abating and confining CO_2 from fossil fuel burning. The starting-point is the situation, where CO_2 actually has been produced. Hence, preventive options such as energy saving, renewables and nuclear energy are not considered in detail, though there are boundary cases (e.g. the application of CO_2 for energy farming - which is actually a utilisation of solar energy) which are nevertheless discussed.

After a general introduction regarding the character of the greenhouse problem, attention is paid to the CO_2 situation in EUR 12. Statistics show that 13% of the global CO_2 emission stems from the EC. Some 25% of this emission originates from point sources – mainly large-scale power plants; the remaining CO_2 emission (traffic and transport, industries, built-up areas) is mainly diffuse.

Solutions for reducing the CO_2 emissions can be found in influencing the fuel mix, and in removing CO_2 from fossil fuel burning processes. The removal of CO_2 would be followed by its storage in geological formations or in the ocean. Other solutions are found in energy farming, reforestation, afforestation, and the prevention of deforestation. This prevention is particularly relevant in tropical areas.
Each of these various options is considered in some detail. It appears that the prospects of changing the fuel mix are limited. Though switching from coal to methane does reduce the CO_2 emission by 42%, it should be realised that the natural gas reserves are limited. Moreover, increased use of natural gas leads to an increase in leakage of the distribution system (today this leakage is approximately 1%). The greenhouse effect of one molecule of CH_4 is 20 to 27 times that of one molecule of CO_2.
In order to store CO_2 from power plants effectively, it has to be separated from the other exhaust gases, primarily nitrogen. This can be done by scrubbing, absorption or adsorption, or with the help of (bio)chemical methods. In this context, absorption techniques are relatively attractive. However, burning the fossil fuel with pure oxygen is also an attractive option, making the separation of the exhaust gases superfluous.

Useful application of CO_2 would be most effective in the form of energy farming, where liquid fuels (ethanol, vegetable oils) could be produced.
Injection of CO_2 into the subsurface is possible in depleted gas fields and in aquifers. The first option is attractive because it simultaneously stimulates natural gas production. However, distances between gas fields and power plants are often a problem. Storage in aquifers is prospective as well, though there are still many uncertainties.
Whether or not large quantities of carbon can be stored in the ocean remains to be seen. There is currently some consensus, that any CO_2 injected will come out again in due time. Nevertheless, also gaining time may be useful. The most practical option for EUR 12 seems injection of CO_2 near Gibraltar; from there it would spread with the help of the natural currents over the Atlantic Ocean at a depth of about 1200 m.

Next the role of biomass is discussed. The total area of the world's forests is some 3 x 10^9 ha, and biomass is the most natural tool for storing CO_2, simultaneously producing O_2. In EUR 12, in the near future, 20 to 30 x 10^6 ha of farmland will be redundant, due to overproduction, and may well be utilised for reforestation and/or the energy farming mentioned earlier. Thus, by utilising carbon from vegetation as a fuel, actually carbon subcycles are created, replacing (in part) the emission of new carbon from geological formations into the atmosphere.
Moreover, EUR 12 has an important task in the prevention of deforestation in developing countries, where 10 to 25 x 10^6 ha of forest are vanishing each year.

In the context of an evaluation of cost and effectiveness of the various options for abating and confining CO_2 from fossil sources, preventive options, viz. energy saving, nuclear breeding reactors and renewables are also considered. This is done in order to see where they fall in terms of ECU/ton CO_2 emission reduction.
In order to obtain a better comparibility of the figures, distinguishment is made between GROSS and NET costs. This is notably relevant for the options of energy saving, renewables, nuclear energy and energy farming, where the benefits of avoided fossil energy production are subtracted from the GROSS costs in order to obtain the NET costs.
It appears that in particular energy saving (2% per year, over a period of 10 years) and nuclear energy are NET relatively cheap. Renewables are also attractive. Storage options are more expensive, but still relatively attractive. Biomass options are the most expensive, specifically energy farming. The latter option, however, entails positive side effects, such as avoided export premiums of cereals and avoided fallow premiums.
In fig. 1, the various options have been summarised quantitatively.

It should be emphasised that this is, of course, a very rough comparison of costs. Actually, from each of the options presented, a large number of versions exist, ranging from "cheap" to "expensive". However, at this stage of premature thinking on the subject, even for the same option, considerable differences in cost estimates exist. Moreover, each option implies a number of effects that have not been taken into account here. Storage of CO_2 in aquifers or in depleted gas fields, for instance, requires extra energy. On the other hand, renewables and energy saving imply a decrease in acidification, and conservation of natural resources. Nuclear energy for a great deal lacks public acceptance and implies certain environmental risks, forests may promote tourism, etc.
However, if the aspect of CO_2 emission reduction is considered exclusively, a total CO_2 emission reduction of roughly 60% seems to be feasible, at a cost of some 110 milliard ECU/a GROSS, or 55 milliard ECU/a NET.

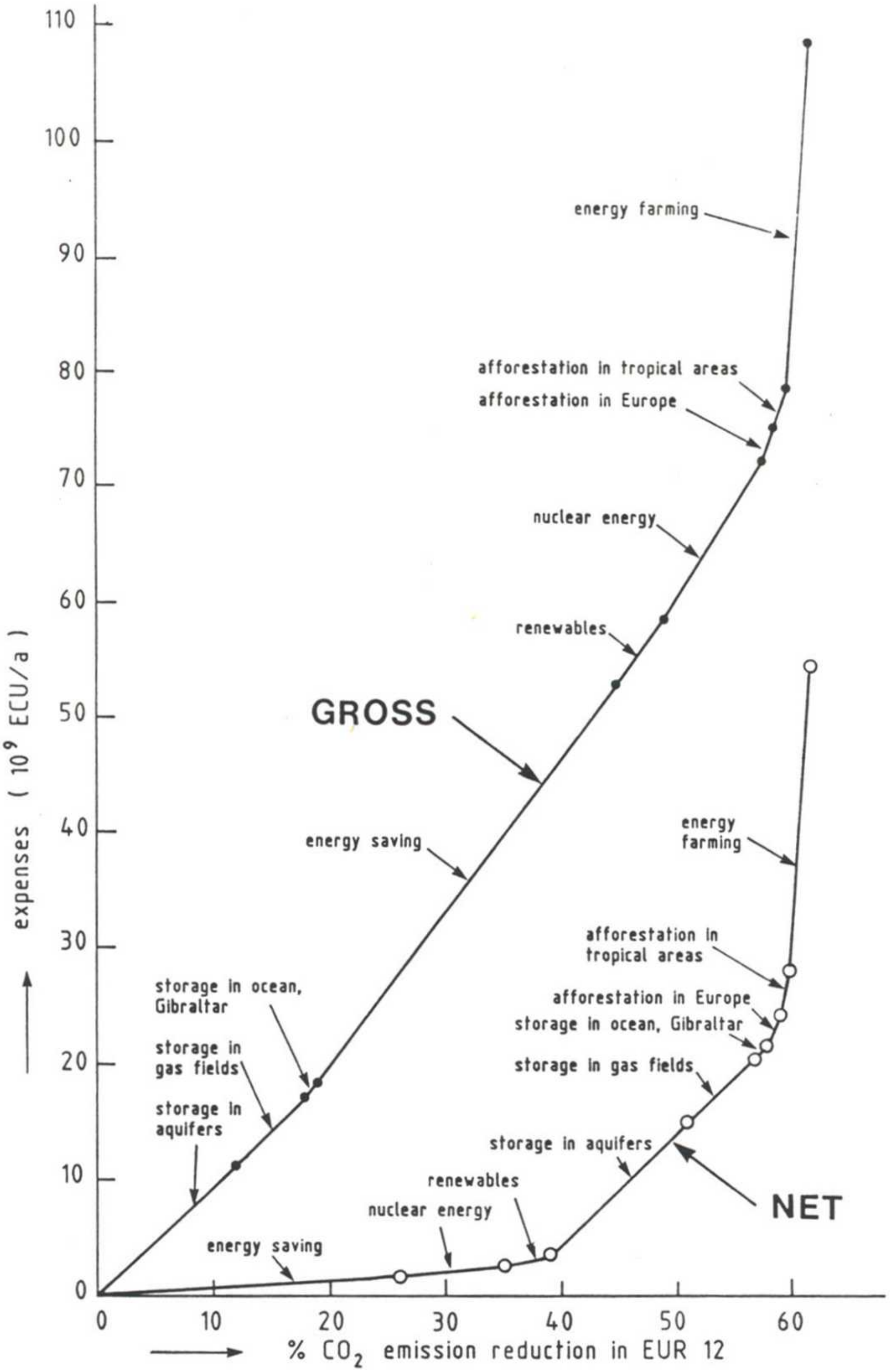

Figure 1 *Options for CO_2 emission reduction in EUR 12, NET and GROSS cost , and effectiveness.*

It should be realised, though, that a 60% CO_2 emission reduction implies only a 30% reduction in greenhouse gases. Therefore it is logical that the reduction of other greenhouse gas emissions, notably CH_4, N_2O and CFCs is considered simultaneously, in order to arrive at a maximum reduction of CO_2 emission *equivalents* at minimum costs.

Further, more drastic CO_2 emission reduction is only conceivable on the basis of the "breach-of-trend" concept. This implies that fundamentally new norms and goals have to be set in society, at least in the EC, but preferably on a global level. Examples of these breaches of trend relevant in this context are an increase in the use of wind energy by a factor 100 or more, a breakthrough in general public acceptance of inherently safe nuclear energy, including breeding reactors, and an integrated, systematic approach to controlling world population.
In practice, a mix of the options presented in this study and these breaches of trend would probably constitute the optimum policy.

Further it is suggested that the best way to tackle the problem as a whole is possibly emphasising nonfossil energy use as much as possible in the developed areas of the world, leaving the application of technologically simple renewables to the developing countries, thus minimising their use of fossil fuels.

Finally it is recommended to use the present study as a basis for a detailed scenario study, in which the relevant parameters are set out as a function of time for, say, the next 25 years.
Together with the latter study, a number of basic policy decisions regarding this issue have to be made by the EC.

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Annexes

1. CO_2 emission in the EC. From: "Energy in Europe; major themes in Energy. Commission of the European Community, special issue, September 1989

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1 Introduction

(E. Mot)

1.1 Some history

During the past 20 years, profound changes have taken place in our perception regarding energy and environment.

In this context, the 1973 energy crisis is noteworthy, since it triggered the international consciousness that energy resources are finite. And though today it is generally recognised that the crisis centred on politics rather than energy, it was a realistic view of the late Dutch prime minister, Joop Den Uyl, when he stated:

'After this, the world will never be the same'

He was right, but probably in a somewhat different way than he perceived at that time. When the crisis was over, the car-free Sundays and other restrictive measures taken in various EC-countries became history. And, though the concern about our fossil reserves remained, the actual energy use continued to increase. Though even today there is still more oil found than used, the point of view that in a finite world growth has to be limited is gradually gaining public acceptance. The warnings of the Club of Rome of the 1970's, their sequel in the various dynamic global models of Forrester and Meadows, the recent Brundtland report - they all add up to the same conclusion, viz. that any state of global non equilibrium eventually leads to disasters.

Under the influence of these forces, the fear that there would be a shortage of energy was gradually replaced by the perception that we cannot afford to use (fossil) energy without limits, for environmental reasons.

At first, acidification, due to energy production and use, was considered the major problem. Emission of SO_2 and NO_x, causing damage to forests, agriculture, buildings and constructions, and cultural heritage. Technologies for abating these emissions have been developed and now exist, though they are often expensive and for a large part still have to be implemented.

1.2 The greenhouse effect

A second problem, larger and more fundamental in nature, associated with the use of fossil energy, concerns the emission of CO_2. This is known to contribute for about 50% to the increase of the **greenhouse effect**, the warming of the earth, due to enhanced adsorption of long-wave radiation from the earth's surface by the atmosphere.

There is compelling evidence that the CO_2 content of the atmosphere is increasing rapidly. (Figure 1.1, 1.2) [1]

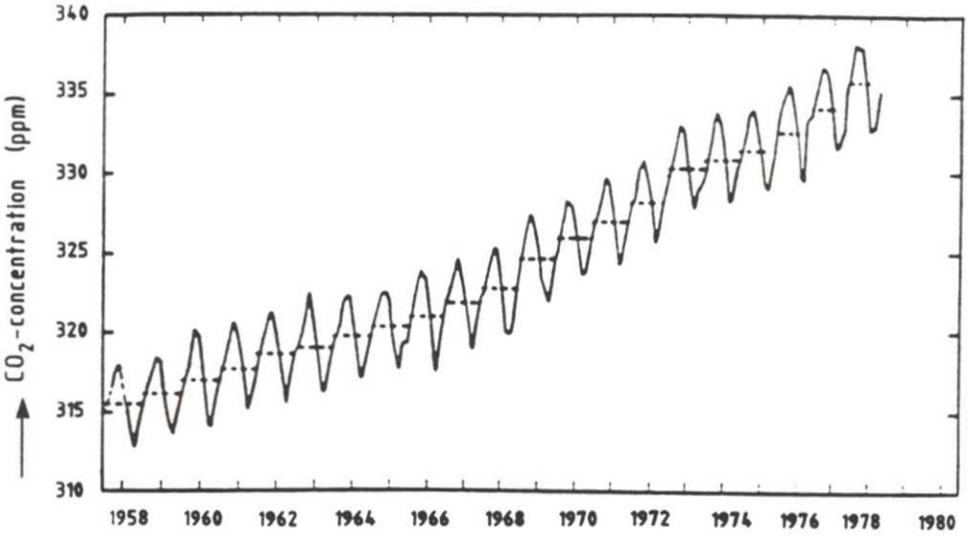

Figure 1.1 CO_2 concentration in the atmosphere, measured on Mauna Loa (Hawaii)

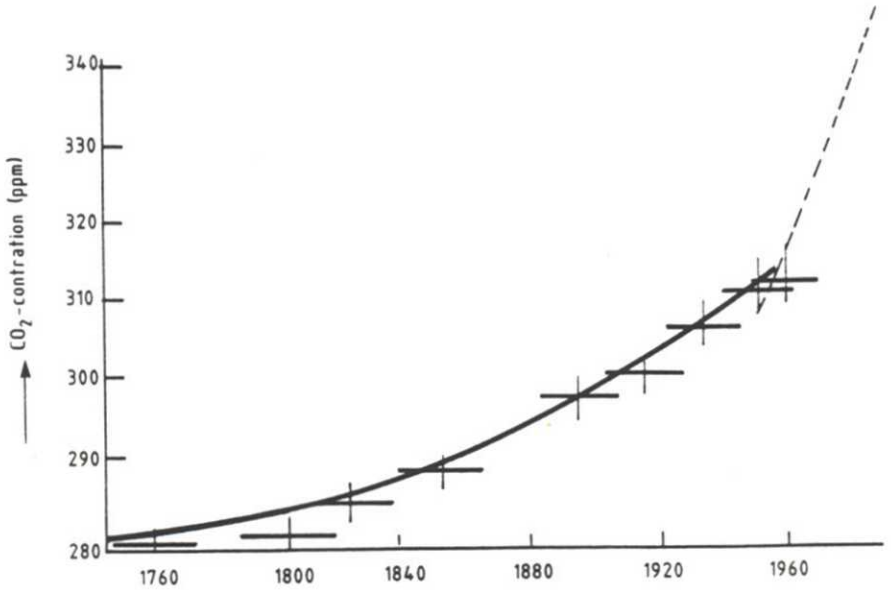

Figure 1.2 CO_2 concentration in ice-cores, since the beginning of the industrial revolution. From 1960: Atmospheric CO_2 concentration Mauna Loa (Hawaii)

For the actual increase of the global temperature, the indications are less convincing (e.g. figure 1.3, [2])

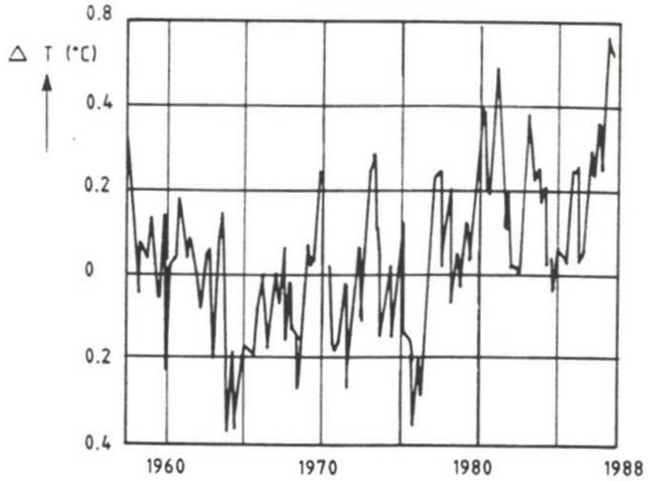

Figure 1.3 Quarterly average of the average world temperature at 2 m height

The essential problem regarding the greenhouse effect lies in its irreversible character. The world simply cannot afford the risk of waiting to find out whether it is 'true' or 'not true', since the potential consequenses are too negative. This has been clearly stated in the first international Ministers' Conference on Climate change in Noordwijkerhout, Netherlands, in November 1989, in which 60 countries participated, and also in the more recent ministers' conference on the same subject in the USA, in April 1990.

On the other hand, it should be realised that there is no unanimous agreement about the negative consequences of the greenhouse effect. Mikhail Budyko, one of the most prominent climatologists in the USSR, states: 'The greenhouse effect is not a disaster. On the contrary, climate and living circumstances in large parts of the world will improve considerably.' [3].
Though the latter point of view definitely has its merits, it seems more adequate to summarise that on a global level the costs due to climate change will doubtlessly be much larger than the profits. However, the many conflicting interests imply that reducing the global CO_2 emission is, politically, a very difficult matter.
In this context, the expected world population growth (figure 1.4, [4]), as well as the emancipation of developing countries, should also be taken into consideration.

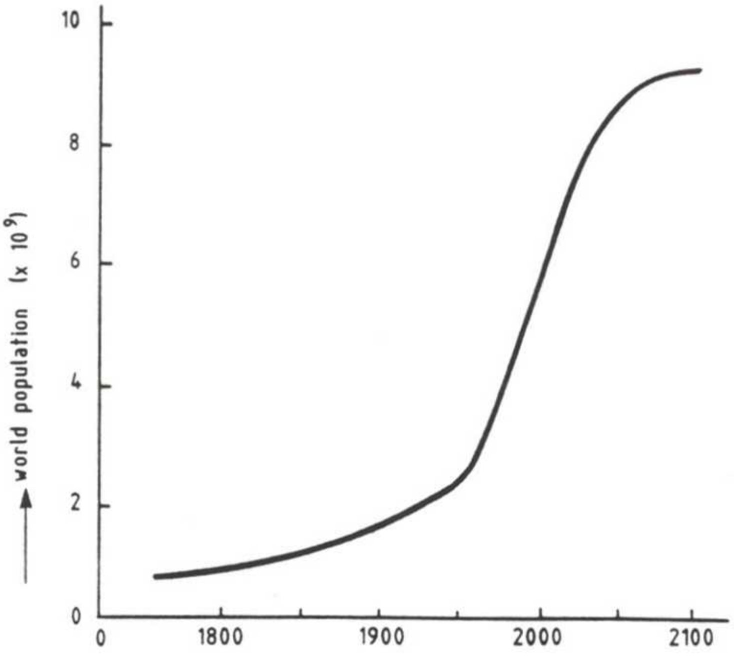

Figure 1.4 Expected growth of world population

The fundamental difference between reducing the acidifying emissions (SO_2 and NO_x) and the emission of CO_2 lies in the **quantity** of the latter. The acidifying emissions are undesired by-products of fossil fuel burning; CO_2, however, is the main combustion product. Each kg of C results in 3.7 kg CO_2. Moreover, CO_2 is no 'poison'. On the contrary, it is a prerequisite for life.

Further, it is noteworthy that there is a remarkable similarity between the options for energy saving (the 'energy crisis' approach) and those for reducing CO_2 emissions. More specifically, the options for the latter are [5,6].

a. **Energy saving**
   This concerns both technological, behavioural and institutional changes .
b. **Renewable resources**
   Solar, wind, water, geothermal, biomass, wood.
c. **Creation of sinks**
   By reforestation, increase of bioproduction.
d. **Removal of CO_2 from combustion**
   Followed by storage in the ocean, or underground.
e. **Changing the fuel mix**
   Natural gas, uranium.
f. **Optimising secondary energy**
   Electricity, hydrogen.

Dependent on the local circumstances, each country has to choose its own mix. From a conference on 'Climate and Energy', in Utrecht, Netherlands, on September 27, 1989, of which [5] is a synopsis, the following comments on these options can be summarised.

ad a. The SVEN (the Dutch Foundation for Energy Conservation) estimates, even with the low natural gas price in The Netherlands (for private use (early 1990) 0.2 ECU/m^3, incl. VAT; industrial 0.12 ECU/ m^3) that further energy savings up to 12% are feasible, with a pay-back period of $1^1/_2$ years or less.

ad b. In particular, solar energy is considered to be of importance. Further, also wind energy and water power are of interest.

ad c,d The prospects for sinks of CO_2 and its removal from exhaust gases are considered to be limited.

ad e,f By changes in the fuel mix and by optimising the use of secondary energy carriers, a significant decrease in CO_2 emissions is possible.

It will be seen that the results of the present study are not quite the same as those cited above. In particular, the present study is more optimistic about CO_2 storage in the subsurface, and less optimistic about changing the (fossil) fuel mix.

1.3 Framework of this study

For the present study, only the aspects 'abating' and 'confining' are relevant. This implies that the options a and b from section 1.2 are not considered; neither will nuclear energy be discussed.

Thus the above constitutes the framework of this study. More specific, efforts will be made to find answers to questions of the following nature:

- What technologies are available for binding CO_2 from fossil fuel burning equipment? What increase in efficiency is still feasible? Can the fuel mix be changed in order to decrease CO_2 emission?
- Once the CO_2 has been produced, can it be injected into geological formations? Dito deserted gas fields, salt cavities, aquifers?
- Is injecting CO_2 into the ocean a realistic option?
- What is the role of biomass? Reforestation, possibly outside Europe, 'energy farming', increased use of wood in buildings and constructions?

Within the context of these questions, attention will be paid to the total amount of CO_2 that could thus be stored or avoided, the financial consequences, the societal acceptability and the logistics.

The results will be placed against the background of the present global and 'EUROPE 12' situation regarding CO_2 emissions, which will be dicussed in the next chapter.

From the above it is clear that the prospects of the options to be considered are limited. However, the urgency of the problem justifies their analysis, because it is very probable that the solution of the CO_2 problem - if there is any - will be built up from a wide range of partial contributions. In exploring, and possibly implementing these options, the EC might also act as a guide for other nations.

More tangibly, **chapter 2** of this report presents a review of the CO_2 situation, both on a global and on an EC-level.
In **chapter 3**, attention is paid to the present fuel mix, and the possiblities to modify it with regard to the CO_2 problem. **Chapter 4** presents the various options to remove CO_2 from the exhaust gases emitted in fossil fuel burning processes.
The **chapters 5, 6, 7 and 8** review the scope of CO_2 sinks. In this context, attention is paid to useful applications of CO_2 to injection into the subsurface, the role of the oceans, and the role of biomass, respectively.
Next, the costs and effectiveness of the various options are evaluated in **chapter 9**. On that basis, in **chapter 10** an integrated vision on the problem as a whole is presented. **Chapter 11**, finally, contains a number of conclusions and recommendations, resulting from this study.

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2 The CO_2 situation

(R.J. Nielen)

2.1 Situation worldwide

The greenhouse effect is, together with the destruction of the ozone layer, an environmental problem that can only be tackled effectively when measures are taken worldwide. The greenhouse effect made us aware of the fact that there are no borders in the air. In the seventies, the subject received primarily scientific attention. Recently, however, the political attention for the greenhouse effect has increased strongly. The first actual recommendations for abating the greenhouse effect were launched at the Ministers' Conference 'The Changing Atmosphere: Implications for global Security, in Toronto, July 1988 [1]. There it was proposed to reduce CO_2 emissions worldwide by 20% by the year 2005. Despite new international conferences (i.e. The Hague, Washington), and the formation of an Intergovernmental Panel on Climatic Change (IPCC), no further international agreements have been achieved as yet.
However, though some significant countries are reluctant to make such decisions now, and want to do more research before commitments with such large consequences are made, there is a growing tendency to consensus. Recently, the UK decided to commit itself to CO_2 reductions.

Model studies indicate that CO_2 has accounted for about two-thirds of the total global warming over the last century, approximately, but that its relative importance has declined to about half of the total of the emissions in recent years. This is due to a more rapid growth of the emissions of other gases during the last few decades [2]. In this context, particularly the recent growth in chlorofluorocarbon (CFC's) concentrations has been important. Table 2.1 gives an overview of the present contributions from the various greenhouse gases. The international proposals currently focus on reduction of CO_2 emissions and, though in a different context, on CFC's.

Table 2.1 Contributions of different gases to the greenhouse effect [3]

	Growth per annum	Effect per molecule	Contribution
CO_2	0.5%	1	49%
CH_4	1.0%	20	18%
CFC's	5.0%	20.000	14%
N_2O	0.3%	200	6%

2.1.1 CO_2 emission

Two activities account for most of the anthropogenic CO_2 emissions, viz.
- the production and consumption of energy
- the modification of land use.

The major human activity affecting CO_2 emissions is the consumption of energy from fossil fuels. Fossil fuels now provide about 85% of the world's total energy requirement [11]. In industrialised countries, even over 95% of all energy needs are satisfied by fossil fuels.

Global consumption of fossil fuels has increased rapidly over the past century, due to the growth of the human population and its economic activity. CO_2 emissions grew from less than 0.1 Gt C annually in the mid-nineteenth century to about 5.4 Gt in 1986 (See figure 2.)

In recent decades there has been a significant shift in global energy patterns. In 1950, OECD countries consumed about 75% of all commercial energy supplies, the centrally planned economies of Europe and Asia 19%, and developing countries 6%. By 1985, OECD countries consumed just over 50% of all commercial energy globally, while the European and Asian centrally planned economies and the developing countries had increased their relative shares to 32% and 15%, respectively. Between 1950 en 1985, commercial energy use in the OECD grew from 93 to 189 GJ per capita (GJ/cap), in centrally planned economies from 16 to 59 GJ/cap (269%), and in the developing countries from 3 to 18 GJ/cap (500%) [11]. The percentage of energy consumed by OECD countries is expected to decline further as energy requirements in developing countries expand, due to both economic activities and population growth.

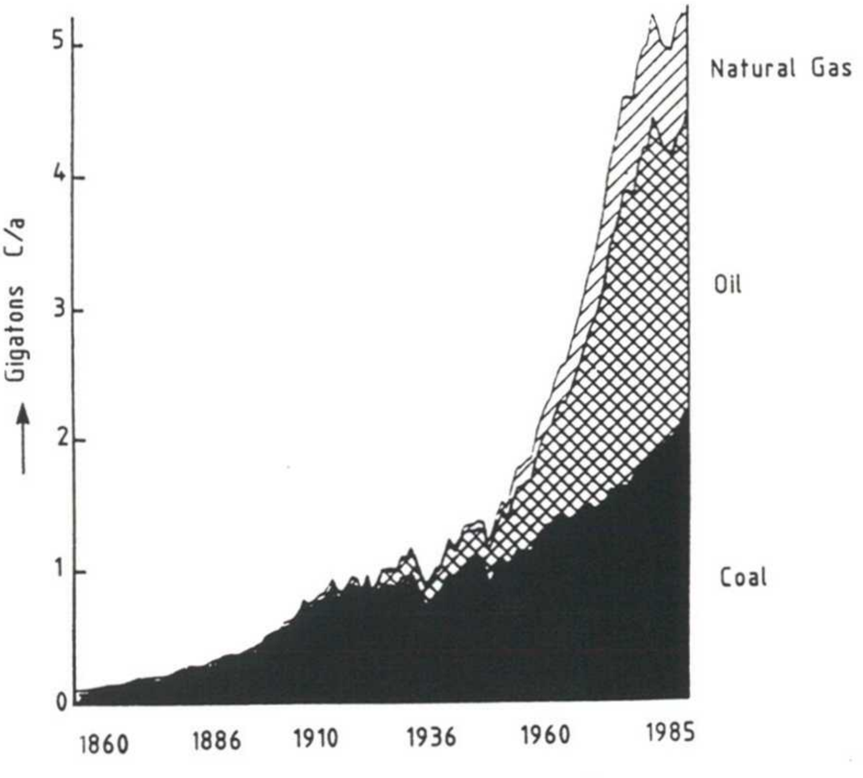

Figure 2.1 CO_2 emissions from the combustion of fossil fuels (world level) [6]

The allocation of energy consumption among sectors varies considerably from country to country. Three important sectors are industry, traffic & transport, and residential/commercial use of energy. A documentation and summary of the fossil fuel sources of CO_2 has been given by **Rotty** [4,5].

Another source of CO_2 emissions is the modification of land use. In general, land-use modification is a net source of CO_2 to the atmosphere. CO_2 is released as a result of burning and decay of dead plant matter and oxidation of soil organic matter. The amount of this release exceeds the amount of CO_2 absorbed as a result of regrowth of live vegetation and accumulation of soil organic matter. Recently, **Houghton** [7] and **Detwiler** [8] estimated a net source of 0.4 - 2.6 Gt C/a to the atmosphere from land-use changes, deforestation in the tropical areas accounting for nearly all the flux. This would constitute a considerable percentage (up to 50%!) of the total yearly increase of carbon in the atmosphere.

Many scenario studies have been carried out to predict future CO_2 emissions from human activities [4,5,6]. A study by **Keepin et al.** (1986) reviewed and re-evaluated the range of previous energy and CO_2 projections. It concluded that the feasible range for future energy use in 2050 will be somewhere between about 10 and 35 TW[*], with CO_2 emissions between 2 and 20 Gt C/a (the large range indicates the uncertainty of the experts concerning future developments).
Most researchers, however, expect a further growth in CO_2 emissions due to:
- increase of world population
- deforestation/erosion
- increased use of energy
- changes in fuel mix.

On this basis, a 20% reduction by the year 2005 implies a heavy task on a global scale. In this context, many problems have to be solved, many of them of a fundamentally new nature, both technically and non technically. Perhaps the major challenge is sharing the costs between the rich countries and the developing countries, respectively, bearing in mind that currently energy consumption is especially growing fast in the latter. In particular the expected further growth in world population is a reason for concern.

2.1.2 Fluxes of carbon dioxide

In order to obtain a better understanding of the effects of a decrease in emissions, a thorough knowledge of fluxes of CO_2 is necessary. Rapidly increasing emissions do not directly imply higher concentrations in the atmosphere; the capacity of ecosystems to compensate for emissions is large. A large part (some 40-60%) of the CO_2 emitted is absorbed by the oceans (see chapter 7). In fig 2.2, a simplified overview is given of the fluxes of carbon dioxide.

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[*] M = Mega = 10^6; G = Giga = 10^9; T = Tera = 10^{12}; P = Peta = 10^{15}; E = Exa = 10^{18}

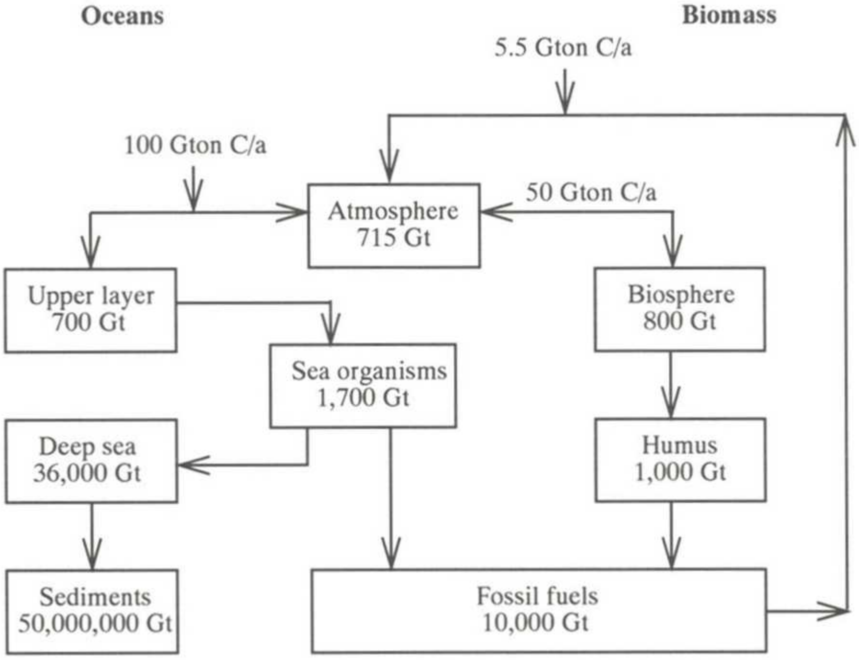

Figure 2.2 Fluxes of carbon dioxide (simplified) [10]

From figure 2.2 it may be concluded that the anthropogenic CO_2 emission of 5.5 Gton of carbon is relatively small compared with the other fluxes. There is still uncertainty about these fluxes. Many national and international research programmes have been and are being executed, in order to obtain a better insight into the very complex underlying biochemical interactions between the various elements [9]. The three most important sources and sinks of CO_2 are the burning of fossil fuels, the biosphere and the oceans.

2.2 Europe 12

In this section the situation of carbon dioxide emissions in Europe 12 is described. Figures for CO_2 emissions, ranging from 1960 till 1987, are analysed and developments are discussed which determine carbon dioxide emissions in Europe 12.

The European community has a population of 325 million. Together, the member states emitted in 1987 a total of 0.745 Gt of carbon, which is about 13% of the world's total emissions (fig. 2.3). In this context, the production of CO_2 **per capita** is, of course, very relevant. In the community there are seven countries (Annex I) producing between 2 and 3 t C per capita per year. The remaining countries produce less. The world average is 1 t C per capita per year.

2.2.1 Energy and growth

From the above it is clear that carbon dioxide emissions are primarily related to energy consumption. The future use of energy in Europe will be determined by many factors, but will be dominated by the economic growth. From history we see that the structure of economic activity, its volume and rate of growth has always been strongly correlated to the types of energy sources available. Today coal, gas, oil and electricity compete in many markets. For power generation, for example, gas, coal and nuclear energy are available.
Therefore, the most important challenge of the future will be the weakening of the relation between economic growth and the use of energy.

2.2.2 Internal market

Another relevant development is the open internal market from 1993, of which energy will be a segment. From the completion of the internal market many economic benefits are foreseen, including an increased growth in the Community's GDP[*]. In order to realise an internal energy market, the Commission proposed a number of priority actions, implying:

- the removal of technical and fiscal barriers to trade
- the application of Community law to energy markets
- the application of the provisions in the Single European Act concerning environmental protection.

The implications for future energy growth are not very clear. One of the policy areas, on which the Commission is currently focusing, is the integration of the electricity and gas sectors. The effects on the internal market can be assessed only after the proposed actions have been defined. This is an ongoing process, requiring time, and its impact will be felt in the long run.
It is obvious that the internal energy market, as it is gradually being defined, will change the parameters of future energy policy structures.

2.2.3 Demographic factors

Over the next twenty years no major change in the population size of 'Europe 12' is expected; only an increase of some 5×10^6 people is foreseen. However, due to a falling birthrate and increased life expectancy, the average age of the population will rise. In the future, the average person will probably have more money and more leisure. Further, the number of households will increase appreciably and more people will own cars. Both houses and cars may be larger. This results in a further increase in energy per capita, even if more energy-efficient appliances are developed. Thus, the rate of penetration of energy-efficient technology, both in end use and in production, is one of the key policy variables.

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[*] GPD = Gross Domestic Product

CO_2 production is scattered all over Europe. Confinement of CO_2 is only possible from large point sources of CO_2, such as power plants, and major industrial plants, such as oil refineries, cement industries and furnaces.

The costs of preventing CO_2 emissions into the atmosphere are built up as follows:

- binding and separating the CO_2 from exhaust gases
- transportation
- storage.

A detailed analysis lies outside the scope of this general study. However, since it is important to know the distances between the large sources of CO_2 and the location of possible storages, the geographical positions of fossil power plants in the EC-countries are given in *Annex II* (Von Brecht, 1988). In this context, storage both in the subsurface and in the oceans depends on geographical location. On the other hand, reforestation and prevention of deforestation is not geographically restricted.

The various options for confinement and abatement of CO_2 emissions are discussed in more detail in the next chapters.

2.3 Sources

From table 2.2 it can be seen that the main sources of CO_2 are power generation, industry, traffic and transport and 'other sectors', amongst which the built-up area. In this context it is important that power plants are point sources, while most other sources are diffuse. In total, some 25% of the total CO_2 emission stems from point sources.

In principle, CO_2 free scenarios are conceivable for each of these sectors. However, in this study only the abating and confining of CO_2 that has actually been generated is considered; options in which the element carbon does not play a part at all are not discussed.

Nevertheless, for the sake of completeness, a short review of CO_2 prevention options is presented in chapter 9.

2.3.1 Power generation

In this sector much attention has been paid to the improvement of the efficiency of electricity production. With the help of new technologies (**combined cycles**, such as steam and gas turbine, magneto-hydrodynamic conversion, **topping cycles**, such as the potassium topping cycle, and **bottoming cycles**, such as the application of a waste gas boiler), efficiencies as high as about 65% can be realised. These techniques require, however, high investments, while with conventional techniques efficiencies well over 50% are currently being realised. Hence, their scope, though intrinsically valuable, is still limited with regard to the CO_2 problem.

Another way of reducing the CO_2 emission lies in the choice of the fossil fuel (chapter 3). Methods of separating CO_2 from flue gases are reviewed in chapter 4. For confining CO_2, power plants are the most attractive options, since they are localised sources. This option will be discussed in more detail in chapter 10, in the context of integrating and evaluating the problem as a whole.

2.3.2 Traffic and transport

Traffic and transport imply a very particular problem, since their character is intrinsically diffuse. Solutions to their CO_2 emissions can be found in three different directions, viz.:

a. *Application of bioethanol as a fuel*
   Though in this option CO_2 is still produced, the carbon is already part of the atmospheric carbon cycle. Hence, it substitutes fossil carbon and is, in fact, a form of solar energy. The energy content per unit weight is 50%, approximately, of that of fossil fuel.
   An important option developed by the TNO Road Vehicles Research Institute is a system enabling the application of any mix of petrol and ethanol in spark ignition engines, while for each mix the air/fuel ratio and some other parameters are adapted for obtaining an optimum engine performance [11, 12].
b. *Electrical transport*
   Electrical transport is silent and clean; the storage, however, implies a problem. Lead batteries represent about 50% of the weight of an empty car with an action radius of some 70 km. A new development is the sodium-sulphur battery which, however, operates at 300 °C, and still has a radius of action of only 200 km.
   Of course, in this context the electricity should be produced from nonfossil sources.
c. *Hydrogen as an energy carrier*
   This is an expensive, yet promising option in the long run. Also in this case, the storage is a problem. It may be liquefied, (-235 °C), pressurised (600 bar), or stored in metal hydrides. The radius of action is again some 200 km.
   The combination of hydrogen, fuel cells and electricity may yield an efficiency of up to 75%.

2.3.3 Built-up area (urban region)

Carbon-free energy in the built-up area leads to the concept of the 'all-electric society' on the one hand, where the problem of CO_2 generation is shifted towards the power plants. On the other hand, particularly in the vicinity of power plants, co-generation of heat and power for delivery to the built-up area is attractive.

2.4 Sinks

In the chapters 5, 6, 7 and 8 the prospect of CO_2 sinks are discussed in some detail. In this context, attention is paid to:

Applications of CO_2 (chapter 5)

Applications on a scale relevant for the present purpose are virtually unknown. The most promising option might be a large-scale production of algae (but only under strictly controlled conditions), as a fuel, or as a nutrient for fish and cattle. Thus, actually, new carbon subcycles are created, confining more carbon on earth instead of in the atmosphere. Energy farming (e.g. for the production of ethanol) is also an interesting option.

Injection of CO_2 into the subsurface (chapter 6)

Injection of CO_2 into the subsurface is possible into deserted gas fields, aquifers and salt domes. In this context, injection into aquifers appears to be the most promising option.

Injection of CO_2 into the ocean (chapter 7)

The prospects of this option are considered to be limited, since there is a good chance that any CO_2 injected will come out again in due time. However, for EUR 12 the injection of CO_2 near Gibraltar may be reasonably promising, since in that case it is spread at about 1200 m depth throughout the Atlantic Ocean. However, to this end the CO_2 has to be transported over a long distance.

The role of biomass (chapter 8)

Reforestation and prevention of deforestation are very important factors in this context. The confining of carbon by an increased application of wood in service (buildings, constructions) is also relevant.

2.5 References

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3 The influence of the fossil fuel mix

(H. Bartelds)

3.1 Energy consumption in EUR 12

For reducing CO_2 emissions from fossil fuel burning, one of the options is switching over to fossil fuels with less carbon and more hydrogen. In other words, from coal ($CH_{0.37}/CH_{0.76}$) to fuel oil ($CH_{1.6}/CH_{2.2}$), liquefied petroleum gas ($CH_{2.5}/CH_{2.67}$), natural gas (CH_4), respectively.

In order to arrive at a proper evaluation of this matter it is necessary to consider the consumption of energy in EUR 12. In this context, use is made of the Energy Statistical Yearbook 1988 [1] of the EC, and also of the Dutch Energy Yearbook 1988 [2], in which more detailed information is presented for The Netherlands. Both refer to the year 1988.

In table 3.1 the gross domestic consumption of energy in EUR 12 is given for the major energy sources. It can be seen that more than 84% of the energy consumption is based on fossil fuels; some 14% is of nuclear origin, while about 2% ('primary electrical energy') has a solar, wind or water power origin.

Table 3.1 Gross domestic consumption of energy in EUR 12 during 1988

Energy source	Oil equivalents Mtoe	Net calorific value EJ	Fraction %
Hard coal	193.7	8.11	18.1
Lignite	33.4	1.40	3.1
Crude oil	487.4	20.40	45.4
Natural gas	192.6	8.06	18.0
Nuclear heat	147.4	6.17	13.7
Primary electrical energy	18.3	0.77	1.7
Total	1072.8	44.91	100

Quite a large fraction (some 30%) of the gross energy consumption is consumed by energy conversion processes, etc. In table 3.2 the consumption of the remaining fraction is presented for the main sectors of economic activities. Table 3.3 presents the consumption of final energy by type of use.

Table 3.2 Energy consumption in main sectors in EUR 12 during 1988 [1]

Sector	Oil equivalents Mtoe	Net calorific value EJ	Fraction %
Energy	55.6	2.33	7.3
Industry	218.7	9.15	28.7
Transportation	211.8	8.87	27.8
Households, etc.	275.8	11.54	36.2
Total	761.9	31.89	100

Table 3.3 Energy consumption by type of use in EUR 12 during 1988 [1]

Type of use	Oil equivalents Mtoe	Net calorific value EJ	Fraction %
Petrochemical feedstock	53.9	2.26	6.9
Other non energetic uses	21.1	0.88	2.7
Processing heat	198.6	8.31	25.4
Power	233.0	9.75	29.8
Heating	258.0	10.80	33.0
Lighting	17.2	0.72	2.2
Total	781.8	32.72	100

It is obvious that not only in primary energy conversion (e.g. from crude to petrol and electricity), but also in conversion to the end use large quantities of energy are lost. In EUR 12 some 500 x 10^6 installations are used to convert fossil energy into the required form. These installations include boilers, process furnaces, ovens, cookers, geysers, gas turbines, internal combustion engines, etc. varying in power input from less than 10 kW to more than 1000 MW.

3.2 CO_2 emission coefficients

In table 3.4 CO_2 emission coefficients are presented for various fossil fuels [3, 4]. It can be seen that the maximum reduction of CO_2 emissions is realised when subbituminous coal firing is replaced by methane firing (reduction 47%). Practical reductions are 42% (coal replaced by gaseous fuels), 30% (liquid fuels replaced by gaseous fuels) and 18% (coal replaced by liquid fuels).

Table 3.4 CO_2 emission coefficients for different fossil fuels

Fuel	**CO_2 Emission Rate (kg C/10^9J)**	**Ration Relative to Methane**
Methane	13.5	1
Ethane	15.5	1.15
Propane	16.3	1.21
Butane	16.8	1.24
Gaseous fuels	**13.8 *)**	**1.02**
Gasoline	18.9	1.40
Diesel Oil	19.7	1.46
No. 6 Fuel Oil	20.0	1.48
Liquid fuels	**19.7 *)**	**1.46**
Bituminous Coal	23.8	1.73
Subbituminous Coal	25.3	1.87
Coal	**23.9 *)**	**1.77**

*) weighted average

3.3 Effects of changing the fuel mix

Taking into account the gross domestic consumption of fossil fuels in EUR 12 (table 3.1) and the carbon dioxide emission coefficients (table 3.4), the effects of changing the fossil fuel mix can be calculated. In table 3.5 some results are presented, taking the 1988 fuel mix as a reference. If only natural gas were fired, the CO_2 emission would be reduced by about 30%. If, on the other hand, natural gas and crude oil reserves were exhausted and only coal were fired, the CO_2 emission would increase by some 23%. The fuel mix distributions of table 3.5 are found by replacing one or two fuels of the 1988 fuel mix (table 3.1) with another fuel.

Table 3.5 Effect of fuel mix on CO_2 emissions in EUR 12

Fuel mix distributions (% energy)					**CO_2 emission % (mass)**
gas ↓	**+**	**liquid ↓**	**+**	**coal ↓**	
100					70.8
75			+	25	83.8
46	+	54			87.1
21	+	79			94.7
21	+	54	+	25 (1988)	100
		100			101.1
		75	+	25	106.5
		54	+	46	111.1
21			+	79	111.6
				100	122.6

Hence, concentrating on gaseous fuels reduces CO_2 emissions; concentrating on liquid fuels causes small changes, while concentrating on coal increases CO_2 emissions. In this context, differences in attainable conversion efficiencies for the various fuels were not considered. The percentages would have deviated somewhat more if these differences had been accounted for.

The question has to be answered, whether concentrating on natural gas firing is actually a feasible option. Though the direct effects are of some significance, there are also a number of drawbacks that have to be taken into account:

- up to 2% of the processed natural gas will be emitted unburnt and natural gas is a greenhouse gas with per molecule CH_4 20 to 27 times stronger effect than CO_2 [5];
- all installations fired by liquid and solid fuels need to be replaced or retrofitted to be suited for natural gas;
- the gas transport throughout EUR 12 would need to be multiplied by a factor of more than 4 and, consequently, the leakage of methane would increase;
- the natural gas reserves are smaller than those of crude oil and coal, and therefore only one or two generations could profit from extra burning of natural gas;
- on the other hand, the availability of depleted gas fields for CO_2 storage would be accelerated (!).

If natural gas were the only fossil fuel to be burnt in the future, enormous economic and logistic problems would have to be solved. Apart from lower CO_2 emissions, natural gas firing would result in a lower emission of NO_x, SO_2 and particulates, but in a higher emission of CH_4.

Replacing 1 EJ of coal with 1 EJ of natural gas would reduce the CO_2 emissions roughly by 42%. We assume that methane emission due to the natural gas processing and transport is approximately 2% of the natural gas. The reduction in the CO_2 emission would be 37.8 Tg/EJ. The increase in the CH_4 emission from natural gas would be 0.42 Tg/EJ. Assuming that CH_4 has a 27 times stronger effect than CO_2 as a greenhouse gas (molecule basis), the extra emission of methane would reduce the effect of the lower emission of CO_2 by some 80%. Instead of a reduction of 42% in the CO_2 emission by replacing coal by natural gas, the effective reduction would be less than 10%.
In this context methane emissions from coal mines and natural gas production fields are not taken into account.
Grubb [5] concludes that the remaining emission, when switching from 100% coal to 100% gas, is 2/3 rather than the commonly cited 1/2.

Another important greenhouse gas is N_2O, with a greenhouse effect per molecule of about 200 times that of CO_2. Grubb [5] states that N_2O accounts for perhaps 5% of the total greenhouse effect. However, since only 20% of this N_2O stems from fossil fuel burning, Grubb ignores this effect. Consequently, fuel switching would not significantly influence the small contribution of N_2O to the greenhouse problem [6].

Although much is still unclear in the detailed effects of changing the fuel mix, it may be concluded that its influence on the greenhouse effect is limited.

3.4 References

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4 Removing CO_2 from fossil fuel burning

(H. Bartelds)

In this chapter, the removal of CO_2 from (flue) gases will be treated; the discussion will be restricted to combustion and gasification equipment. In this context, some attention will be paid to changes in operation of such equipment with the object of facilitating the removal of CO_2. On the basis of these removal processes, the options for its confinement will be discussed in chapters 5, 6, 7 and 8.

The main fossil fuels are hard coal, lignite, crude oil and natural gas (table 3.1). The compositions of each of these fuels as burnt may differ, depending on origin and refining processes applied. Some typical examples are given in tables 4.1, 4.2 and 4.3 [1]. Depending on local environmental restrictions, the quantities of undesired components like ash and sulphur may be lowered by improved refining/ pretreatment.

Table 4.1 Typical composition of solid fuels (mass basis)

Fuel Type	moisture %	ash %	carbon %	hydrogen %	nitrogen %	sulphur %	oxygen %
Anthracite	12	8	78.2	2.4	0.9	1.0	1.5
Steam coal	10	8	77.4	3.4	1.2	1.0	2.0
Coking coal	10	8	68.8	4.4	1.5	1.7	5.5
Lignite	15	5	5.6	4.0	<1.6	<1.6	18.4

Table 4.2 Typical composition of liquid fuels (mass basis)

Fuel Type	ash %	carbon %	hydrogen %	nitrogen %	sulphur %	oxygen %
Diesel fuel		86.5	13.2		0.3	
Gas oil		86.1	13.2		0.7	
Motor spirit		88.5	11.5		<0.1	
Light fuel oil	<0.2	85.6	11.7	<0.2	2.5	<0.2
Heavy fuel oil	<0.4	85.4	11.4	<0.4	2.8	<0.4

Table 4.3 Typical composition of gaseous fuels (volume basis)

Fuel type	CO_2 %	N_2 %	CH_4 %	C_2H_6 %	C_3H_8 %	C_4H_{10} %	C_5H_{12} %	C_6H_{14+} %	C_3H_6 %
Natural gases:									
North Sea	0.2	1.5	94.4	3.0	0.5	0.2	0.1	0.1	
Groningen	0.9	14.0	81.8	2.7	0.4	0.1	0.1		
Liquefied petroleum gases:									
Commercial propane			0.1	1.5	91.0	2.5			5.0
Commercial butane				0.5	7.2	87.0			4.2

Fossil fuels are normally burnt with air. To guarantee complete combustion, excess air is required. The amount of excess air depends on both the type of fuel and the type of combustion installation (power station boiler, refining furnace, gas turbine, internal combustion engine, etc.). For efficient energy utilization, low excess of air is required. Low excess air factors are applied in gas-fired power station boilers (less than 5% excess). For other fuels and/or combustion installations, excess air factors of 10%, 15%, etc. may be required for complete combustion. Theoretical compositions of flue gases from fossil fuel burning (based on stochiometric conditions, excess air 0%) are given in tables 4.4, 4.5 and 4.6 [7]. The excess air results in higher concentrations of N_2 (and O_2), and lower concentrations of CO_2 and H_2O in the flue gases.

Table 4.4 Theoretical composition (volume basis) of wet flue gas from solid fuel burning

Fuel type	CO_2 %	H_2O %	N_2 %	NO_x %	SO_x %	Ash %
Anthracite	18.6	4.5	76.6	yes	yes	yes
Steam coal	17.9	5.6	76.2	yes	yes	yes
Coking coal	16.8	7.8	74.9	yes	yes	yes
Lignite	17.5	10.0	72.2	yes	yes	yes

Table 4.5 Theoretical composition (volume basis) of wet flue gas from liquid fuel burning

Fuel type	CO_2 %	H_2O %	N_2 %	NO_x %	SO_x %	Ash %
Diesel fuel	13.7	12.3	74.0	yes	yes	-
Gas oil	13.6	12.3	74.1	yes	yes	-
Motor spirit	14.0	11.0	75.0	yes	-	-
Light fuel oil	14.1	11.4	74.5	yes	yes	yes
Heavy fuel oil	14.2	11.2	74.6	yes	yes	yes

Table 4.6 Theoretical composition (volume basis) of wet flue gas from gaseous fuel burning

Fuel type	**CO_2 %**	**H_2O %**	**N_2 %**	**NO_x %**	**SO_x %**	**Ash %**
Natural gases:						
North Sea	9.6	18.8	71.6	yes	-	-
Groningen	9.6	18.5	71.9	yes	-	-
Liquefied petroleum gases:						
Commercial propane	11.7	15.4	72.9	yes	-	-
Commercial butane	12.0	14.9	73.1	yes	-	-

Flue gases contain CO_2 in concentrations between some 9 and 15%. The water vapour can be separated from the flue gases by cooling below 100 °C. After that, a mixture of CO_2, N_2, O_2 and pollutants (including CO, C_xH_y, SO_x, and ash) remains. In order to separate CO_2 from it, this mixture has to be treated further. In the following sections, a number of options for concentration or separation are indicated.

4.1 Increasing CO_2 content of flue gases

As storage of the entire flue gas in subsoil or subsea is obviously very inefficient, the CO_2 should be concentrated first. Three basic methods exist to produce (flue) gases with higher CO_2 concentrations from fossil fuel conversion processes:

1. reducing the nitrogen/oxygen content of the flue gases by limiting the air supply, i.e. replacing a combustion process by a gasification process;
2. reducing the nitrogen content of the flue gases by changing the oxidant, i.e. replacing combustion air by oxygen;
3. increasing the CO_2 content of the gases to be stored by separating the CO_2 from the flue gases, i.e. flue gas cleaning.

4.1.1 Integrated gasification combined cycle

An example of the first approach is an Integrated Gasification Combined Cycle (IGCC) power generation plant, like the projected Demkolec plant at Buggenum in The Netherlands [2]. A coal gasifier converts coal with oxygen into syngas, primarily consisting of CO and H_2 (table 4.7).

Table 4.7 Syngas composition (dry, volume basis) from coal gasified with oxygen

Component	Fraction %
CO	50-70
H_2	20-40
CO_2	1-12
C_xH_y	0- 7
N_2, Ar	2-10

During a shift reaction CO converts into CO_2 and H_2 when steam is added [3].

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

The shifted syngas stream contains a high concentration of carbon dioxide (about 40%), hydrogen and a small amount of carbon monoxide. The carbon dioxide may be absorbed by a solvent. Finally, the carbon dioxide recovery from the syngas stream can be as high as 98%. After that, the CO_2-poor gas is burnt in a gas turbine, while part of the hydrogen is recycled in the absorption process.

4.1.2 Burning fossil fuel with oxygen

The second approach – burning fuel with oxygen – requires oxygen production. To this end cryogenic technology can be applied [2] (preferably without consumption of fossil fuels). The combustion of fossil fuels with oxygen will need major modifications, or even a redesign of the combustion equipment.

If 95% pure oxygen is used for combustion, the nitrogen content of the flue gases will be very small. Only the nitrogen left in the oxygen and the nitrogen in the fuel will be found in the flue gases. Thus, the carbon dioxide content of the flue gases will be high, varying between some 80% (for fuels with a high nitrogen content) and 95% (for relatively pure fuels).

4.1.3 CO_2 scrubbing

Various techniques are available to follow the third approach of separating CO_2 from flue gases. More details on these techniques will be presented in section 4.2.

Depending on the characteristics of the fuel and the combustion installation, combinations of the approaches described may be used. In the IGCC power plant at Buggenum, Netherlands, gasification, combustion with pure oxygen, and gas cleaning from CO_2 could be applied.

If CO_2 emissions need to be reduced by storing CO_2 in the subsoil/subsea, complex additional equipment is needed for collecting the CO_2. Therefore, the most logical first step would be starting at the largest combustion installations, i.e. power plants.

In table 4.8 the 1988 fuel consumption of power plants in EUR 12 is presented [15]. About 60% is fossil fuel based; nuclear energy consumption is about 40%. Comparing table 4.8 with table 3.1 leads to the conclusion that more than 60% of the solid fuels are fired in power plants. From liquid fuels 7%, and from natural gas some 12% is consumed by power plants. Nuclear heat is consumed in power plants only.

Table 4.8 Fuel consumption of power stations in EUR 12 during 1988

Energy type	**Fuel consumption EJ**
Solid fuels	5.95
Petroleum products	1.48
Natural gas	0.99
Other fuels	0.33
Total thermal power	8.75
of which:	
- for electricity	8.54
- for heat	0.21
Total nuclear power	6.15

Even if it were decided to separate and store all CO_2 originating from power plants completely, only 22% of the consumed fossil fuels would stop emitting CO_2. Since the share of the solid fuels that is fired in power plants is relatively large, it actually corresponds with a reduction of 25% in CO_2 emissions from fossil fuel burning. Since all other CO_2 sources are more diffuse than power plants, methods for preventing CO_2 emissions from power plants will be treated in more detail later. In the first place, techniques to separate CO_2 from flue gases will be presented; secondly, the option of changing the conversion processes (combustion versus gasification) will be discussed. Thirdly, the possibilities of separating the nitrogen from the combustion air in order to produce flue gases consisting of CO_2 and some impurities will be considered.

4.2 CO_2 scrubbing processes

At present at least six different processes for scrubbing CO_2 from flue gases are being developed:

- adsorption of CO_2 to suitable materials, like clay, and storage of the saturated material in pits;
- absorption of CO_2 to liquid solvents (amines, sea water, etc.) and recovery of CO_2 concentrate;
- condensation of CO_2 under cryogenic conditions and recovery of CO_2 concentrate;
- chemical/biochemical reaction of CO_2 with plankton/algae, to photosynthesise CO_2 into biomass;
- trapping of CO_2 by molecular sieves;
- CO_2 separation in selective membranes.

These processes differ as to their stages of development. Absorption processes are used extensively by the petroleum industry for acid gas removal [4]. Their efficiency is quite low, thus energy consumption is high. Cryogenic techniques have been used extensively for separating oxygen and nitrogen (air separation). For multi-component flue gases (including pollutants), experience with CO_2 separation is scanty. The development of photosynthesis is progressing slowly and it will probably take several decades before this technology may contribute significantly to the solution of the CO_2 problem. Little information is available concerning the suitability of molecular sieves and selective membranes for separating CO_2 from flue gases.
Available data on the different methods are summarised in the following sections.

4.2.1 Adsorption of CO_2

For adsorption, porous materials such as clay can be used [4]. The CO_2 saturated clay must be stored, e.g. in clay pits. For obtaining a 90% CO_2 concentration, some 50% of the original total plant capacity is required. Thus, unless the efficiency of adsorption processes is increased significantly, adsorption is not feasible in this context.

4.2.2 Absorption of CO_2

Absorption seems to be the most mature one of the CO_2 scrubbing options. Yet, **Lashof and Tirpak** [14] state that these technologies are unproven and very costly. In one process, CO_2 from the flue gas is mixed with water in a solvent solution at a temperature slightly above ambient conditions. The CO_2 binds to the reagent and passes into a regenerator chamber where temperatures are elevated. The reverse reaction takes place and CO_2 is released, removed, pressurised and liquefied. The reagent is regenerated and reused. The liquid CO_2 can be applied in various commercial applications or can be stored. In table 4.9 some rough CO_2 scrubbing (absorption methods) costs are presented. The total costs are approximately 0.03 - 0.04 ECU/kWh.

Table 4.9 Data on energy and costs of CO_2 scrubbing for 90 percent removal

Capital Cost ($/kW)	
Scrubber	810
Pipeline/Disposal	80-710
Variable Operation and Maintenance Cost (mills/kWh)	NA
Energy Penalty (%)	25
Capacity Penalty (%)	22
Fixed Operation and Maintenance Cost ($/kWyr)	NA
Total Cost (mills/kWhe)	36-47
or: (ECU/kWhe)	0.029-0.037
1 US $ = 0.794 ECU [11]	
1 US $ = 1000 mills	

Torrens [6] states that CO_2 can be recovered from 12 - 15% CO_2-containing flue gases using existing scrubbing technology, like chemically alkaline absorbent systems, followed by liquefaction and transport to end disposal or reuse. According to **Steinberg and Cheng** [7], recovering and transporting CO_2 would add 35% to 80% to the electricity costs.

Kane and South [4] state that absorption is used extensively by the petroleum industry for acid gas removal. Liquid solvents (amines, sea water, etc.) are used to scrub flue gases. It is thought feasible to concentrate 90% of CO_2 with a power derating of 30%.

The development of a more concentrated amine solution could produce a 30% efficiency gain and, consequently, would reduce power derating to 20%. If, however, the CO_2 control process is integrated with the power plant operation, at 90% removal of CO_2, the power plant efficiency would be reduced by only 3 percentage points, e.g. from the present plant efficiency of 38% to a value of 35% with the control system. This seems to provide an option for realistic, economic feasibility of CO_2 binding, according to **Hamilton** [8].

According to **Hecq** [9], experience demonstrates the superiority of processes using alkaliamine-based solvents. In table 4.10, data on energetic and financial penalties are given for a coal-fired and for a gas-fired power station, respectively. The costs of CO_2 removal in table 4.10 are between 45 and 97% of those mentioned in table 4.9. From table 4.10 it is clear that CO_2 removal from combined cycle (steam and gas turbine) gas fired power stations is much cheaper than from coal-fired power stations.

Table 4.10 Data on energy and costs of CO_2 scrubbing for a coal-fired and for a gas-fired power station, respectively

Power station	**Coal**	**Natural gas**
Input, MWth	1500	625
Generator type	Pulverised coal Dry bottom	Gas turbine Steam turbine
Operating time, h/a	5000	5000
Efficiency, %		
. emitting CO_2	39.6	48.0
. scrubbing CO_2	32.7	42.7
Investments, 10^6 \$	242.5	97.5
. scrubbing CO_2	55	45.5
. compression/liquefaction	88.5	27.5
. transport/storage	99	24.5
Annual costs, 10^6 \$/a	87.5	28
. capital	50	20
. energy	34.5	7
. solvents	3	1
Costs per kWhe, \$/kWhe	0.035	0.021
or (ECU/kWhe)	0.028	0.017

Aresta [10] mentions, next to amines (ethanol amine), alcohols, glycols, organic carbonates, ether and basic oxides as possible scrubbing materials.

According to KEMA [2], the price of electricity would increase by 56 to 100% if 90% CO_2 were to be removed. For The Netherlands, an increase of 65% to 75% is mentioned. However, these figures are questioned by the Committee on Environmental Effects Reporting [11], which mentions a price increase of only 30%.

Blok et al. [12] describe two processes to reduce CO_2 emissions from the burning of fossil fuels by means of CO_2 recovery:

1. CO_2 recovery from exhaust gases by an absorption process;
2. CO_2 recovery from syngas from coal gasification, using a shift reaction and a physical absorption process.

In tables 4.11 and 4.12, energetic and financial data for these two processes are given.

Table 4.11 Calculation of the costs of CO_2 recovery from a coal-fired and a gas-fired power plant

	Coal plant		**Gas plant**	
	without recovery	**with recovery**	**without recovery**	**with recovery**
Fuel input (MWth)	1460	1460	1250	1250
Gross capacity (MWe)	600	600	600	600
Power loss by steam extraction (MWe)		-118		-60
Power demand control system (MWe)		-6		-3
Power demand for compression (MWe)		-42		-21
Net capacity (MWe)	600	434	600	515
Overall efficiency (LHV, %)	41	29.7	48	41.2
Plant investment costs (ECU/kW)	856	1180	535	623
MEA-absorption unit (ECU/kW)		394		190
Compressor (ECU/kW)		295		146
Total investment costs (ECU/kW)	856	1870	535	959
Plant O&M costs (ECU/kW.year)	31.7	42.8	12.9	15
Additional O&M costs (ECU/kW.year)		14.1		7.3
MEA purchase and recovery costs (ECU/kW.year)		17.6	9.0	
Yearly exploitation at 6000 running hours				
Capital costs (mln ECU)	33.0	62.2	20.5	31.7
O&M costs (mln ECU)	18.8	33.0	7.7	14.6
Fuel costs (mln ECU)	53.9	53.9	69.3	69.3
Electricity price (ECU/kWhe)	0.030(a)	0.053 (b)	0.027(a)	0.037(b)
Disposal of CO_2 (ECU/kWhe)		0.002 (c)		0.002(c)
Cost effectiveness 23 ECU per ton CO_2				
Extra for CO_2 removal/disposal (ECU/kWhe) b + c - a		0.025		0.012

Tabel 4.12 Calculation of the costs of carbon dioxide recovery from an Integrated Gasification Combined Cycle Plant

	Without recovery	**With recovery**
Fuel input (MWth)	1630	1630
Syngas production (MWth)	1316	1206
Syngas cooler steam production (MWth)	302	302
HRSG steam production (MWth)	352	321
Gross power (MWe)	802	802
Gas turbine power (MWe)	480	440
Steam turbine power (MWe)	322	307
Internal power demand (MWe)	-92	-92
Power demand for compression (MWe)		-24
Net capacity (MWe)	710	631
Overall efficiency (LHV, %)	43.6	38.7
Plant investment costs (ECU/kW)	942	1060
Shift reactor, absorption unit and compressor (ECU/kW)		235
Plant O&M costs (ECU/kW.year)	34.2	38.5
Additional O&M and chemicals (ECU/kW.year)		7.3
Yearly exploitation at 6000 running hours:		
Capital costs (mln ECU)	42.8	52.2
O&M costs (mln ECU)	24.4	24.4
O&M for recovery (mln ECU)		4.7
Fuel costs (mln ECU)	60.3	60.3
Electricity price (ECU/kWhe)	0.030(a)	0.037(b)
Disposal of CO_2 (ECU/kWhe)		0.001(c)
Cost effectiveness 8.9 ECU per ton CO_2		
Extra for removal/disposal (ECU/kWhe)		
b + c - a		0.008

Again it appears that CO_2 disposal from natural-gas-based flue gases is cheaper than from conventional coal conversion based flue gases. However, CO_2 scrubbing from IGCC units appears to be still cheaper. The costs to dispose of CO_2 from flue gases varies strongly (ECU/kWh) : 0.029 - 0.037 (table 4.9), 0.017 - 0.028 (table 4.10), 0.012 - 0.025 (table 4.11) and 0.008 (table 4.12). The same authors as those responsible for tables 4.11 and 4.12 present slightly different costs in another publication [3]. It is clear that the available data are still quite uncertain. In order to produce firm data, CO_2-removing pilot and demonstration plants should actually be designed and tested. Further research to validate the data presently available on IGCC power stations, gas-fired power stations and pulverised-coal-fired power stations is of prime importance for developing an EC CO_2 policy.

4.2.3 Condensation of CO_2

According to Kane and South [4], condensation is the least mature of the CO_2 scrubbing options. It is capable of removing 90% of the CO_2 at the penalty of a 20 - 30% power derating. Hecq [9] mentions the cryogenic technique, but does not give further details. Other authors [6, 7, 8, 14] do not mention the cryogenic technique. **Hendriks et al.** [3] state that the cryogenic technique is less cost-effective than chemical absorption.

In table 4.13, data on flue gas compositions and boiling points of flue gas components are given. It appears that the boiling point of CO_2 is quite far away from the boiling points of other components. To produce oxygen from air cryogenically, the costs are in the order of 20 ECU per ton O_2. To produce CO_2 from flue gases cryogenically, it is expected that the costs are in the same order, or less. To produce CO_2 from flue gases by absorption, the costs are in the order of 9 - 26 ECU per ton CO_2. Based on this information, it is thought worthwhile to conduct further investigations into the cryogenic technique for separating CO_2 from flue gases.

Table 4.13 Flue gas compositions and boiling points of flue gas components

Component	Concentration %(vol)	Boiling point °C
CO_2	9 - 19	-78.5
H_2O	4 - 19	100
N_2	70 - 76	-195.8
NO	0.002 - 0.2	-151.8
SO_2	0 - 0.5	-10
O_2	0.2 - 2	-183

4.2.4 Chemical/biochemical removal of CO_2

The chemical/biochemical reactivity of CO_2 relies on plankton/algae for photosynthesis. The CO_2 is captured and converted into living matter, e.g. cellulose. Kane and South [4] state that this technique will not be available before the year 2000, unless development plans are speeded up.

4.2.5 Trapping CO_2 by molecular sieves

Molecular sieves are e.g. aluminosilicates with high porosity and pores of uniform size of essentially molecular dimensions. They adsorb small molecules and select by molecular shape. The technique is mentioned by Hecq [9] and Aresta [10], but they do not present further details.

4.2.6 Separating CO_2 by selective membranes

Gases are fed along a porous membrane. Due to pressure differences in partial pressures, different parts of the gas components pass the membrane. If the membrane is selective, it is more permeable for one component than for another one. Thus, the composition of the gas streams produced will deviate from the original one. Separation using selective membranes is mentioned by Aresta [10], but the author does not present further details.

Summarising the available scrubbing technologies for CO_2 from flue gases, only the absorption technique seems to be sufficiently mature for demonstration. The other techniques still need further research and development.

4.3 Combustion versus gasification/combustion

In previous sections it has been stated that CO_2 absorption processes are cheapest when applied to natural gas combustion and to Integrated Gasification Combined Cycle installations. However, natural gas combustion is a proven technology, while the IGCC process is still in the demonstration phase. At this moment, it is not yet clear whether the IGCC process will actually replace the proven conventional pulverised coal-fired-process. Therefore it seems reasonable to start a demonstration project on CO_2 absorption at a natural-gas-fired power station. Moreover, a study seems worthwhile to evaluate whether natural-gas firing with flue gas CO_2 scrubbing could be replaced by understoichiometric natural-gas firing to produce a syngas (see 4.1.1), followed by a shift reaction and CO_2 scrubbing [12], and firing of the remaining gas (primarily H_2) in a gas turbine. Thus, a natural gas conversion process would be developed, analogous to the IGCC process, aiming at reduced CO_2 disposal costs.

4.4 Oxyfuel combustion

Oxyfuel combustion produces flue gases mainly consisting of CO_2. Thus, CO_2 scrubbing becomes superfluous.
According to Hendriks et al. [3], it is impossible to feed pure oxygen to the combustion chamber because of the high flame temperature which would result from this type of combustion. This statement is, however, not correct, since the flame temperature can be properly controlled by adapting the heat transfer

process. Moreover, for certain processes (glass making, steel heating, etc.), high-flame temperatures are required. Thus, in a number of cases high flame temperatures are advantageous.

Wolsky and Brooks [13] describe the combustion of coal using an O_2/CO_2 mixture instead of air. It seems worthwhile to investigate the characteristics of coal combustion with pure oxygen as an oxidant. The same holds for natural gas and fuel oil combustion.
Hereafter, a simplified cost estimate of O_2 production versus CO_2 scrubbing will be presented.

Coal combustion:

$$\begin{array}{llll} C & + O_2 & \rightarrow & CO_2 \\ 12\text{t(ons)} & + 32\text{t} & \rightarrow & 44\text{t} \end{array}$$

Fuel oil combustion:

$$\begin{array}{lllll} 2CH_2 & + 3O_2 & \rightarrow & 2CO_2 & + 2H_2O \\ 28\text{t} & + 96\text{t} & \rightarrow & 88\text{t} & + 36\text{t} \end{array}$$

Natural gas combustion:

$$\begin{array}{lllll} CH_4 & + 2O_2 & \rightarrow & CO_2 & + 2H_2O \\ 16\text{t} & + 64\text{t} & \rightarrow & 44\text{t} & + 36\text{t} \end{array}$$

The production costs of oxygen are about 21.4 ECU/ton oxygen. In table 4.11 and 4.12, some costs for CO_2 scrubbing are presented. Hendriks et al. mention the following costs (ECU/ton CO_2 avoided): 27.4 (pulverised-coal firing), 22.2 (natural-gas firing) and 11 (IGCC) [3].

Thus it appears that O_2 production is cheaper than CO_2 scrubbing for pulverised-fuel firing, while for natural gas firing and for integrated gasification-combined cycle processes O_2 production is more expensive than CO_2 scrubbing. Taking into account that the CO_2 scrubbing costs, as mentioned by Hendriks et al. [3], are lower than the costs mentioned by other authors (compare tables 4.9 to 4.12), it seems that oxyfuel firing is competitive with air/fuel firing with CO_2 scrubbing. Hence, further research on oxyfuel firing would be necessary. In that context, attention should be paid to:

- design of the combustion installation,
- conditions in the flame,
- storage of CO_2 flue gases.

4.5 References

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5 Useful applications of CO_2
(R.J. Nielen)

In order to prevent CO_2 emissions, in the first place the options for increasing the useful applications of CO_2 should be considered. So far, these options have not received much attention in literature. Further investigations will be needed to obtain more insight into the present applications of CO_2, their prospects in general and in the EC in particular.
In this context, however, the basic problem is that the amounts of CO_2 being emitted are some orders larger in magnitude than needed for any of the present applications. Nevertheless, it is important to consider the various prospects. Thus, the development of large-scale useful applications of CO_2 has to be considered as a long-term strategy.
The various options can be subdivided into three categories, viz. chemical, biological and miscellaneous applications. They are discussed briefly in the following sections.

5.1 Chemical uses

Though, also apart from the greenhouse effect, the utilisation of carbon dioxide seems very attractive, as this molecule is cheap and redundant, at this moment only few industrial processes based on CO_2 exist. The total global amount of CO_2 currently used for the synthesis of chemicals is estimated to be around several x 10^6 of tons per year; the major applications have been summarised in figure 5.1

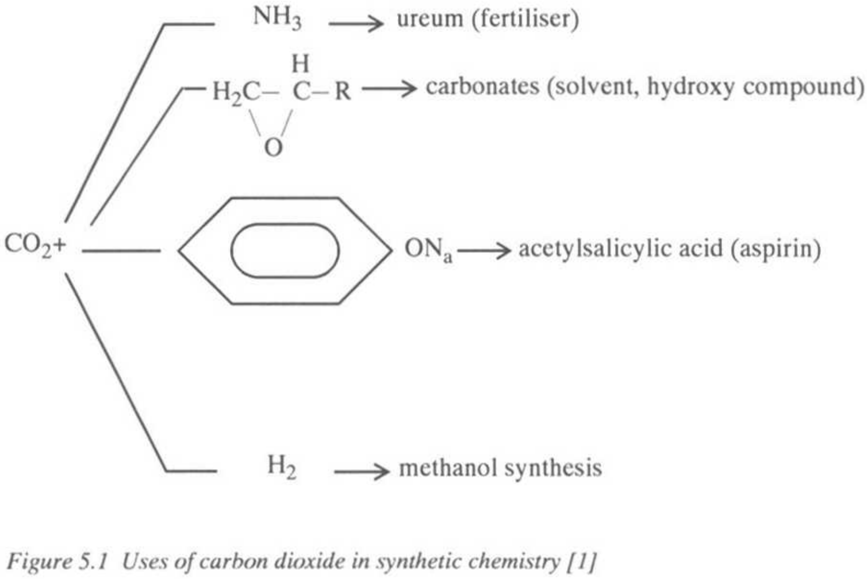

Figure 5.1 Uses of carbon dioxide in synthetic chemistry [1]

However, the utilisation of CO_2 in synthetic chemistry might become worthwhile in due time. For example, these future developments may improve safety in laboratories by substituting carbonyl chloride in the synthesis of carbamates. Yet, such applications have very little impact on the enormous amounts of CO_2 now being released.

Apart from these current industrial applications, researchers are working on new chemical reductions of CO_2. In this context, three options can be distinguished:

- Photochemical methods
- Electrochemical methods
- Thermochemical methods

From a formal point of view, all processes utilising carbon dioxide have to be regarded as reduction reactions which thus require energy. This implies that the effectiveness of the solutions is limited (or perhaps even negative) if the energy required for these processes is generated by fossil fuels. A logical remedy is the use of renewables, in particular solar energy. Especially photochemical methods focus on the use of solar energy.

5.1.1 Photochemical methods

This option is mostly referred to as 'artificial' photosynthesis. Man-made systems are able to capture solar energy and thus transfer solar energy into chemical energy. However, the conversion efficiency is still some two orders of magnitude lower than that observed in natural photosynthetic processes. In order to improve the performance of these systems, new, more active and more selective catalysts have to be synthesised. In this context, two major processes can be considered for the CO_2 reduction:

- the utilisation of transition metal complexes for solar energy transfer;
- the utilisation of enzymes isolated from bacteria

Although artificial photosynthesis is possible, it has to be seen as a long-term option. Photochemical and photoelectrochemical reductions of CO_2 are still in infancy. Much research is being done; **Aresta and Forti** [2] summarised new developments. A major drawback in the use of transition metal complexes is their cost.

5.1.2 Electrochemical methods

Electrochemical potential is another driving force for the reduction of CO_2. There are two ways of electrochemical reductions, direct (involving H^+ ions) and indirect. In this case, only indirect reduction is (energetically) relevant. The indirect reductions involve the use of metal complexes in solution or on the electrode surface, acting as electron transfer mediators and as catalysts for reduction. Numerous studies on the electrochemical reduction of CO_2 have been reported. A summary of the more current and important results is given by

O'Connell and Hommeltoft [3]. However, all efforts are still in the research phase.
A disadvantage of this method is that the energy necessary for the electrochemical potential lowers the net efficiency of the process.

5.1.3 Thermochemical methods

There are a few examples of thermochemical methods.
The Sabatier reaction:

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O$$

is an important catalytic process of wide industrial and academic interest. Although significant progress has been made in this field, elevated temperatures (> 300 °C) and pressures are still required. **Thampi** [4], however, reported the selective conversion of CO_2 to methane at room temperature and atmospheric pressure, using highly dispersed Ru/RuO_x, loaded onto TiO_2 as a catalyst. The reaction is activated by light.

5.2 Biological uses

All green plants, including seaweeds, algae and some bacteria, show photosynthesis. Photosynthesis implies that carbon dioxide is reduced to hydrocarbons with the aid of solar energy. This process leads to a net uptake of CO_2 as long as the produced biomass is not burnt or decayed. In this context, two biological methods for controlling CO_2 concentrations in the atmosphere should be distinguished:

1) Expansion of the **storage of carbon** in biomass, i.e reforestation. This option is discussed in chapter 8.

2) Utilisation of biomass as a **source of energy**, i.e. energy farming. This option is discussed briefly in section 5.2

5.2.1 Energy farming

With energy farming there is actually no fixation of carbon, but rather a carbon subcycle. When biomass is converted to energy, the CO_2 which is released merely replaces the amount taken from the atmosphere before. However, since energy from biomass is utilised instead of energy from fossil fuels, there is a net emission reduction of CO_2.

Biomass can be transformed into a number of different energy carriers, viz.:
- heat
- electricity
- liquid fuels (i.e. bioethanol)
- vegetable oils

Depending on the characteristics of the biomass, different conversion technologies are necessary. Five routes have been summarised in figure 5.2 [17].

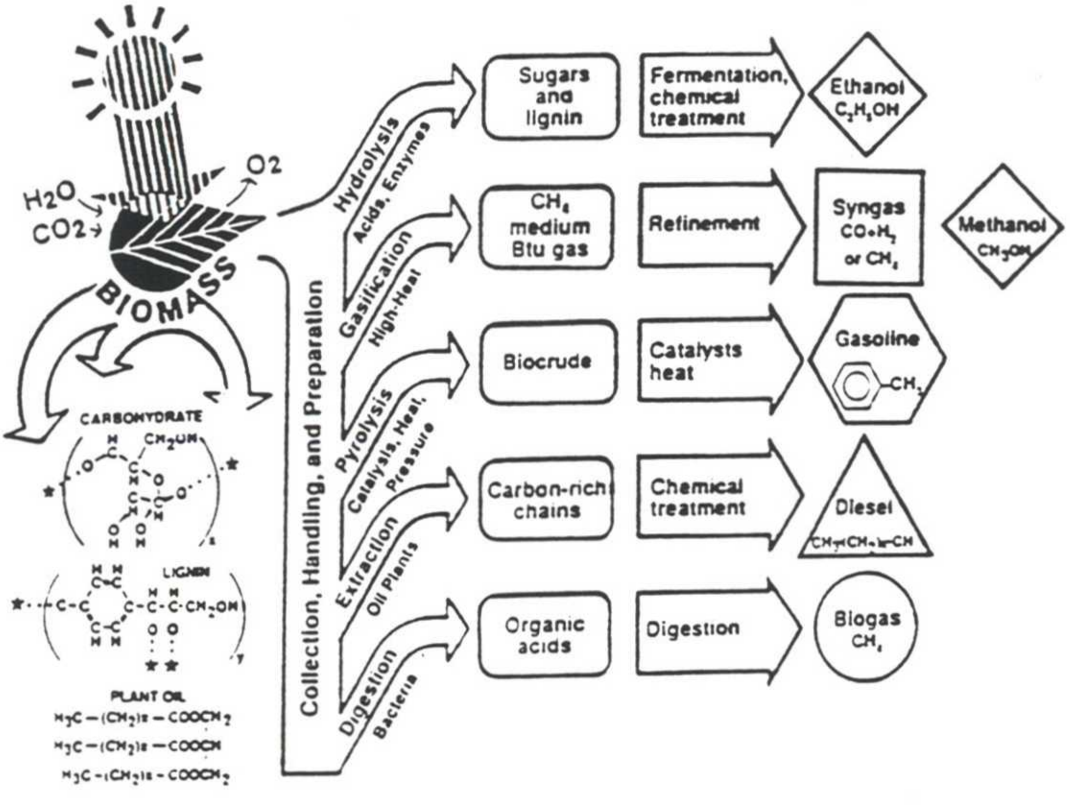

Figure 5.2 Five major routes for production of fuel from biomass

The development of large-scale implementation of biomass for energy purposes depends on developments in agriculture, biotechnology and the energy sector. There are restrictions and limitations both from a technical and an economical point of view.

One problem, characterising almost all biomaterials, is that the resource is dispersed and the materials are bulky, with a relatively low energy content. And, perhaps even more important, there is always a competition between food and energy crops. Energy farming has no commercial applications on a large scale without subsidies. On the other hand, fossil fuels are subject to heavy taxations and levies. Thus, if energy farming should be implemented on a large scale, political choices have to be made.

5.2.1.1 Agricultural energy crops

In the next decades, a further increase in agricultural productivity is to be expected in the EC. This will result from improved farm management, from concentration of production on soils of a better quality, and from a wide range of biotechnological measures. At the same time, there is a stable demand for food. As a result, it is estimated that there will be a surplus of farmland of between 15 and 16 mln ha in the EC by the year 2000 [5].
On this basis, the Stockholm Environmental Institute [6] estimated the total potential energy production from energy crops in the EC (table 5.1). The high potential scenario (B) reportedly involves using a total of 15.8 mln ha, including 2.9 mln ha for "catch" crops (fast-growing crops, planted during a time interval between two successive harvests of the main crops), 4.3 mln ha of marginal lands, and 8.6 mln ha on retired pasturelands (representing a 25% decrease in pasture land in France, Germany, Italy, Ireland and the UK). Thus, scenario B apparently assumes an average yield of 3795/15.8 = 240 GJ/ha year. Scenario A assumes a lower availability of land for energy crop production.

Table 5.1 Potential energy production from energy crops in the EC [6]

Country	Potential				Consumption	Contribution	
	A	B	A	B		A	B
	PJ	PJ	GJ/cap-yr		PJ	%	%
Belgium + Luxemburg	13	29	1	3	1550	1	2
Denmark	42	113	8	22	800	5	14
France	671	1877	12	34	6400	10	29
Germany, Fed. Rep.	146	525	2	9	10300	1	5
Greece		83		8	700		12
Italy	104	430	2	7	5500	2	8
Ireland	208	505	57	140	300	70	168
Netherlands	4	233	0	16	2400	0	10
Total	1188	3795	6	18	27950	4	13

Adapted from OECD [1984]

Replacement of fossil fuels by energy from biomass seems in particular attractive for two forms of energy:
- heat
- liquid fuels for transportation

Heat generation is attractive on the basis of fast-growing crops, like Phragmitus and Miscanthus (see table 5.2)

Table 5.2 Energy yield from agricultural crops [7]

Feedstock	Yield tons dry weight/ha	Heat capacity GJ/ton	Yield energy GJ/ha
Straw/wheat	4 - 5	18.8	75 - 94
Coleseed	2 - 3	21.2	42 - 64
	4 - 5	21.2	85 - 106
Pragmithus	1 - 6	18,8	9 - 113
	15	18.8	282
Miscanthus	30	19	570

There is no commercial culture of Miscanthus at this moment [7]. This crop is in its phase of development, and investigations for cultivation and processing are still necessary. There are two institutes in Denmark investigating Miscanthus: The Danish Agricultural Engineering Institute and the Institut for Landskasplanter. A four-year EC research programme has started with the accent on its cultivation methods. In several EC countries, experimental fields have been arranged.

A second option, liquid fuels for transportation, has been investigated in detail in a Dutch study [8]. A comparison was made between fossil and nonfossil fuels for transportation. Table 5.3 gives the ratio between the energy content of such a fuel and the total energy (except solar energy), required to produce it.

It appears that, compared with fossil fuels, this ratio is favourable. Moreover, in quite a number of other respects, the environmental properties of nonfossil fuels are superior to those of fossil fuels (table 5.4).

Table 5.3 Ratio between the energy content of a fuel and the total energy, needed to produce it [*] *[2]*

A. **Fossil fuels**	
– methanol	0.6
– MTBE	0.65
– Gasoline	0.75 - 0.85
B. **Nonfossil fuels**	
– Bioethanol	2.0 - 2.85
– ETBE[1])	2.0
– Coleseed oil	2.7
– Cellulose oil	2.5 - 2.85

1) Ethyl tertiair butyl ether (actually a composite from fossil and nonfossil fuel)

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[*] Solar energy for the production of the biomass itself is not included

Table 5.4 Qualitative indication of the contribution to the reduction of pollution in using transport fuels of vegetable origin, compared with those of fossil origin [7]
(assuming the use of petrol engines with three-way catalysts)
(+ = positive contribution;
0 = neutral,
- = negative contribution)

Transport fuel	Bio-fuel				
	Ethanol in petrol engine		Coleseed oil in diesel engine		
Environmental concern	**Ethanol**	**ETBE**	**non esters**	**non esters + Elsbett 1)**	**esters**
Carbon dioxide	+	+	+	+	+
Hydrocarbons	0	+	-	+	+
Nitrogen oxides	0	0	-	+	-
Ozone	0	+	-	+	+
Benzene and other aromatics	+	+	-	?	?
Ketones	+	+	-	?	?
Pesticides	-	-	- -		-
Particles	0	0	+	+	+
Carbon monoxide	+	+	-	+	+
Aldehydes					
– primary	-	-	-	?	+
– secondary	+	+	?	?	?
Area needed	+	+	+	+	+
Risks	+	+	+	+	+

1) Experiments with the Elsbett motor have been carried out in West-Germany and The Netherlands

In table 5.5, the CO_2 emissions of the various fuels are shown. It appears that the price of one litre of biomass-derived fuel is 0.36 ECU to 0.8 ECU, depending on resources, market circumstances and production methods. One litre of ethanol is roughly equivalent to half a litre of petrol. The latter costs now (July 1991) about 0.41 ECU. Hence, the difference is not extreme, and therefore biomass-derived fuels may be worthwhile for large-scale implementation. It should, however, be realised that the price of petrol consists for a considerable part of taxes and levies, while the price of biomass-derived fuel mentioned here represents the actual costs.

Table 5.5 CO_2 emissions of various fuel types in g CO2/MJ [8]

Fuel type	Consumption	Total chain
A. Fossil		
CNG	56	70 - 80
Natural gas	56	60 - 65
Petrol	73	86 - 97
Diesel	73	80 - 90
LPG	66	85
Petrol oil	78	91 - 104
Methanol	70	93 - 107
B. Nonfossil		
Ethanol	0 ^{1})	25 - 36
Vegetable (coleseed oil)	0 ^{1})	27
Cellulose oil	0 ^{1})	27
ETBE	unknown	36

1) CO_2 is absorbed during the growth; when bioethanol is combusted, 66 g CO_2/MJ is released.

Yet, the above implies that the use of biomass for transportation could actually be considered to be a contribution to solving the problem.

5.2.1.2 Algae

Besides agricultural crops, several researchers suggested using algae for fixation of CO_2. There are a number of large-scale projects for algae production, most of them being pursued for purposes other than energy production. An advantage of producing algae, compared to other forms of biomass, is that the potential space available is much greater, since water surfaces like ponds, lakes and oceans may thus be utilised. Another important advantage is the higher CO_2 efficiency. Algae grow fast and possess an efficient photosynthesis mechanism, which is considerably stronger than that of land crops. With the aid of technology it is possible to create optimal conditons for growth. Research in this area is being done with algae reactors enabling optimal growth conditions. A disadvantage is the comparatively high investment required. Further, chemicals are needed for algae production as sources of mineral nutrients. There is also a danger of accumulation of environmental pollutants from water, chemicals, and/or atmospheric emissions. This potential hazard is common to all microbial biomass production systems and has, in the case of microalgae, been investigated by **Payer** et al [9].

The algae produced can be used directly as a fuel. Some species (for instance botryococcus braunii) contain much oil. Another possibility is the anaerobic fermentation to methane.
Utilisation of biomass from algae is restricted for three reasons. The price of 1 ton of oil from algae is estimated to be about $ 200 - $ 300 per barrel of oil equivalent [6], which means that oil prices have to rise dramatically before this option might become interesting. Nevertheless, experiments on a pilot scale have been carried out. A second restriction, and perhaps still more relevant, is that techniques for harvesting and drying algae on such a large scale still have to be developed. A study of the feasibility of this option seems useful. And third, the water area required to catch sufficient solar energy for algae growth forms a severe restriction.

An option that has been suggested by various researchers is increasing the uptake of CO_2 by the oceans. One possibility might include the suppletion of iron, which in some cases may be one of the limiting nutrients for algae. There is, however, much discussion concerning the relevance of adding iron to the ocean (see chapter 7). Moreover, at this moment there is no harvesting equipment available.

Pirt [11] is working on a specific photobioreactor for algae. The algae are cultivated between glass to increase the effect of the solar energy. Photobioreactors, a firm associated with the University of Reading is experimenting with these methods gaining two grammes of algae per hour/m^2. The costs of this fuel is estimated at £ 800/ton of biomass.

The knowledge currently available has been summarised by **Braun** [12]. Especially in Japan there are efforts for large-scale utilisation of algae.

Toha and Jaques [13] calculated, that in a one-hectare pond, with a depth of one meter, 1800 kilograms of CO_2 are absorbed daily by algae.

All options mentioned above are in an early stage of development, or even in the stage of premature thinking, at least from the point of fixation of CO_2. Anyway, in all cases very large investments will be necessary.
At this moment the most realistic options for large-scale utilisation of biomass for energy purposes are the use of heat and liquid fuels.
The boundary conditions under which these options are actually feasible on a large-scale should be investigated in more detail.

Finally, it should be remarked that **Morley** [10] suggested to grow seaweed (which is actually also a type of algae) on cords in the sea and to harvest, dry and burn them. On one meter of polypropylene rope, in the North Sea, from April to October, 15 kg of seaweed (Saccorhiza Polychides) would grow. Thus, on 900 km^2, an equivalent of 10^6 ton of coal would grow, on 10^8 m of rope ($2^1/_2$ times the length of the equator).
Also in this case, equipment for harvesting still has to be developed.....

5.3 Miscellaneous

There are several options for industrial technological application of CO_2:

- Use for enhanced natural gas production. A study has been carried out by Shell to investigate this option for the situation in The Netherlands. It was concluded that the cost of storage could be reduced considerably, in case this storage of CO_2 would coincide with an increased gas production
- Food packaging and freezing
- Extraction of active components from natural products (supercritical CO_2 applications)
- Oil extraction
- Fire extinguishers
- Sprays
- Growing plants in greenhouses

However, non of these options contribute significantly to a solution of the problem. Moreover, in most examples presented above, the CO_2 is still emitted into the atmosphere within a short time. The CO_2 applied in these processes stems from various sources. Table 5.6 gives an overview. Which source is used depends, among other factors, on the required purity.

Table 5.6 Industrial sources of carbon dioxide

- Fuel
- Cement manufacture
- Fermentation
- Other industrial processes
- Natural wells

The estimated release of carbon dioxide (worldwide) used in the applications mentioned here ranges around 8 Mt per year. It is obvious that this quantity is in fact negligible (round 0.1%) compared with the 5.5 Gt of carbon released yearly.

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6 Injection of CO_2 into the subsurface

(A.J.M. Huurdeman)

As indicated before, the main point sources of large quantities of CO_2 are power plants and large industrial complexes. In most European countries, as in the Netherlands, these sources do not, or only by accident, coincide with geological formations in which CO_2 can be stored. It is therefore of importance to consider all potential storage possibilities and not to exclude options unless absolutely necessary.
The options that will be considered in this context are (depleted) gas fields, aquifers and caverns in salt domes. Injection of carbon dioxide into oil fields is a technique for improved oil recovery in light oil reservoirs. Due to the unstable displacement of oil by CO_2, carbon dioxide will return rather quickly to the (oil) production site, which makes it an unattractive option from a disposal point of view. Therefore this option will not be considered here.

In figures 6.1 to 6.6, some important characteristics of CO_2 are presented [11]. The density, as well as the viscosity of CO_2, is higher than that of natural gas. The density of fluid CO_2 is lower than that of water, except at very high pressures. These characteristics influence injection pressures, displacement behaviour in the reservoir and storage potential. Within the scope of this study, this subject will not be treated in depth.

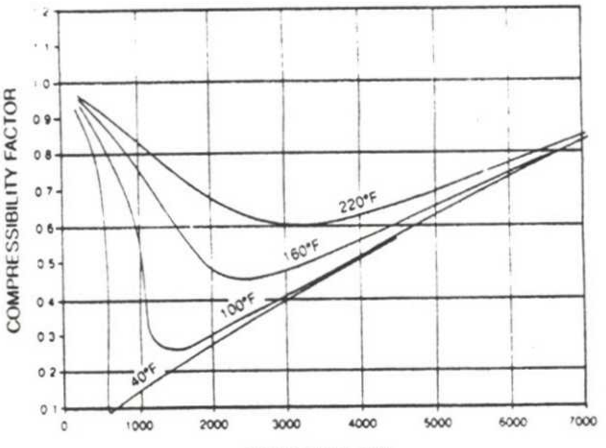

Figure 6.1 Compressibility factors for carbon dioxide [10]

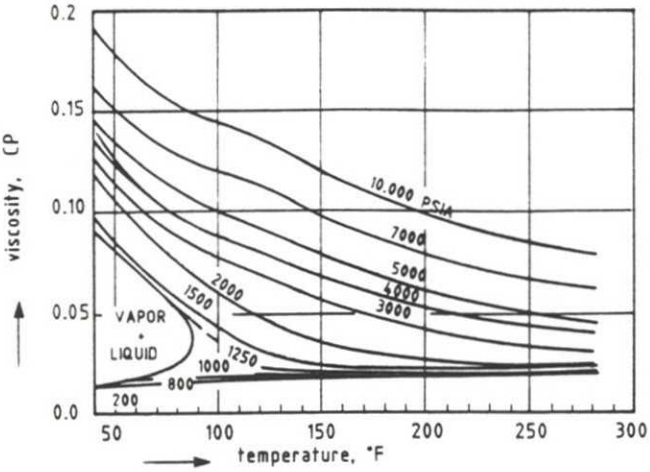

Figure 6.2 Viscosity of CO_2 [10]

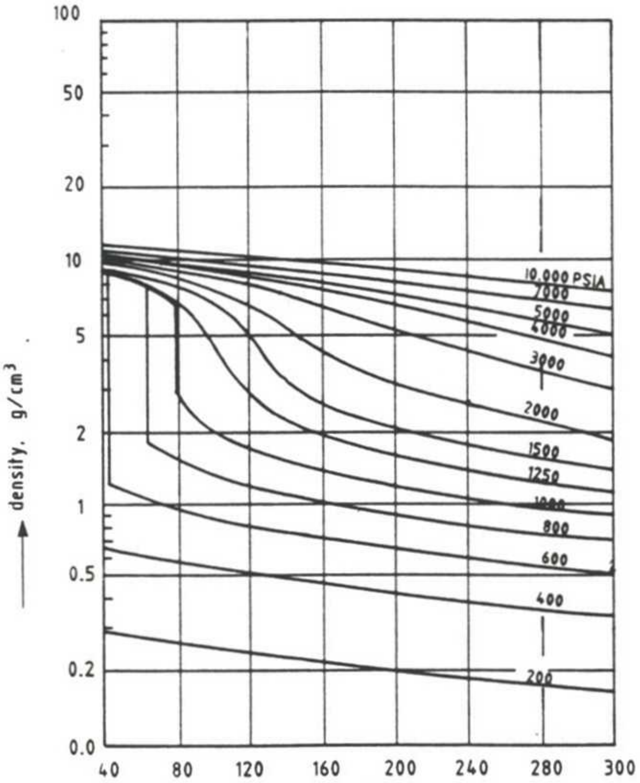

Figure 6.3 Carbon dioxide density vs. temperature at various pressures [10]

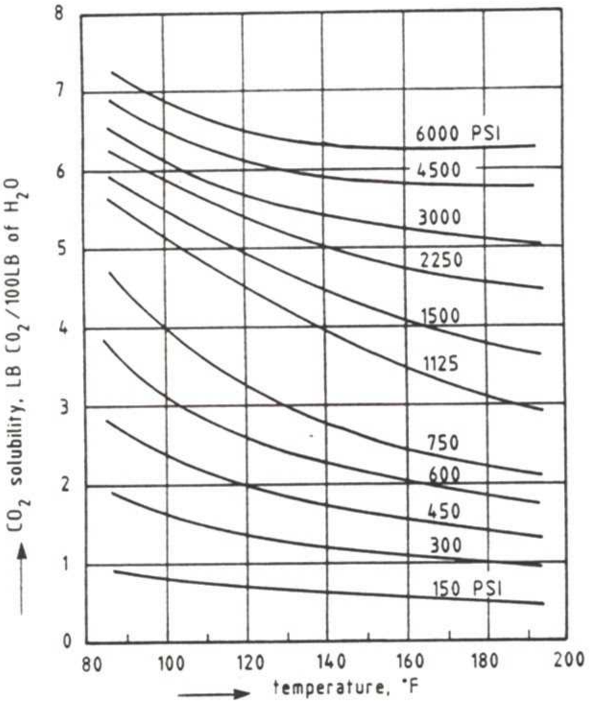

Figure 6.4 Effect of temperature and pressure on the solubility of CO_2 in water [10]

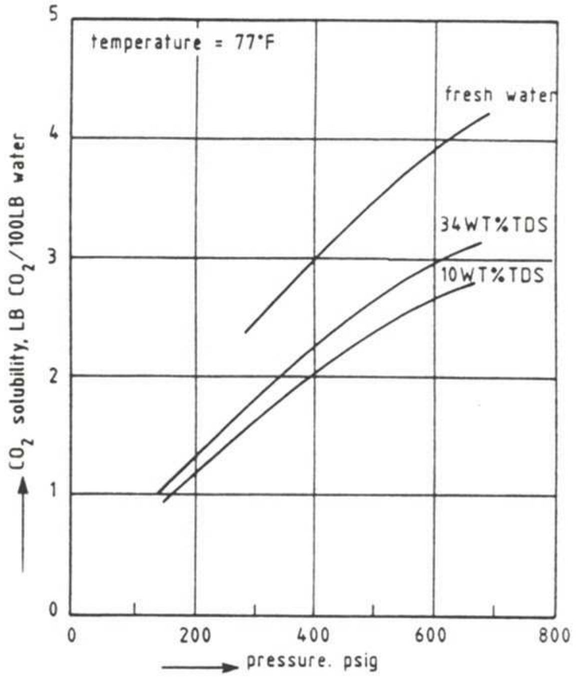

Figure 6.5 Effect of salinity on CO_2 solubility in water [10]

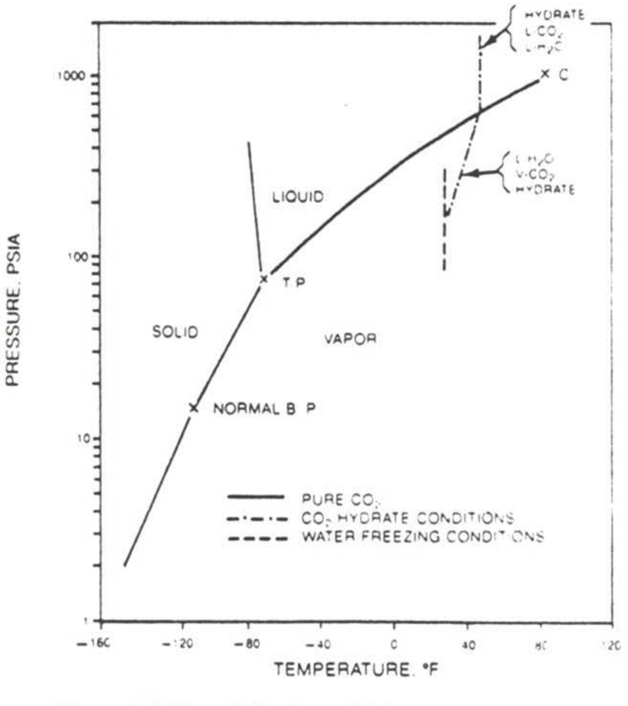

Figure 6.6 Phase behaviour of CO_2 and CO_2/water mixtures [10]

6.1 Storage in gas fields

6.1.1 Possibilities in The Netherlands

The total recoverable gas reserves in The Netherlands are estimated at 1865 Gm^3 (1-1-1990); the initial reserves were round 3400 Gm^3. These reserves concern mainly reservoirs of Rotliegend age. The division of the reserves over Groningen, onshore and offshore fields is given in table 6.1 [6].

Table 6.1 Division of reserves over Groningen, onshore and offshore fields (Gm^3 st) (1-1-1990)

Reservoir	Remaining reserves	Initial reserves
Groningen	1292	2508
onshore	232	429
offshore	341	477
Total	1865	3414

The location of the gas fields in The Netherlands is shown in figure 6.7. Present policy is to preserve Groningen and preferentially to produce from smaller fields, onshore and offshore. Hence, these fields are being depleted faster than Groningen. Abandonment is foreseen in the late 1990's, and compression is already taking place in some cases. Abandonment of Groningen is envisaged to take place around 2050. Compression facilities will be installed there approximately in the mid-1990's.

The best moment to start CO_2 injection for storage purposes is during the abandonment stage. In view of the late abandonment date of Groningen, the field cannot be used immediately, but due to its size about 8 Gtons of CO_2 could be stored in the Groningen reservoir in the future.

Other onshore gas fields are mainly located in the northern part of the country. The total CO_2 storage potential in these gas fields is about 1.3 Gton of CO_2. The total offshore storage potential amounts to 0.3 Gton of CO_2 [3]. This adds up to a total storage potential of 9.6 Gton of CO_2, or 2.6 Gt of C.

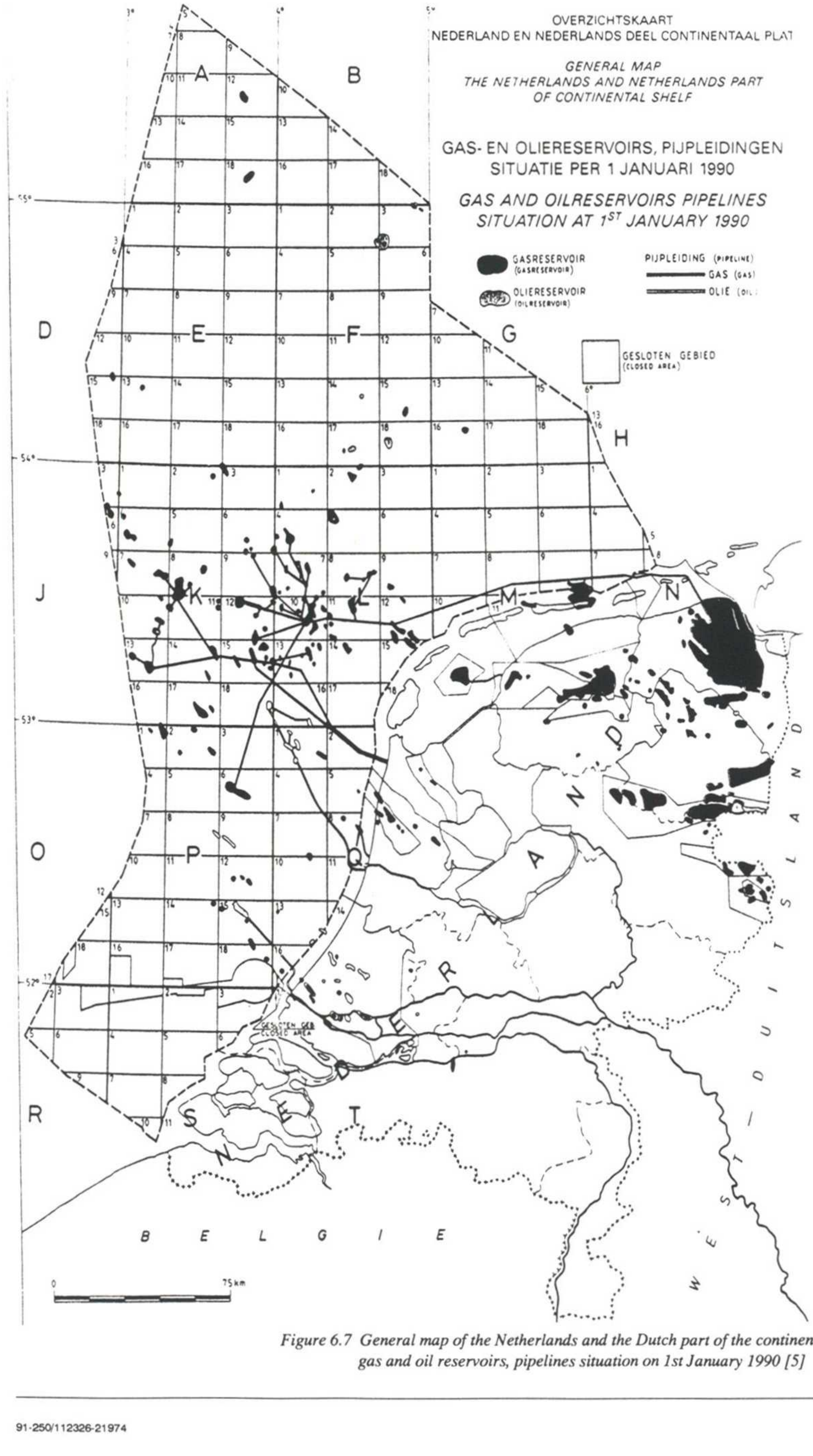

Figure 6.7 General map of the Netherlands and the Dutch part of the continental shelf; gas and oil reservoirs, pipelines situation on 1st January 1990 [5]

6.1.2 Possibilities in the EC

The hydrocarbon provinces of north-west Europe are shown in figure 6.8 [1]. Current proven reserves in north-west Europe are estimated to be approximately 6000 Gm^3 of gas (Netherlands included). Together with the amount of gas produced until now, the storage potential is estimated to be approximately 9000 Gm^3 of gas, or 28 Gtons of CO_2 (7.6 Gt of C). It is difficult to determine the abandonment date of these reserves, but it can be assumed that this will be in the early decades of the next century.

6.1.3 Practical aspects

Due to the local temperature and pressure circumstances in gas fields, the CO_2 will generally be in the supercritical phase. Since a depleted gas field is filled with water, the CO_2 will float on the water and be stored under the caprock. Injection of an inert gas into a natural gas reservoir implies a displacement mechanism that will increase the total recovery of natural gas. From an economic point of view, with the current gas prices this technique can only be applied in major gas fields. However, if the CO_2 must some day be stored anyway for environmental reasons, the storage economics will benefit from this recovery increase. The displacement of methane by CO_2 is unconditionally stable, which means that the risk of production of CO_2 from the reservoir can be prevented.

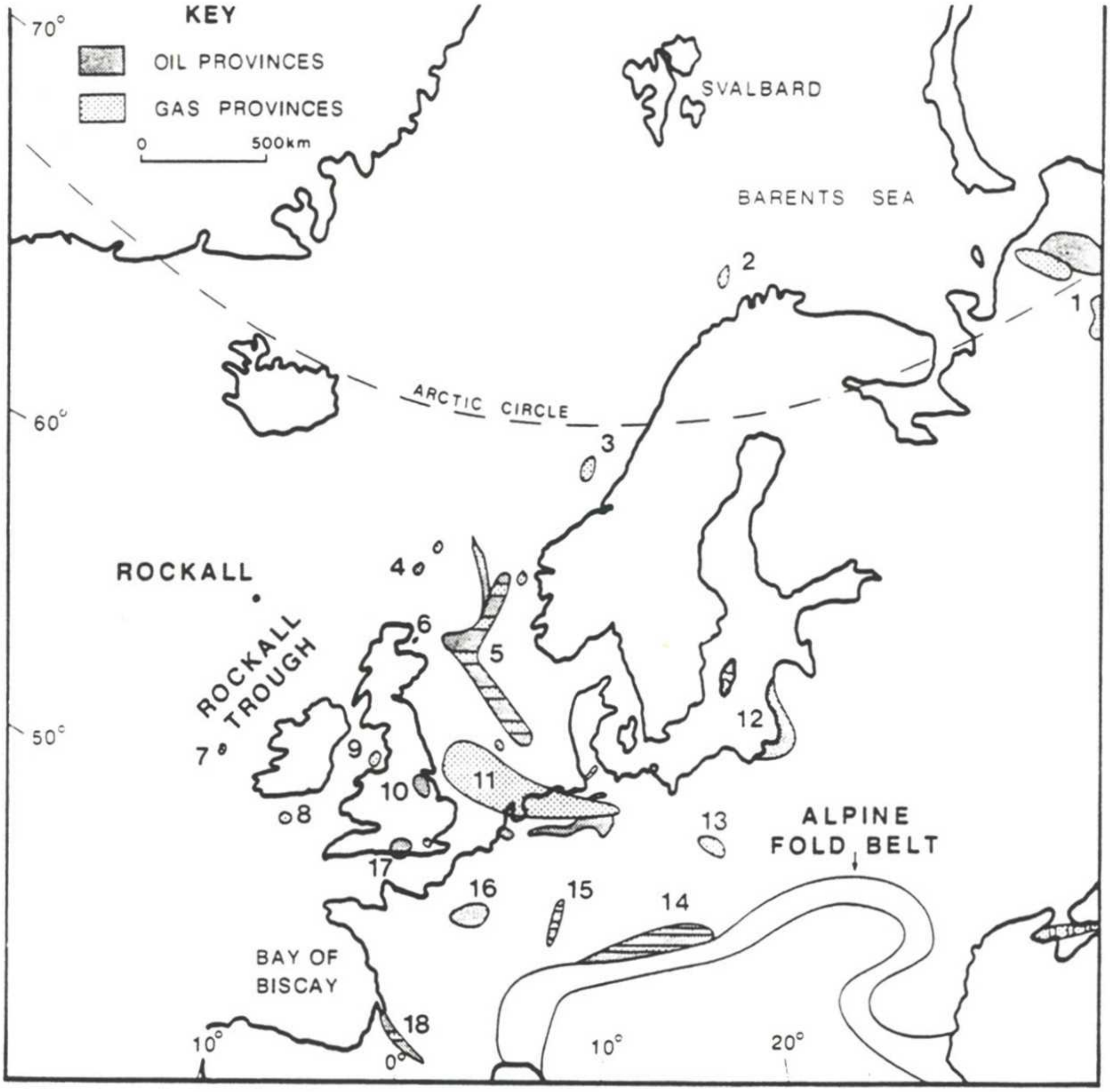

Figure 6.8 Hydrocarbon provinces of north-west Europe.
1, Pechora basin; 2, S. Barents Sea; 3, Mid-Norway offshore; 4, W. of Shetlands; 5, C. and N. North Sea; 6, Inner Moray Firth; 7, W. of Ireland; 8, Celtic Sea; 9, Irish Sea; 10, English Midlands; 11, S. North Sea – North Germain Plains; 12, Baltic Sea Estonia; 13, Poland; 14, Alpine foreland; 15, Rhine Graben; 18, Aquitaine Basin [1].

The reservoir should not be exposed to pressures higher than the initial one, in order to prevent leaks of CO_2 through the caprock. Leaks through cemented casings of the injection wells are unlikely, but not impossible. Leak detection equipment therefore will be required.

Carbonic acid will be formed by the reaction of carbon dioxide with interstitial water in the storage reservoir. It will have to be investigated whether in the course of time the strength of the formation could be decreased by this acid.

6.1.4 Costs

Obviously, the costs of CO_2 storage offshore far exceeds that of storage onshore. It is estimated [3] that for a coal-fired 600 MW plant with CO_2 production of 450 ton/hr, 6300 hr/year in service, and a CO_2 transportation distance of 100 km, the costs of storage onshore correspond to 3.2 ECU per ton of CO_2. Storage offshore may easily increase these costs by a factor of 3. In this cost estimation, it is assumed that existing wells can be used for injection purposes.

6.2 Storage in aquifers

6.2.1 Possibilities in The Netherlands

Aquifers are redundantly available in The Netherlands. In contrast with gas fields, aquifers can be used for storage immediately. The major disadvantage of storage in aquifers is the relatively few data available on reservoir properties and sealingness of the caprock. These data are necessary to determine the storage potential. However, as a result of studies with respect to the geothermal energy potential of The Netherlands [2, 7, 10] and to the adiabatic compressed air energy storage [4], the following knowledge is available:

Reservoir sands of Tertiary age with reasonable to good reservoir properties (100 - 600 mD[*]) and with an acceptable chance that a caprock is available are:
- Heers Sand
- Basal Dongen Sand
- Brussels Sand
- Berg Sand
- Voort Sand

The distribution of these sands in the Dutch subsurface is not continuous; however, more than one potential reservoir is available everywhere.
Older reservoir sands, in which hydrocarbon reserves are also found, are:

a) *sands of the Rijnland Group (Vlieland Formation)*:
   in the Western part of the country
   - Rijswijk Sandstone
   - Berkel Sandstone Member
   - IJsselmonde Sandstone Member

   in the Eastern part of the country
   - Bentheim Sandstone Member
   - Gildehaus Sandstone Member

   offshore
   - Vlieland Sandstone

   Permeabilities vary from 10 mD to 10000 mD.

b) *sands of the Lower Trias Group:*
   in the Western part of the country
   - Volpriehausen Sandstone
   - Solling Sandstone

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[*] mD = milliDarcy

in the Eastern part of the country
- Volpriehausen Sandstone
- Detfurth Sandstone
- Hardegsen Sandstone
- Solling Sandstone

in the Southern part of the country
- sand complex of the Main Bundtsandstein Formation

Permeabilities vary between 50 mD and 600 mD.

c) *sand of the Upper Rotliegend Group:*
- Slochteren Sandstone

which can be found in the provinces of Groningen, Friesland, Utrecht, Gelderland, North Holland and offshore. Permeabilities vary between 10 mD and 600 mD.

Based on the geothermal resource calculations given in [2], it is estimated that the volumetric potential of the aquifers in The Netherlands is approximately 70.10^9 m^3 of water, equivalent to 50 Gton CO_2.

6.2.2 Possibilities in the EC

In all countries of the European Community much work has been done over the past few years on the assessment of geothermal resources. The results of this work have been compiled in an atlas of geothermal resources [2]. The data presented in this atlas are to some extent also useful to estimate the CO_2 storage potential in aquifers in the EC. However, when considering these estimates, one has to take the following into consideration.

Potential geothermal reservoirs are not identical to potential CO_2 reservoirs. In most, but not all cases geothermal resources are defined as reservoirs where the temperature exceeds 30 °C (which implies a depth of more than 600 m) and transmissibilities higher than 5 Dm*. This implies that part of the storage potential for CO_2 is not incorporated. On the other hand, storage of CO_2 requires the availability of structural or stratigraphical traps, which means that not all of the geothermal reservoirs are suitable. Furthermore, in some countries the resource assessment is further advanced than in others. Known geothermal resources in the EC are shown in figure 6.9. Not all potential reservoirs may have been taken into account.

Nevertheless, based on the available information, the CO_2 storage potential in aquifers can be estimated within certain limits, which enables us to compare it with the storage potential in depleted gas fields. After the volumetric potential of aquifers per country has been presented, a tentative correction factor will be applied on the basis of the above considerations to establish the storage potential (table 6.2).

In this context, the assumption is made that the maximum aquifer depth is 3000 m and that on average 1 ton CO_2 occupies 1.4 m^3 of pore space at reservoir conditions.

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* Dm = Darcymeter

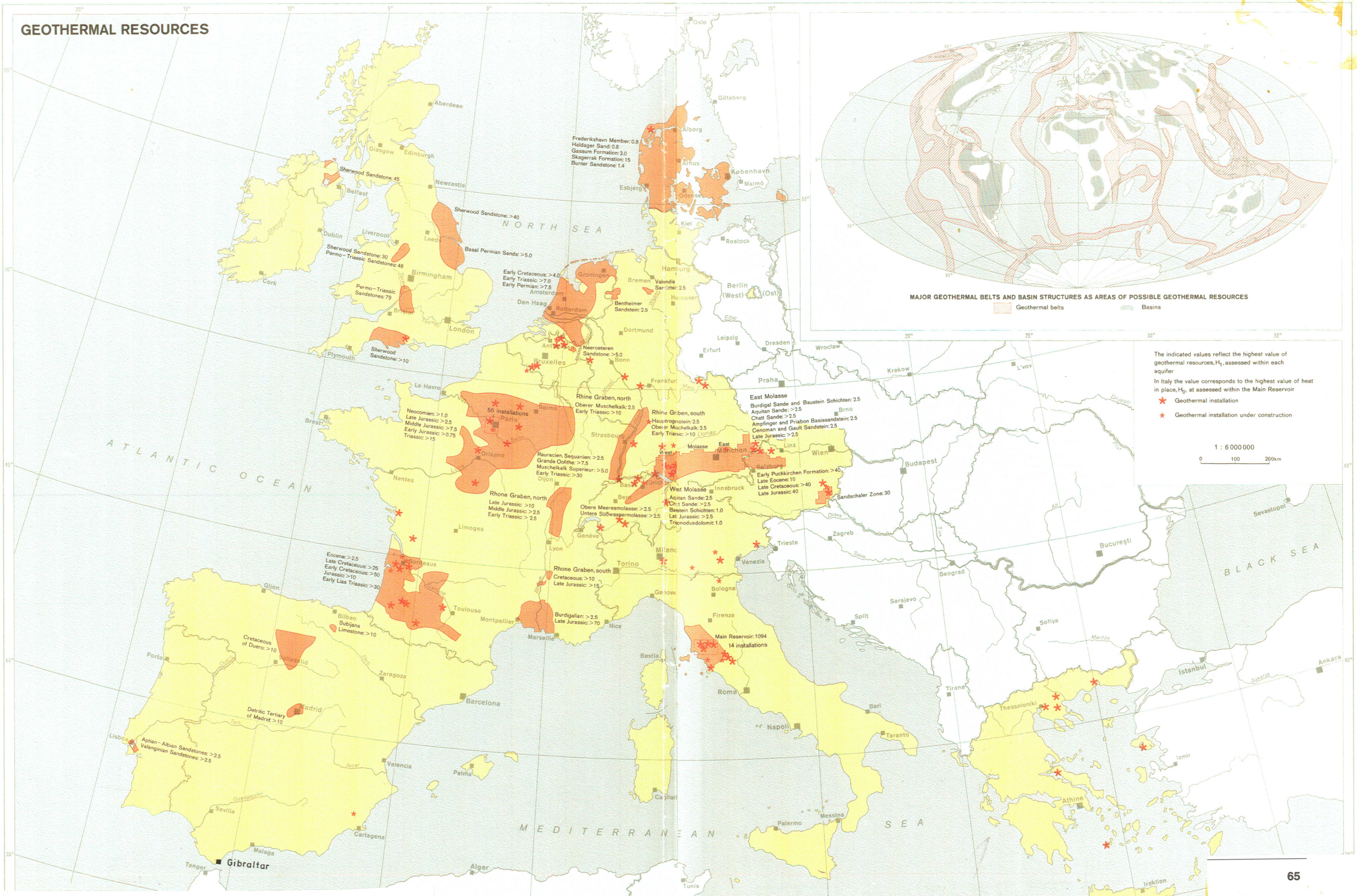

Figure 6.9 Geothermal resources (indicated in red) in the EC, Switzerland and Austria

Commission of the European Communities, Directorate - General for Science, Research and Development

Commission of the European Communities, Directorate - General for Science, Research and Development

Belgium
Only Dinantian karstic limestones are taken into account. In this reservoir the volumetric potential is approximately 0.18 Gton CO_2.

Denmark
A complete assessment has been made of
- the Bunter Sandstone
- the Skagerak Formation
- the Gasum Formation
- the Haldager Sand
- the Frederikshavn Member

The volumetric potential is approximately 230 Gton CO_2.

Federal Republic of Germany
The following basins have been studied:
- Northern Basin
- Upper Rhine Basin
- Southern German Molasse Basin

In these basins the volumetric potential in aquifers is estimated at approximately 143 Gton CO_2.

Greece
Only the Thessaloniki Basin has been considered. The storage potential has been estimated at approximately 0.27 Gton CO_2.

Spain
In Spain, only three reservoirs have been assessed for their geothermal potential. These are:
- the Subijana limestone in the Ebro Basin,
- the Creraceous of Duero in the Duero Basin and
- the detrital Tertiary of Madrid, near Madrid.

It is expected that further investigations of potential areas will increase the resource estimates considerably. Based on existing estimates, the volumetric potential is approximately 68 Gton of CO_2.

France
France is one of the countries where the evaluation of the geothermal potential is very advanced. Most of the clastic reservoirs have been investigated. However, very few limestone reservoirs are incorporated in the resource estimates.
Based on the figures given in the atlas, the volumetric potential for CO_2 is estimated at approximately 1220 Gton.

Ireland
No data were available for Ireland. If it is assumed that the basins in Ireland will contain some aquifers that have storage potential, the volumetric potential may be estimated at approximately 0.25 Gton CO_2.

Italy

The figures that are given in the atlas of geothermal resources refer mainly to the resources in Tuscany. Since this a high enthalpy area, it was not possible to determine reservoir properties from these figures and to make an estimate of the storage potential. In view of the number and the extent of the aquifers in Italy, it is assumed that the volumetric potential is at least 200 Gton CO_2.

Portugal

The Lower Tejo Basin has been investigated. In this basin the Aptian/Albian reservoirs and the Valanginian sandstones have storage potential. The volumetric potential is estimated to be approximately 1.3 Gton CO_2.

United Kingdom

In the U.K. most onshore clastic reservoirs have been mapped. Based on the figures in the atlas, the volumetric potential was estimated to be approximately 120 Gton CO_2.

As a summary, the figures given above for the volumetric potential of aquifers with geothermal resources in which also CO_2 may be stored are presented in table 6.2. It was mentioned earlier that not all geothermal resources may have been taken into account. On the other hand, the fact that storage of CO_2 requires structural or stratigraphic traps will reduce the actual storage potential drastically. It will therefore be assumed that 5 to 20% of the potential of the aquifers can actually be used for storage of CO_2.

Table 6.2 Volumetric potential and actual storage potential for CO_2 in the EC (Gton CO_2)

	Volumetric potential	Actual estimated potential	
		minimum	maximum
Belgium	0.18	0.009	0.036
Denmark	230	11.5	46
FRG	143	7.15	28.6
Greece	0.27	0.0135	0.054
Spain	68	3.4	13.6
France	1220	61	244
Ireland	0.25	0.0125	0.050
Italy	200	10	40
the Netherlands	50	2.5	10
Portugal	1.3	0.065	0.26
U.K.	120	6	24
Total (Gton CO_2)	2033	101.65	406.6
Total (Gton C)	554	27.7	111

6.2.3 Practical aspects

Some of the aspects that were discussed for depleted gas fields also apply to storage in aquifers.
Specific aspects for the storage of CO_2 in aquifers are that the availability of sealing caprocks and structural or stratigraphic traps will have to be investigated. In the end, the sealingness of a caprock can only be determined by in-situ tests.

It can be seen from figure 6.4 that CO_2 is soluble in water. It will have to be investigated whether, in the absence of a sealing caprock, carbon dioxide in solution will be able to reach the surface. If such a risk does not exist, the storage potential and flexibility of storage in aquifers would increase drastically, compared to the figures mentioned in table 6.2.

For the actual implementation of storage of CO_2 in aquifers, no infrastructure is available. Wells, pipelines and compressors will have to be installed, especially for the disposal project.

6.2.4 Costs

It will be assumed that the same costs apply as those for the storage in depleted gas fields [3], but that in addition new wells will have to be drilled (4 wells for 600 MW plants). In countries with an abundance of aquifers, the average transportation distance is estimated to be 50 km. The storage costs per ton CO_2 will then decrease by approximately 8%. If the average transportation distance were 200 km, the cost per ton CO_2 would increase by approximately 30%.

6.3 Storage in salt caverns

6.3.1 Possibilities in The Netherlands

Approximately ten salt domes can be found in The Netherlands, in the provinces of Groningen, Drenthe and Overijssel. The salt deposits from which these domes originate can be found in larger parts of the Dutch subsurface, but these deposits usually do not have the uniformity necessary for a stable cavern. In some of the salt domes, caverns have been made for the purpose of salt mining. Typical volumes of a cavern are 0.2 to 1.5 Mm^3. At a depth of 500 m, the carbon dioxide storage potential would be 0.035 to 0.25 Mton per cavern. More than one cavern can be made in a dome.

6.3.2 Possibilities in the EC

Within the scope of this study it was not possible to assess the availability of salt domes in the European Community. It may be assumed, though, that the volume of the salt domes in The Netherlands is a considerable percentage of those in the EC.

6.3.3 Practical aspects

If there is no commercial use for the salt that is mined from the caverns, the costs and environmental consequences of salt disposal would have to be considered.

Stability criteria for the design of salt caverns are [5]:

- When more than one cavern is made in a dome, the distance between the centres of the caverns should exceed four times the cavern diameter.
- The distance between the boundary of the cavern and the boundary of the dome should exceed three times the cavern diameter.
- The distance between the top of the cavern and the top of the dome should exceed 150 m.
- The height-diameter ratio should be between one and five.
- The maximum allowable diameter is approximately 60 m.
- The maximum allowable injection temperature is approximately 80 °C.
- The maximum allowable pressure gradient is 1.639 MPa per 100 m depth.

6.3.4 Costs

Each cavern needs at least one well, and since the storage potential per cavern is limited, it can be assumed that the cost per ton of CO_2 will be approximately 4 ECU.

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7 Why not store more fossil fuel CO_2 in the oceans?

(H.J.W. De Baar)

In this chapter, the role of the ocean as an ultimate depository of fossil fuel CO_2 is reviewed.

Section 7.1 describes the ways the ocean controls atmospheric CO_2 today and the ways it has in the past. Since the onset of the industrial revolution, the ocean has absorbed about half of the fossil fuel CO_2 released by mankind. Over longer time scales the biology of the oceans has had a major impact on atmospheric CO_2 and climate changes from glacial to interglacial periods.

Section 7.2 provides an overview of the various schemes for enhancing storage of CO_2 in the oceans as a means to solve the fossil fuel CO_2 problem. The proposed schemes tend to rely either on (7.2.1) fertilization of the ocean as to accelerate photosynthesis or on (7.2.2) pumping CO_2 directly into the deep sea.

The immense prospect of a CO_2 'greenhouse' effect has given rise to many imaginative schemes for fixing the problem. Virtually all these schemes were reviewed most adequately by **Marland** (1986, [72]). In Europe, several scientists were among the first to point out the importance of the CO_2 greenhouse problem (**Postma**, 1963, 1964 [86, 87]). More recently, the CO_2 greenhouse problem has also become an issue among the general public. European scientists are now also being asked to look for ways to solve the problem. In this context, a joint effort in The Netherlands is most relevant for this report (**Okken et al.**, 1989, [131]).

7.1 Science fact: the ocean has a slow but firm grip on the global carbon cycle

7.1.1 Carbon in the global ocean

The oceans cover most of the surface of the globe. Its metabolism, i.e. the internal cycling and boundary exchanges of chemical constituents, has a major impact on the atmosphere and the terrestrial biosphere.

Here we are interested in a prime example, the cycle of Carbon, the prime building block of all biomass (figure 7.1). The seawater reservoir contains about 40,000 Gton of carbon (largely as the bicarbonate ion: HCO_3^-), and its annual exchange rate with the atmosphere is in the order of 100 Gt C per year. The atmospheric reservoir itself contains only about 700 Gt C as CO_2 and exchanges at a rate of about 70 Gt C/a with the terrestrial biosphere. The latter contains about 2000 Gt C, of which some 70 percent, say 1400 Gt C, is in the soil (humus) with the remaining 600 Gt C aboveground as plants.

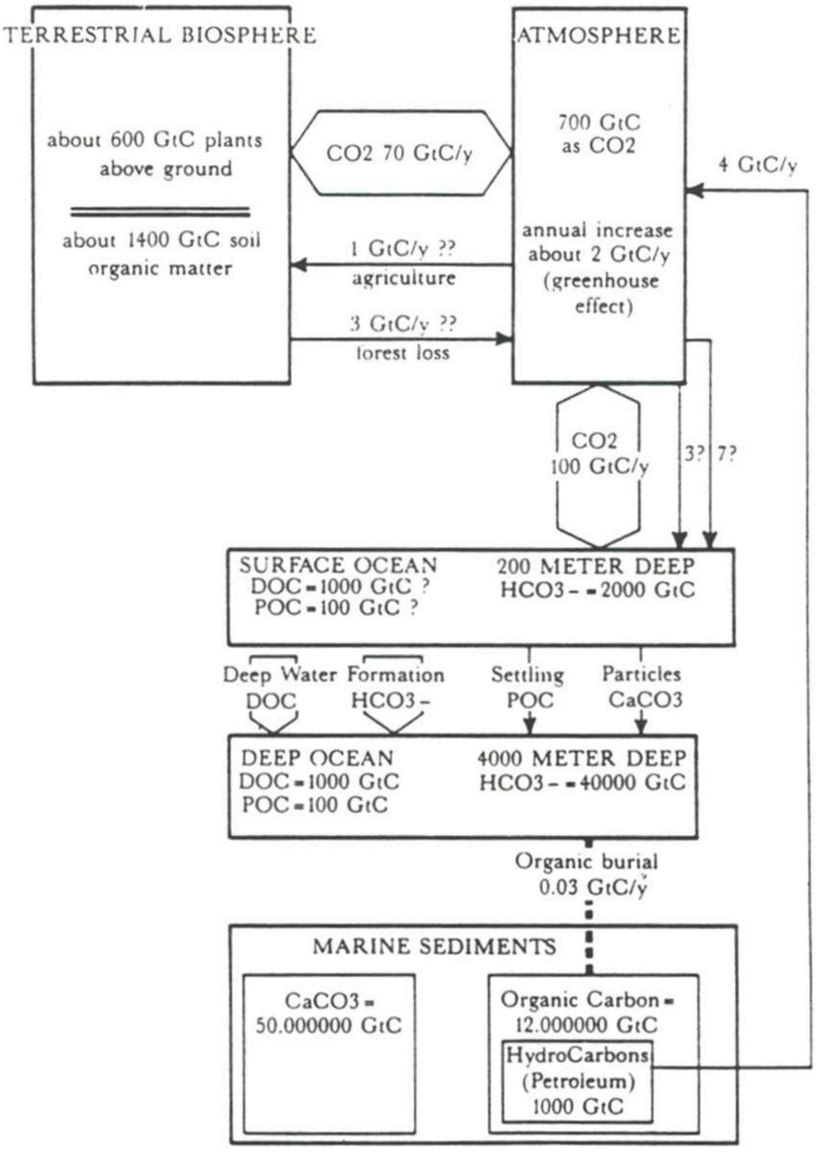

Figure 7.1[*] The global Carbon budget [76]. Inventories (1 Gigaton Carbon = 10^{15} gram C) and Fluxes (GtC/-year) are large relative to atmospheric CO_2 content and its annual increase. Large arrows for natural fluxes, small arrow fluxes arise from human activity.
DOC: Dissolved Organic Carbon
POC: Particulate Organic Carbon

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[*] The figures presented here differ somewhat from those of figure 2.2, since they stem from a different reference. In this context these differences are, however, not relevant.

Throughout geological time there have been variations in the geosphere/biosphere system, including shifts in the above inventories and fluxes of the C system. For example, records over the past 160,000 years derived from Antarctic ice cores (Figure 7.2) show atmospheric CO_2 variations between about 120 x 10^{-6} atm and 270 x 10^{-6} atm, the latter correlating with variations in surface temperature [10].

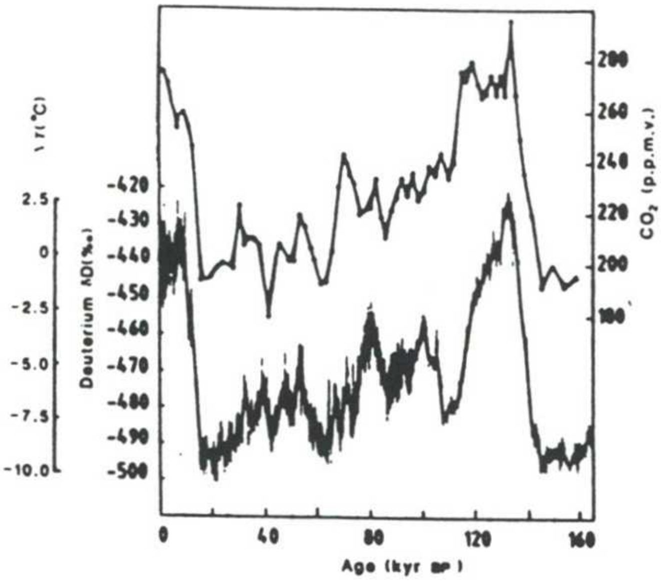

Figure 7.2 CO_2 concentrations from ice cores ('best estimates') and smoothed values (spline function) in parts per x 10^6 (volumetrically) plotted against age in the Vostok record (upper curve), and atmospheric temperature changes, derived from the isotopic profile (lower curve) of Deuterium [10]

The apparent cause/effect relationship of this glacial/interglacial CO_2 shift [78] is the subject of considerable debate [67, 21, 22, 90, 74, 16, 17]. Recently, **Broecker and Denton** (1989) synthesised all available evidence, suggesting that the oceanic C cycle functions as an amplifier of the climatic response to ultimate orbital force. Great emphasis is placed on the formation and shutting off of North Atlantic Deep Water during interglacial and glacial periods, respectively.

Deep-water circulation patterns shift; the result is a change in distribution of the nutrient elements nitrogen and phosphate. The shift in nutrient supply, in turn, will affect photosynthesis of plankton, i.e. biological fixation of CO_2. Though their suggested scenario is very fascinating, one ought to realise that there is not enough hard evidence for properly ruling out other conceivable scenarios which are not favoured by the authors. Yet there is no doubt that the oceans, through variations in circulation, biological productivity, nutrient regime, etc., play a crucial role in governing global climate [106, 76, 15, 24, 91].

7.1.2 The oceans already take up fossil fuel CO_2

Simple bookkeeping of CO_2 inputs by mankind versus observed atmospheric CO_2 increase tells us that about half of the input has gone elsewhere: into the oceans.

Comparison of emission rates derived from fossil fuel (coal, oil, gas) statistics [77] with the observed CO_2 increase has shown that only about half (estimates vary between 25-60 percent) of the fossil-fuel-derived CO_2 is retained in the atmosphere. The other half (range 40-75 percent) is presumably taken up by the oceans. The uncertainty stems from the fact that net CO_2 emissions due to **changes** in terrestrial biomass (deforestation, agriculture) are very difficult to assess (chapter 8). Estimates vary between extremes of -1 and +4 Gt C/a, corresponding to a small increase or larger decrease of terrestrial biomass, respectively. Nevertheless, it is obvious that the oceans serve as the major sink for fossil fuel CO_2. Through dissolution of CO_2 in the upper mixed layer (about 75 m depth) of the ocean, as well as biological C fixation (photosynthesis), the surface ocean can take up about 2-3 Gt C/a, with an extreme upper estimate of 7 GtC/a (figure 7.1). Biological activity in the ocean may well be the most crucial factor, controlling the actual rate of CO_2 uptake. The net amount is only a fraction of the gross 100 Gt C/a annual atmosphere/upper ocean exchange. The strictly physico-chemical net uptake of CO_2 in surface waters is further predicted actually to decrease with increasing overall CO_2 levels in the future [107]. In other words, at increasing atmospheric CO_2 level, the ocean is less and less capable of taking up CO_2. This feedback will lead to an acceleration of the CO_2 greenhouse effect in coming years.

The actual effectiveness of the net ocean sink is otherwise not well known anyway, and also varies from year to year. For example, significant changes in atmospheric CO_2 were noted during El Niño - Southern Oscillation events (a periodic irregularity in the current pattern in the South Pacific Ocean) [3, 4, 65]. The exchange of CO_2 between atmosphere and ocean is clearly not in a steady state, but is subject to dynamic variability throughout the frequency domain, further enhanced by the recent changes generated by industrial CO_2 emissions and dramatic clearing of tropical forests.

The excess CO_2, say 2-3 Gt C/a, taken up in the surface ocean, is eventually carried downward by both water circulation (sinking of CO_2 saturated water at the poles) and biogeochemical processes. We are now, however, not able to quantify whether the physical and chemical processes (ocean heating, cooling, mixing, CO_2 dissolution) or the biological processes (photosynthesis and respiration) predominate the contemporary oceanic sink, both with respect to capacity as well as actual uptake rate of CO_2 [19]. Clearly a better understanding and quantification of the latter processes is crucial for modelling the atmospheric CO_2 content and the ensuing 'greenhouse' effect. Scenarios for the latter [48, 117, 119, 120, 96, 97] are in great need of proper oceanographic constraints before they can serve as reliable tools for policy decisions on matters as deforestation, curtailing CO_2 emissions and anticipation of a possible sea level rise [41].

7.1.3 Natural routes for bringing excess CO_2 into the deep sea

For bringing CO_2 from the atmosphere down into the deep sea, the surface ocean unfortunately acts as a barrier. The key problem lies in passing this barrier. The ocean has been doing this modestly, yet over a very large surface area, and has taken up fossil fuel CO_2 along four different pathways. Three of these routes, namely:

(i) the settling of dead plankton material;
(ii) the settling of calcareous shells; and
(iii) the transport of dissolved organic matter,

are ultimately driven by photosynthesis. The other route is:

(iv) the physico-chemical uptake of CO_2 in seawater, which in the real ocean is strongly intertwined with photosynthesis, but which would also operate in a hypothetical dead ocean without plankton.

The surface ocean as a barrier

Throughout most of the world's oceans, there exist both a seasonal and a permanent thermocline (temperature jump) at depth intervals typically near 50-150 m and 200-800 m respectively, which are characterised by strong temperature gradients. The corresponding density gradients largely prevent vertical mixing of water and its dissolved constituents between the surface ocean and the deep ocean interior.

Only in the surface mixed layer, the upper 25-250m driven by wind mixing, are gases like CO_2 exchanged with the atmosphere. The direction of CO_2 gas exchange is dictated by relatively straightforward equilibrium considerations (undersaturation or oversaturation). The actual rate of exchange lies in the order of one year [23], determined by interaction of complex processes and concepts such as wind-induced mixing, bubble injection and surface film thickness [79].

Photosynthesis

The same surface layer is also known as the euphotic zone, the depth interval (down to about 1% light penetration) where photosynthetic C fixation (primary production) by algae is responsible for the massive conversion of dissolved inorganic bicarbonate into plant organic matter. The process is regulated by physical forces: light regime, upward mixing of necessary nutrient elements (N, P), and temperature. Overall, the C fixation leads to lower values of Dissolved Inorganic Carbon (DIC) in the surface ocean (figure 7.3), so that further physicochemical dissolution of atmospheric CO_2 is possible. Much (typically 80-95%) of this Gross Primary Production (GPP) is converted through grazing by zooplankton, microbial degradation and other processes within the complex food web of the upper ocean. The net results are the build-up of a pool of Dissolved Organic Carbon (DOC) as well as complete recycling back into the Dissolved Inorganic Carbon pool (figure 7.4).

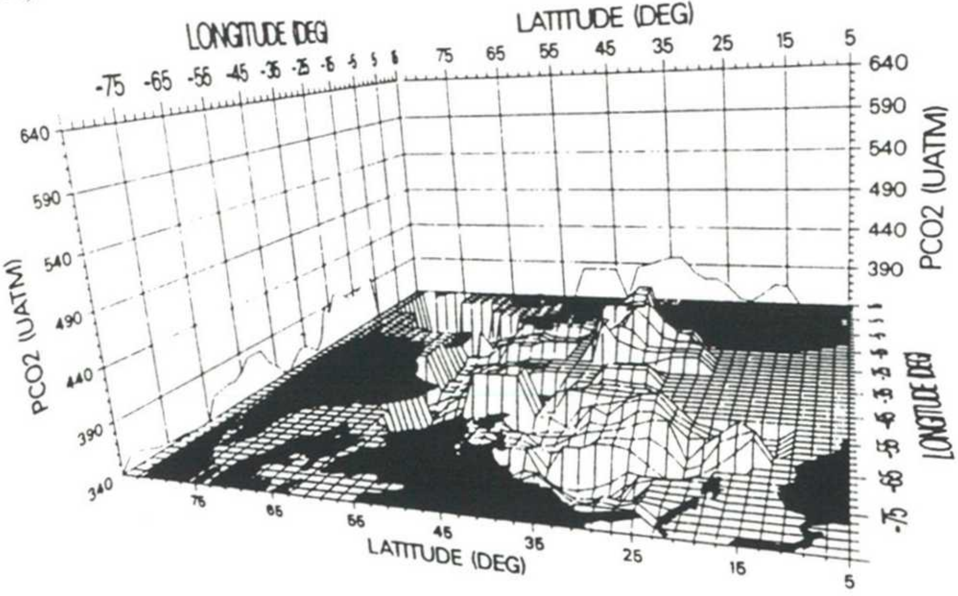

Figure 7.3 The partial pressure of CO_2 in surface seawater (1-15m) of the North Atlantic Ocean as measured during the TTO expeditions. A correction term for the surface excess of O_2 has been applied. This map does not represent synoptic sampling but a clear trend of over- c.q. undersaturation in equatorial c.q. subpolar waters is suggested [19]

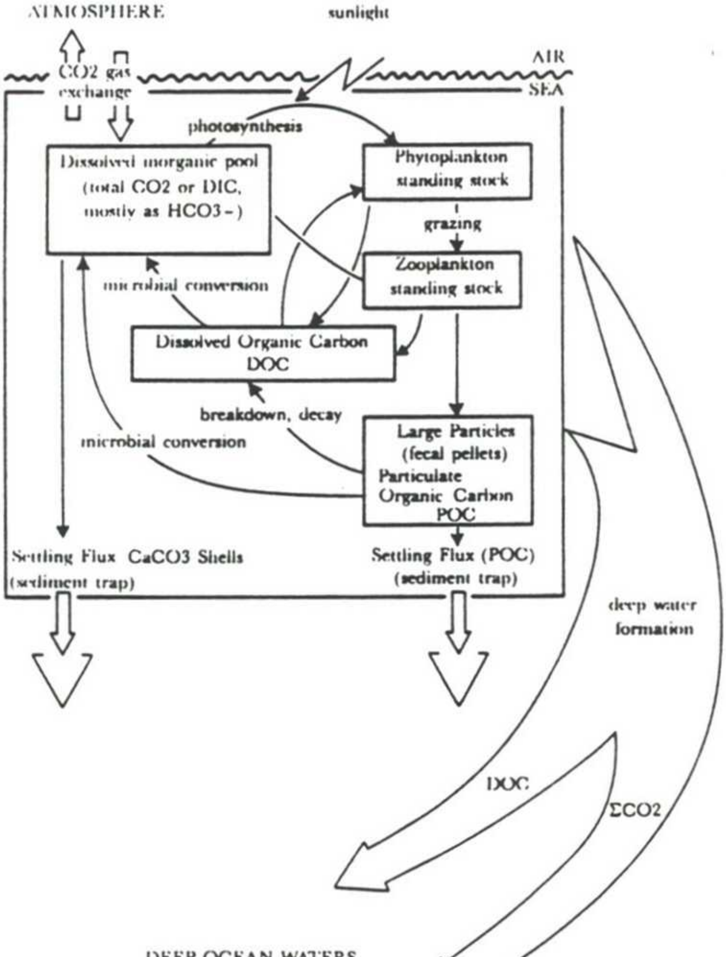

Figure 7.4 Simplified scheme of compartments and fluxes for C in the upper ocean. The large arrows depict the four pathways for 'pumping' Carbon into the ocean interior.
DIC:Dissolved Inorganic Carbon
ΣCO_2: Total CO_2 content

The net effect of photosynthesis

However, some plant/animal material or Organic Carbon (POC as well as DOC) escapes mineralisation and is exported to deeper waters. This 'New Production' term [35, 39] represents the biologically mediated net flow of C from the atmosphere into the deep ocean. New production is typically one order of magnitude less than the Gross Primary Productivity. The larger fractions in the particle spectrum settle down out of the euphotic zone into the deep ocean. This vertical flux of organic particles is one major pathway for transfer of atmospheric C into the deep ocean; the 'biological pump' for removal of atmospheric CO_2. Concurrently, biologically essential elements (N, P, Si) are also being removed to such extent that very little remains available for plant growth. At 'near-zero' levels of nitrate, ammonia, phosphate or silicate the surface ocean productivity is typically limited by N availability. Only through replenishment of N by physical, mostly wind-driven, mixing from deeper waters (or possibly from atmospheric input) can the new production flux be sustained.

For the open ocean regions, which constitute 75% of the world's oceans, both the total rate of photosynthesis, and the portion of carbon which is removed to deep waters, are uncertain to within one order of magnitude [47]. Our poor knowledge of these crucial terms in the global carbon balance implies that future atmospheric CO_2 levels, and therefore the future climate of the earth, can only be predicted with little certainty. Improved accuracy of global estimates for both primary and new production is the objective of the ongoing Joint Global Ocean Flux Study (JGOFS).

Bringing down the biological debris

The settling of large particles [74] has been investigated extensively in the past decade with sediment traps [56, 117, 42, 73, 109, 83]. Compilations of various data suggest that more than 75% of the particle flux is recycled within the upper 500 m [73, 81]. In the deep ocean, vertical gradients of the fluxes of organic matter (C, N, P, organic compound classes, etc.) point at significant microbial mineralisation and transformation during settling [29, 68, 117, 119]. From the observed seasonality of long-term records [31, 5, 32] we now also know that the settling velocity can be very rapid indeed, effectively bringing the C down to the sea floor within about one month after a plankton bloom.

So far we have dealt with organic debris, but there is also shell material, inorganic material produced by nature. In the open ocean, various organisms such as Coccolithophorideae, planktonic Foraminifera and planktonic Ostracods also extract CO_2 (about 3 Gt C per year) from surface seawater in the form of calcareous ($CaCO_3$) shells. Much of this material eventually settles to the sea floor and thus constitutes another flux of C into the deep sea [56, 33]. On an annual basis, the raindown of C in shell material roughly equals that of C as organic matter, and most of the $CaCO_3$ dissolves again in the deep sea. However, over very long (geological) time scales, some of this shell material has been preserved and has thus accumulated in an enormous amount of about 50 x 10^6 Gt C (figure 7.1). Through geological uplift or retreat of the sea, Europeans are permitted a glimpse at some of these huge deposits, e.g. the (metamorphosed) marble in Italy, the white cliffs of Dover or the 'Mergelland' near Maastricht, The Netherlands.

Bringing down the dissolved carbon

Another pathway for downward carbon transport is the sinking of surface water by means of intense winter cooling. Large volumes of cold, hence heavier, water sink to great depth. The process occurs seasonally in the northern North Atlantic (Norwegian and Greenland Seas, Labrador Sea) and the Weddell Sea off Antarctica. Through its tendency to equilibration with the atmosphere, the very cold water acts as a sink for inorganic CO_2 and it also carries down DOC.

Sluggish circulation within the dark abyss slowly fills the deep basins of the oceans; the mean 'age' of the deep water is about 500-1500 years [103, 23]. During this time period, most of the DOC is converted to DIC, and the settling large particles are also remineralised into DIC (mineralisation taking place both while settling as well as at the sea floor). From the vertical and interoceanic distribution of various dissolved tracers (nitrate, phosphate, ΣCO_2, ^{13}C, etc.) in the world ocean, we know that the net flux of organic matter originating from the surface ocean is remineralised within the deep sea and at the sea floor. We are not certain whether this organic matter is brought into the deep sea largely as particles settling from the euphotic zone, or mostly as DOC, carried along with the general water circulation.

The water balance of the surface ocean is restored by a mean upward flow or upwelling, in the order of 4 m per year. In certain regions, e.g. in the equatorial Atlantic, more intense upwelling is noted from excess CO_2 contents of the water as compared with the atmosphere ([23], see also Figure 7.3). Some of this excess is fixed by photosynthesis, and some escapes into the atmosphere, as was concluded from $^{13}C/^{12}C$ analyses of atmospheric CO_2 [64]. The short mixing time of the atmosphere makes each hemisphere fairly homogeneous with respect to CO_2; the ocean 'breathes' CO_2 by inhaling at the poles and exhaling at the equator. This ocean/atmosphere CO_2 exchange is massive (about 40-100 Gt C/a) compared with the modern fossil fuel CO_2 additions (about 5 Gt C/a) (figure 7.1).

What do we know about dissolved organic carbon?

The sinking water masses in subpolar regions have long been known to carry along dissolved (inorganic) CO_2, but what about Dissolved Organic Carbon (DOC)? Recently published results, based on a careful modern rejuvenation of the High Temperature Combustion (HTCO) technique [104], would appear to suggest that we have traditionally underestimated the dissolved carbon and its transport down into the deep sea. The undersaturation of oxygen or Apparent Oxygen Utilisation (AOU) in the deep ocean would be largely accounted for by mineralisation of high inputs of DOC. The suggested oceanographically consistent relations (AOU/DOC) are not unattractive. Once corroborated by additional measurements, they appear to make the other major downward C transport (by settling biogenic debris) less important. These relations and the underlying HTCO methodology are currently the subject of considerable debate [125, 110] and investigations [126].

The gang of four pumps at work in the ocean

In summary, we now know four, rather than three [114], different routes currently used by the geosphere-biosphere system for 'pumping' C into the deep ocean:

1. Dissolved bicarbonate carried down during deep water formation (DIC).
2. Dissolved Organic Carbon carried down during deep water formation (DOC).
3. Vertical flux of organic matter in settling particles (POC).
4. Vertical flux (sedimentation) of calcite shells ($CaCO_3$).

Within the deep ocean the organic matter (2. and 3.) is almost all converted again by microbes and animal respiration to dissolved CO_2. Also, in the deepest parts of the ocean, the settling calcite shells (4.) tend to dissolve again. The total CO_2 content (ΣCO_2) of deeper and older water is therefore larger, for example about 2200 and 2400 micromoles (μM) per litre in deep (4 km) Atlantic and Pacific water respectively, as opposed to values in the order of 2000 μM in surface water. The latter surface waters are more or less in equilibrium with the atmospheric CO_2 partial presssure, but strong oversaturation and undersaturation (figure 7.3) do occur, due to slow rates of air/sea gas exchange as well as biological CO_2 fixation.

7.1.4 Buffering fossil fuel CO_2 by calcite dissolution

Curiously enough, higher concentrations of dissolved CO_2 lead to dissolution of calcareous sediments, effectively buffering the excess (fossil fuel) CO_2. Unfortunately, the process is very slow.
In seawater, CO_2 is involved in a complex system of equilibria, given below in a simplified manner. At the sea surface, CO_2 tends to dissolve in accordance with Henry's Law:

$$[CO_2]\text{dissolved} = \alpha \,.\, P_{CO2gas}, \quad (1)$$

where α is a function of salinity and temperature. Upon reaction with water

$$CO_2 + H_2O = H^+ + HCO_3^-, \quad (2)$$

some of the bicarbonate thus formed further dissociates:

$$HCO_3^- = H^+ + CO_3^{2-}, \quad (3)$$

into another proton (H^+) and the carbonate ion. Reactions (2) and (3) are governed by the equilibrium dissociation constants

$$K_1=[HCO_3^-][H^+]/[CO_2] \quad (4)$$

and

$$K_2=[CO_3^{2-}][H^+]/[HCO_3^-]. \quad (5)$$

Both K_1 and K_2 are functions of temperature, salt content, pressure, etc., in general such that at lower temperature the seawater contains more CO_2. The total amount of CO_2 or ΣCO_2 consists of

$$\Sigma CO_2 = [CO_2] + [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}], \quad (6)$$

where in seawater about 90 percent is bicarbonate $[HCO_3^-]$, about ten percent carbonate $[CO_3^{2-}]$, and very little $[CO_2]$.

Finally, we have to take into consideration that the two anions $[HCO_3^-]$ and $[CO_3^{2-}]$ have an electrical charge, which has to be balanced by the charge difference between all cations (Na^+, K^+, Mg^{++}, Ca^{++}, etc) and other anions (mostly Cl^- and SO_4^{2-}). The latter charge difference or Alkalinity is more or less constant in seawater, and thus matches the sum of charges of the CO_2 system:

$$\text{Alk(alinity)} = [HCO_3^-] + 2[CO_3^{2-}], \tag{7}$$

where Alk is expressed as charge equivalents per litre. Within seawater, the six variables ($[CO_2]$, $[HCO_3^-]$, $[CO_3^{2-}]$, $[H^+]$, Alk, ΣCO_2) of the carbonate system are governed by the relations (4) to (7) which, by the way, also determine the $[H^+]$, i.e. the acidity or p_H. By measuring two variables, e.g. ΣCO_2 and Alk, one may calculate the other four. This way we may, for example, assess $[CO_2]$ in surface water and through above (1) calculate the predicted p_{CO2} in surface water. Latter value is more often than not above or below the p_{CO2} in the atmosphere, i.e. there is no equilibrium distribution between atmosphere and upper ocean. For example, most cold Northern waters are undersaturated, whereas warm equatorial waters are generally oversaturated (figure 7.3). Fixation of CO_2 by plankton growth also leads to undersaturation.

Addition of CO_2 to seawater does take place in the deep sea by respiration of dissolved and particulate organic matter:

$$\text{Organic Matter (HCOH)} + O_2 = CO_2 + H_2O, \tag{8}$$

and yields a higher value for ΣCO_2, which then causes shifts in all above equilibria. Curiously enough, the higher CO_2 content eventually leads to a lower $[CO_3^{2-}]$ concentration. This is understood by looking at (7), where at higher ΣCO_2 (6) the constant Alk can only be accommodated by shifting in the direction of a lesser charged $[HCO_3^-]$ ion. This is exactly what happens in the deep ocean: deeper or older water has a higher ΣCO_2 but a lower $[CO_3^{2-}]$ concentration. At greater depth this concentration is below the Solubility Product (SP) of calcium carbonate

$$SP_{(CaCO3)} = [Ca^{2+}][CO_3^{2-}] \tag{9}$$

and the calcite shells tend to dissolve. The well-documented $CaCO_3$ distribution in the surface layer of marine sediments [66, 23] indeed shows a distinct horizon above which $CaCO_3$ is well preserved, whereas virtually no $CaCO_3$ is found in sediments below that horizon. With increasing age, i.e. increasing ΣCO_2 content and lower $[CO_3^{2-}]$, of the deep water, this horizon shoals from depths around 3.5 km in the North Atlantic to about 1.2 km in the North Pacific Ocean.

On the potential for buffering by calcite

Upon sinking into the deep ocean, the newly formed deep water will in the future contain more and more CO_2, and hence will have a lower $[CO_3^{2-}]$ concentration. The subsequent conversion of organic matter (see above) within the deep waters is assumed to be rather similar in both the current and the doomsday ocean, i.e in both cases an extra amount of CO_2 will be added to ΣCO_2, and the $[CO_3^{2-}]$ will drop accordingly. Overall, the deep water of the future ocean will have a lower and lower $[CO_3^{2-}]$ concentration. This now would lead to more intense calcite undersaturation, i.e. more extensive dissolution of $CaCO_3$ from surface sediments:

$$CaCO_3 = Ca^{2+} + CO_3^{2-}, \qquad (10)$$

where concurrent shifts in the equilibria (4) to (7) would yield readjustment, notably of p_H.
It might be argued that, overall, the addition of CO_2 from fossil fuels will thus simply be buffered by dissolution

$$CaCO_3 + H_2O + CO_2 = Ca^{2+} + 2\,HCO_3^-, \qquad (11)$$

of calcite sediments. With a known reservoir of fossil fuels of 7000 to 10,000 Gt C (of which about 1000 Gt C as petroleum), it appears that the equivalent of CO_2 can be easily compensated for by dissolution of the same 7000-10,000 Gt C of calcite, only a tiny fraction of the total 50,000,000 Gt C in calcite sediments (figure 7.1). Eventually, a new quasi-equilibrium state would be reached, with the CO_2 content of the atmosphere still about twice the current one (600×10^{-6} atm, according to [84, 53]), higher total CO_2 content (e.g. some 20,000 Gt C above the current 40,000 Gt C) and Ca^{2+} content of ocean waters. This doubling of the atmospheric CO_2 is still troublesome but is otherwise the most optimistic scenario. This mass balance or budget approach is in itself not incorrect. However, in order to be effective it requires a very well-mixed atmosphere/ ocean/ sediment system, as to accommodate reaction rates as fast as the rate at which we are now adding fossil fuel CO_2 to the atmosphere.

7.1.5 Emissions of CO_2 are faster than the oceans' capacility to respond

Virtually all fossil fuel will eventually be easily absorbed again within the oceans and, judging from the mass balance alone, there would be no fossil fuel CO_2 problem. However, the natural processes are slow, and meanwhile the atmospheric CO_2 and global temperature will rise dramatically.
The key to the CO_2 greenhouse problem lies in the turnover rates in the geosphere-biosphere system (figure 7.5). Upon introduction into the atmosphere from a car exhaust or smoke stack, the CO_2 within the Northern hemisphere is homogenised within time scales of days or weeks. Mixing of air between the Northern and Southern hemispheres takes several months to a year, hence the p_{CO2} in the Southern hemisphere lags slightly behind that in the more industrialised Northern hemisphere. Surface waters of the ocean need about one year to equilibrate their CO_2 content with that of the atmosphere. It takes several decades for this surface water signal to penetrate into the underlying thermocline region of several hundred metres depth. The real formation of deep water (by sinking in polar regions) and downward transport of associated CO_2 takes several centuries to about one millennium. The majority of ocean water has not been at the surface for more than 500 years, i.e. it was already submerged before CO_2 was discovered, Galileo entered into a trivial debate or Columbus sailed to the Americas.

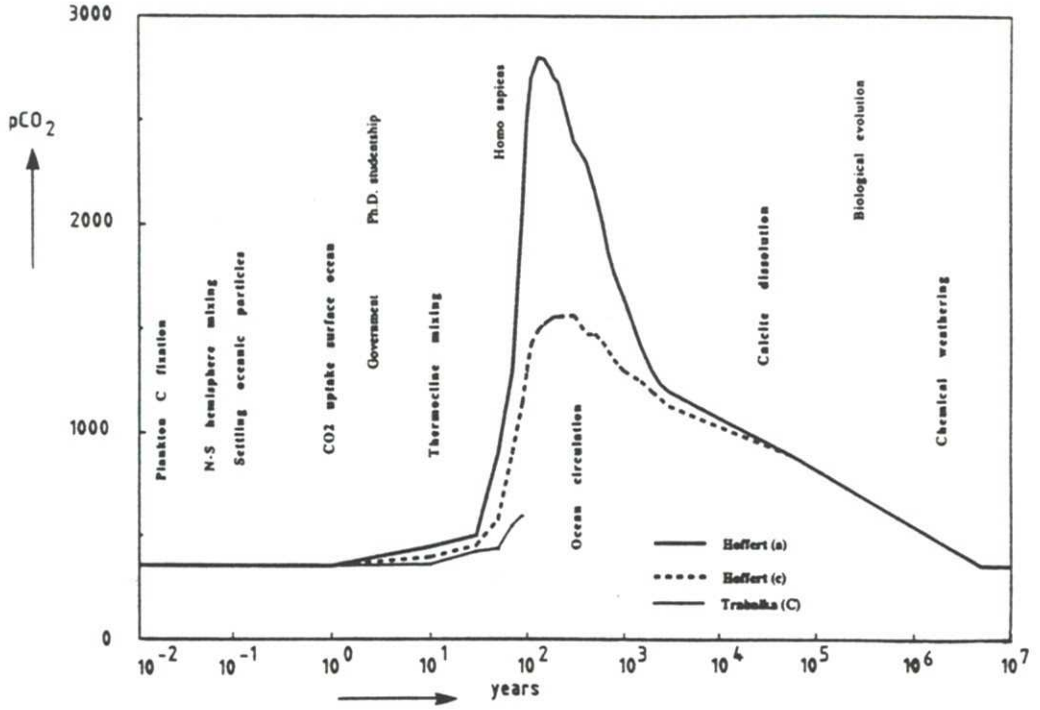

Figure 7.5 Sketch of the typical time response of the geosphere-biosphere to the rapid emission of fossil fuel CO_2. The logarithmic horizontal axis covers the range from one month (0.1 year) to 10 x 10^6 (10^7) years. The logarithmic vertical axis for the predicted atmospheric CO_2 level where actual values are omitted: the curves shown are only indicative of trends and definitely not meant to be taken as accurate absolute values. The first two curves are the scenarios (a)and (c) by ***Hoffert*** *c.s. [54], as shown in figure 7.9. The third curve is the low emission scenario (C) of* ***Trabalka et al.*** *[111] as inspired by the work of* ***Lovins c.s.***

Only a very small portion of the huge $CaCO_3$ reservoir is exposed at the surface of deep-sea sediments available for dissolution, which would in itself also be slow. The response time of this final dissolution step is estimated to be at least 10,000 years, if not much longer [105]. Over even longer, geological time scales of millions of years, the ocean/atmosphere C budget may be further readjusted by shifts in the chemical weathering of continental rocks (figure 7.5), as has happened in the past [12]. Higher atmospheric CO_2 levels lead to enhanced chemical weathering, which removes CO_2 from the atmosphere, a negative feedback loop which, however, takes effect extremely slowly. Evolutionary adaptation of the biosphere also operates in the 100,000- to 1,000,000-year time scale, i.e. the current rate of change will lead to catastrophic extinctions and an overall much lower species diversity. Otherwise, such long time scales are irrelevant for supporting policy decisions with time scales ranging from 4 years (lifetime of a government or a graduate studentship) to a century (lifespan of Homo sapiens). Similarly, for predictive models of the greenhouse effect in the coming 5,000-10,000 years, the calcite buffering can be neglected altogether.

The marine biological pathways have a more promising response. The turnover rate of plankton in the surface ocean is in the order of days (as opposed to about ten years for land plants). The overall marine biomass of about 4 Gt C may be modest compared to land plants (600 Gt C); the annual marine turnover of 50-100 Gt C/a (gross primary production), however, is significant. From all C fixed by marine photoynthesis, some ten percent settle out of the euphotic zone into the deep sea. Within one month after a plankton bloom, such material arrives at the sea floor. Better assessment of marine primary carbon fixation and the ensuing settling flux of C into the deep sea is another focal point of the JGOFS study.

Various models based on these typical time constants generally predict for a given fossil fuel CO_2 input, that the oceans will continue to slow down the atmospheric CO_2 buildup in the first several hundred or thousand years [98, 23].
Assume a constant input of 5 Gt C/a, of which currently 3 Gt C/a is taken up by the oceans. If the latter uptake is dominated by biological processes, it may well remain at about 3 Gt C/a; if it is dominated by chemical dissolution, then the ocean uptake will be sharply reduced in the future. For policy decisions on curtailing CO_2 emissions, accurate predictive CO_2 models over the decade to century time scale are important. Improved accuracy of such predictive models of atmospheric CO_2 can only be achieved by an improved quantification of biological versus chemical CO_2 uptake by the oceans.
Adjustment of the above time constants will yield a different dynamic response within the critical 10- to 1,000-year time domain. Yet eventually, after say 5,000 years, all such models will converge (for a given CO_2 input) to similar final steady-state values for atmospheric p_{CO2} and CO_2 stored in ocean waters.

7.2 Science fiction: from slow-motion ocean to high-tech turbo marine machine

From the above, we realise that the ocean can and will (eventually) take up almost as much CO_2 as we want. So there would not be a CO_2 greenhouse problem if it were not for the fact that the ocean mill is grinding along so extremely slowly. Why not crank the old water body up to an acceptable twentieth-century pace, shifting from one revolution per 1,000 years to the desirable number of revolutions per minute of any properly engineered machine?

We learned that the ocean operates four 'pumps' for bringing CO_2 down. Three of these pumps are driven by photosynthesis; so by speeding up photosynthesis, one might speed up the pumps. Pump number four brings CO_2 down along with downwelling water. Why not bypass this and all other sluggish pumps inherited from the old days? We will build our own, bigger and better, and literally pump CO_2 directly down the tube into the deep, dark ocean.

7.2.1 Cranking up photosynthesis

Photosynthesis means the utilisation of light energy to affix inorganic CO_2 onto live plant material. In the central regions of all oceans (the gyres), photosynthesis of tiny algae is limited, not by lack of light or CO_2, but because stores of essential chemical elements, notably nitrogen and phosphorus, and possibly iron as well, are quickly running out. Addition of these nutrient elements to the 'oligotrophic' gyres would enhance photosynthesis.

The extra fixation of CO_2 may, however, mostly be counteracted again, as animal respiration or bacterial decay is known to convert most of the plant material to CO_2.

Fertilisation with nitrogen or phosphate

When faced with environmental problems, the interested public often combines its awareness of the CO_2 problem with the eutrophication problem in many industrialised countries: "Would the eutrophication of the sea not counteract the CO_2 input, or can we not add extra fertilisers to the ocean?"

Eutrophication of coastal seas and embayments (e.g. the Baltic Sea, the North Sea, Chesepeake Bay) is a serious problem indeed, where blooms of algae have become more common. However, it is very much restricted to coastal waters with little impact on the overall standing stock and C fixation rate of the world's seas. More importantly, it is known that virtually all of the extra C stored in algae is quickly respired again by grazing zooplankton or bacterial decay. Within time scales of weeks or at most months, the extra stored CO_2 is released again into the seawater, and, because shallow coastal seas are extemely well mixed, back again into the atmosphere [127]. Eutrophication is a major problem in its own right, yet its impact on the global C cycle is negligible.

Broecker (1977) [20] prepared a manuscript on the intentional fertilisation of the oceans with the essential nutrients phosphorus and nitrogen. (It is worthwhile to observe that the paper was never published). The central gyres of all oceans are nutrient-depleted and the ecosystem is considered very poor, or oligotrophic. Whenever there are nutrients, the algae in the ocean fix C, N and P in a relative ratio which is remarkably uniform at about

$$C : N : P = 106 : 16 : 1.$$

Thus, in the optimum scenario the 5 Gigaton C to be stored annually would require spreading about 0.9 Gt/a elemental N and 0.1 Gt/a elemental P evenly over the low productivity (N- and P-starved) central regions of all oceans. Taken as ammoniumnitrate and some form of phosphate, the actual weights would be higher at about 2.5 Gt/a N fertiliser, or at least 0.4 Gt/a P fertiliser. This would require a huge demand on the world supply of fertiliser, in the order of 40 percent. When assuming that half of the fossil fuel fuel CO_2 would naturally be absorbed by the oceans, there remains 2.5 Gt C/a left to take care of, requiring at least 1.2 Gt/a and 0.2 Gt/a of fertiliser. This also assumes 100% efficiency of the oceans' biological pumps. However, in 7.1 we have seen the complexities of the surface ocean ecosystem, which as a whole most likely would not be able to utilise all added nutrients for the downward transport of CO_2 out of the euphotic zone into the deep sea. At less than 100% efficiency the amount of fertiliser to be added would increase accordingly.

Growing and harvesting algae in tanks or ponds

Several groups of marine and freshwater photosynthetic microalgae have the potential of growing very rapidly under optimal conditions of light availability, supply of micronutrients, and temperature. By manipulating the latter conditions within a controlled pond or tank, it would appear feasible to fix substantial amounts of CO_2. The resulting algal biomass may be stockpiled as a way of removing CO_2 from the biosphere. Alternatively, the biomass can be converted into fuel; here the anaerobic fermentation to methane (CH_4) would be an obvious process as subject of a feasibility study. By using the methane thus produced as a biofuel, the corresponding amount of natural gas methane could be saved, and the fossil fuel CO_2 input from burning gas would thus be reduced (energy farming, see chapter 5).

Currently available knowledge and technology were recently reviewed by **Braun** (1991, [135]). Briefly, there are several large-scale development projects known for algal production facilities, most of them being pursued for other reasons, for example for producing algae as a food supply for fish. Notably, in Japan there are several examples of this approach, where next to the use of ponds there are also efforts towards developing solar reactors.

Obviously this approach is somewhat outside the oceanic realm, hence outside the scope of this chapter. Nevertheless, a separate study of its feasibility might be useful. However, one word of caution must be expressed. Just as in the natural oceanic or freshwater systems, the algae would need not only CO_2, but also nitrogen (N) and phosphorus (P), as well as some other micronutrients to grow. When contemplating algal cultures at significant scales, i.e. fixing CO_2 at rates of 1 or more Gt C per year, one has to provide corresponding amounts of fertilisers. This problem has already been addressed in the above sections on fertilising the oceans but applies equally to controlled ponds or tanks.

Iron as the ultimate remedy?

In the Antarctic Ocean there are plentiful nutrients available, yet the algae are not using them. Do the algae lack iron, another essential element? If so, man can fertilise the Antarctic with iron to enhance algal growth, thus fixing fossil fuel CO_2.

Recent experimental evidence tells us, however, that iron is after all not the factor limiting biota in the Antarctic ecosystem; hence fertilisation with extra iron would have little or no effect.

We have seen that the central regions of all oceans are extremely depleted in the nutrients nitrate and phosphate. Apparently the algae are able to utilise these nutrients to complete exhaustion. This implies that other factors, e.g. light or CO_2, are not at all limiting algal growth. However, there is one major region with 'abnormally' high nutrient concentrations in the surface waters: the whole Antarctic or Southern Ocean. Apparently, the algae there are limited by some other factor and are thus prevented from fully exploiting their resources of N and P. The abundance of nutrient elements, being contradicted by the very low-standing stock of phytoplankton, is known as the 'Antarctic Paradox' and has been puzzling scientists for several decades. The issue is particularly important for understanding polar ecology. In contrast with other continents, there are virtually no land plants on the Antarctic continent. South of the polar circle, all life is ultimately supported by algae growing in the seas, where the algae somehow appear to be rather ineffective.

Presumably something is amiss in these Antarctic waters. Many factors have in the past been suggested as the missing link. Shortage of light seems a reasonable hypothesis, given the extensive ice cover most of the year, as well as the long dark winters. The low temperature below zero centigrade of the seawater may also lead to slow metabolic rates. Intense grazing pressure has often been observed: the swarms of Antarctic krill are known to be able to clear away algae very effectively, in one sense like swarms of crickets which can ravage tropical regions on land. On the other hand, the availability of trace constituents essential for growth, like vitamin B12, manganese or iron may be inadequate. **Gran** (1931) reflected on high nutrient levels in the Weddell-Scotia Sea as reported by **Ruud**

(1930) by stating "that the growth of the plankton diatoms is determined by other factors than the concentration of phosphates and nitrates, besides light and temperature" and in the very same paper casually mentions his own work elsewhere on iron limitation. Shortly afterwards, **T. John Hart**, B.Sc. (1934) published the impressive monograph on the plankton of the Southwest Atlantic and the Bellingshausen Sea (1929-1931). Within the 196 pages of the now vintage Volume VII of the Discovery Reports, he only dedicates one brief section to the possible limiting role of iron. Since then there have been numerous studies on the role of iron in marine ecosystems. However, **De Baar et al.** (1990, [130]), in their review, suggest that for a long time the analytical methods and experimental techniques were inadequate for working at the extremely low levels of iron now known to exist in seawater. For example, only recently **Martin et al.** (1982, [140]) were the first to report reliable concentration data for Fe in seawater, where levels are at or around 1 nM per litre*.

With the ultraclean methods that are finally available, the field of research on iron-biota interactions is now opening up. In 1988, two independent research teams provided convincing experimental results, suggesting that in the Subarctic North Pacific Ocean the addition of nanomolar amounts of iron actually stimulates phytoplankton growth. The subarctic North Pacific is an area where there is quite some nitrate and phosphate left in the surface waters, i.e. these elements are apparently not limiting factors. In three of the four experimental runs, the control experiment (without extra Fe addition) did not show growth, suggesting that iron is truly a limiting factor - although this conclusion has recently been challenged (**Banse**, 1990, [134]). In the fourth of the experimental series, iron was found to stimulate algal growth. However, the untreated control still grew very well, i.e. there was apparently enough iron available to sustain at least minimal growth.

Nevertheless, there has repeatedly been ample speculation about iron also being a limiting factor for the whole of the Southern Ocean, but none of the published papers provides any supporting evidence.

First experimental test of Antarctic iron limitation

From November 1988 to January 1989, scientists participating in the European Polarstern Study under the auspices of the European Science Foundation executed research in the Weddell and Scotia Seas. The multidisciplinary team focused on the above 'Antarctic Paradox'. Within this context, De Baar et al. (1989, 1990, [30]) ran the first experiments testing the repeatedly publicised hypothesis that iron may be limiting Antarctic biological productivity. In a suite of five experimental runs, they clearly demonstrated that iron always stimulated plankton growth (figure 7.6). However, in the same experiments the controls always grew steadily, eventually outgrowing the chlorophyll a levels (i.e. standing stock of phytoplankton) observed in the field. The conclusion was that although iron is a factor in stimulating growth, a lack of it is not the single factor limiting growth in the Scotia and Weddell Seas, a significant part of the overall Antarctic ecosystem. The same group also measured dissolved iron in the ambient seawater, and found levels ranging from 1.5 to 7 nM in the surface waters [128]. This is low, but still an order of magnitude higher than reported for the North Pacific region, where iron was suggested to be a limiting factor [129]. Apparently, at levels of Fe near or below 1 nM, true limitation might occur in ocean waters, provided of course

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* nM = nanomol; 10^{-9} mol/litre

that the abundance of nitrate and phosphate is not too low. **Nolting & De Baar** (1990, [128]) found very high levels (around 60 nM) of dissolved iron in the vicinity of the South Orkney Islands, and they suggest that the sediments in these shallow regions may be a major source of iron for the surface waters. In other ocean areas it is after all well-documented that shelf sediments are a major source of dissolved iron.

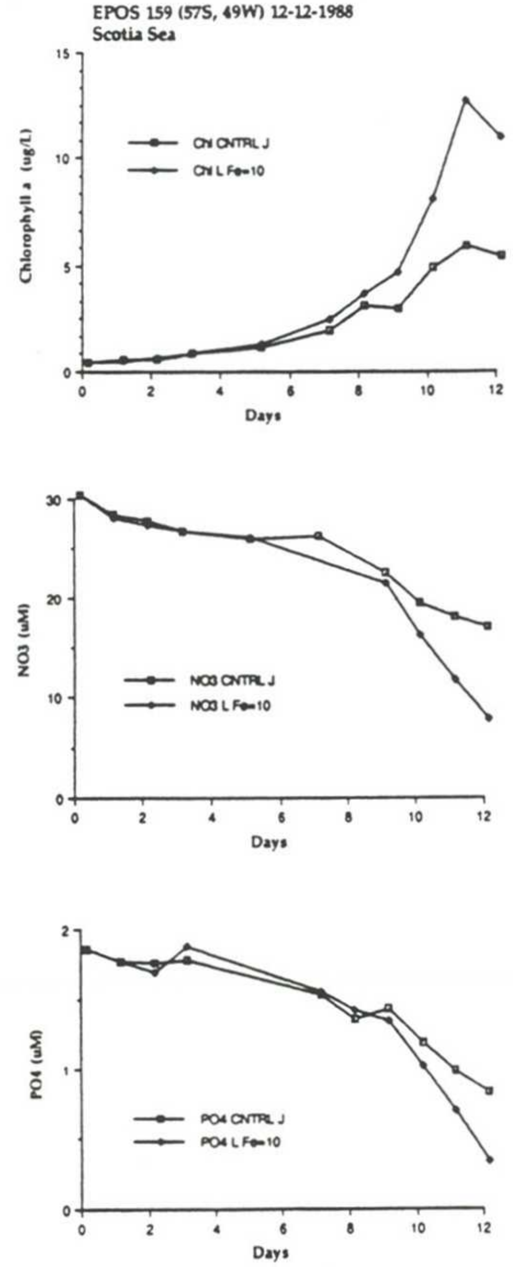

Figure 7.6 The growth response to additions of dissolved iron of phytoplankton as measured by increasing Chlorophyll a and decreasing the nutrients nitrate and phosphate. Experiments in waters from the Scotia Sea in the Antarctic Ocean. Clearly the algae are stimulated by the added iron; however, the control experiments also grow very well, indicating that iron is by no means the limiting factor for the Antarctic ecosystem. Taken from De Baar et al., [130] (1990)

Yet the problem remains that the nutrients nitrate and phosphate are not being utilised in the Scotia and Weddell Seas. Other factors as mentioned above obviously deserve further investigation. In analogy, one would expect that in other parts of the Antarctic Ocean, iron will not be the limiting factor either. However, until experiments have also been executed in more remote regions of the Antarctic Ocean, it cannot be ruled out that in those offshore waters iron might occasionally become a limiting factor for plankton growth.

Efficiency of iron fertilisation

Not being hindered by the absence of any experimental evidence, it was taken for granted by some investigators that iron is a limiting factor for plankton growth in the Antarctic ocean. This has led to some esoteric scenarios for fertilisation by mankind (**Davies**, 1990, [141]; **Anonymous**, 1990, [144]) which, with the first evidence now available [130], can be characterised as science fiction. It has been estimated (**Anonymous**, 1990, [142]) that 260,000 tons of iron need to be deposited annually in the Southern Ocean:

"Although 260,000 tons sound like a large number, our largest ships - ultra large crude carriers - have deadweight capacities of 550,000 tons; thus one shipload a year of Fe would suffice. The trick however is to figure out how to apply about 70 micrograms to each of the $2x10^{13}$ square metres each day for six months".

This action plan appears rather farfetched. In the light of the above experiments, it is clear that in many areas of the Antarctic Ocean, iron does not limit biological production, whereas in other regions such limitation seems most unlikely. Extra fertilisation with iron would thus appear fruitless and uneconomical, apart from the issue of the assumed right and ability of mankind to modify and control the fascinating Antarctic ecosystem.

In the view of widely publicised speculation, the American Society for Limnology* and Oceanography organised a special symposium held in February 1991 in order to review the available evidence in a more responsible manner. The proceedings of this symposium will be published as a special volume of the journal *Limnology and Oceanography* (**Chisholm and Morel**, 1991, [133]). From the various contributions, it has become clear first that iron does play a role in the marine ecosystem, and second that the intentional fertilisation of the Southern Ocean appears a fruitless scheme. Reasons for rejecting latter approach can be summarised briefly (e.g. **Buma et al.** 1991, [132]):

1. Assuming a control of phytoplankton by grazers, the effect of iron fertilisation for the purpose of atmospheric CO_2 reduction would be rather trivial, at best leading to an enhanced but certainly non optimal utilisation of phosphate in surface waters during the growth season. This is the prime reason for expecting that intentional iron fertilisation would have little or no effect, i.e. would be uneconomical.
2. The amount of iron to be added would have to be much higher than the calculated ratio Fe : P : N : C = 0.001 : 1 : 16 : 106. The low efficiency of the ecosystem in exporting carbon to deep waters (i.e. ratio of export/primary production) as well as the effective removal of dissolved iron from surface waters would necessitate much larger iron supplements than assumed above Fe : C = 1 : 106,000 for the CO_2 to be brought down.

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* Science of fresh water areas (lakes, rivers, etc.)

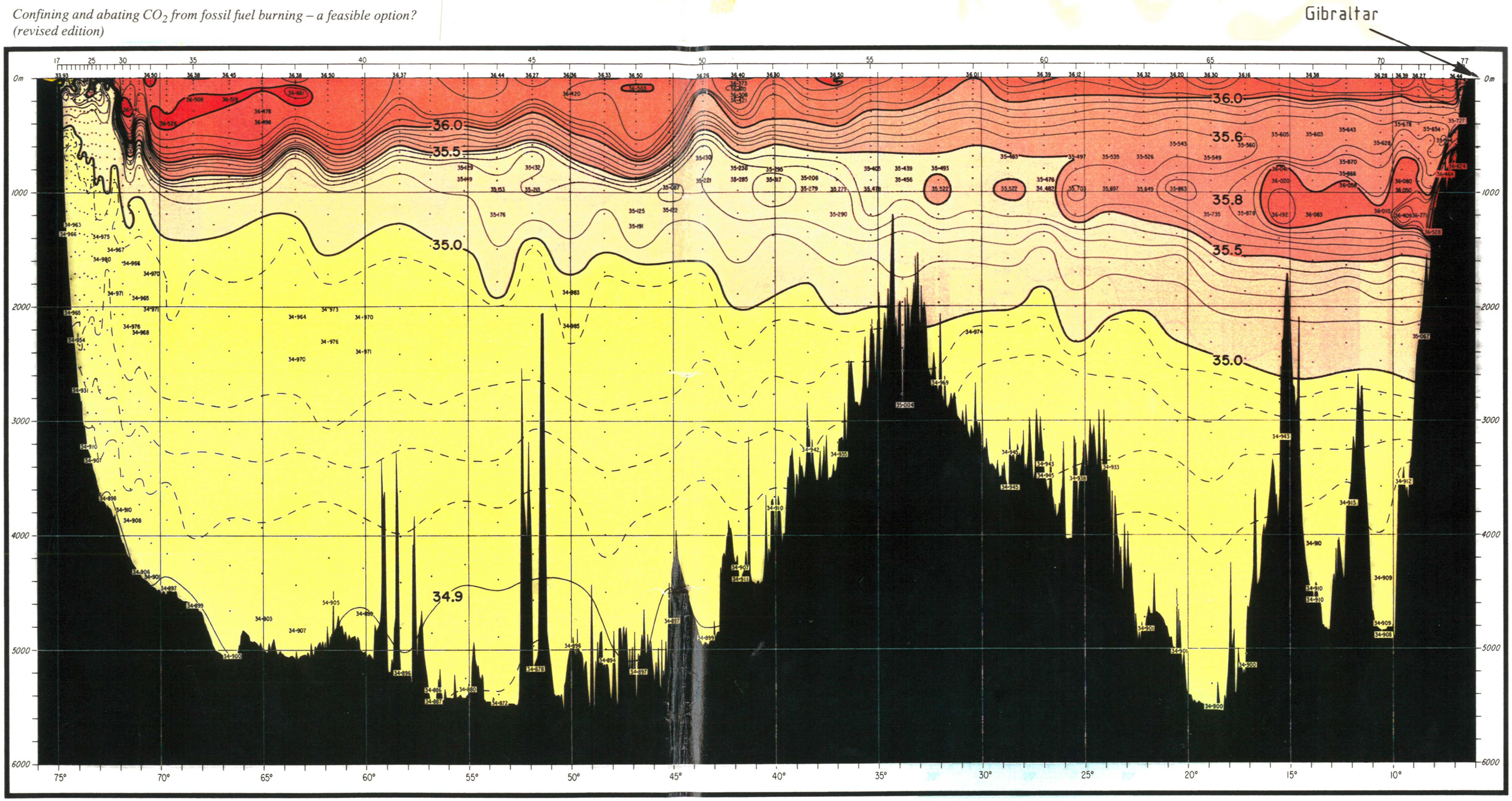
3. Even if it had been possible to bring down nutrients and CO_2 in the above proportion (i.e. negate above 1. and 2.), model calculations have shown the effect on the atmospheric CO_2 budget to be modest at best [136,137].

Ecological impact of ocean fertilisation
In the long run, a higher overall primary productivity accompanied by a higher rate of transport of organic matter into the deep sea will lead to a greater conversion (oxydation) of organic matter in the deep sea. The oxygen minimum, now existing at several hundred metres depth throughout the world ocean would increase [91]. On average, a larger proportion of the organic matter would escape such regeneration and become buried in the deep-sea sediments. Overall, the storage of organic C in sedimentary reservoirs would increase, though at a very slow rate that is compatible only with geological time scales. Eventually, the CO_2 content of the atmosphere would again decrease. In retrospect, the geological record over the past 100,000 or more years has indeed shown that periods of high oceanic productivity are characterised by low atmospheric CO_2 levels, and vice versa (**Berger, Smetacek and Wefer**, 1989, [143]).

7.2.2 By-pass operations: from smoke stack into deep ocean

"Biology and photosynthesis is kind of nice, but generally beyond the scope of technocracy. Why not use the same engineering which caused the problems to solve them: build scrubber plants, strip all CO_2 from the stackgas, compressors will then scuttle it along overland pipelines to offshore installations and down the tube into the deep ocean, never to be heard of again. Did we not build the Panama Canal, the Titanic, the space shuttle and Three Mile Island? We can do it, cannot we?

Dumping down the Gibraltar Falls
Marchetti [70, 71] proposed collecting CO_2 effluent at large point sources (primarily power plants), transporting it by pipeline and disposing of it by injection into natural deep-sea currents, notably the Mediteranean Outflow Water (MOW). Near Gibraltar it would be possible to pump the CO_2 into relatively shallow water flowing out. Just beyond Gibraltar, this water is known to cascade down to about 1200 metres depth, and then to spread laterally in the North Atlantic Ocean (figure 7.7).
In fact, large point sources like power plants account for less than one quarter of total fossil-fuel-related CO_2 flux (the remainder largely consisting of diffuse sources, such as traffic, industries and built-up area). Shifting to other energy carriers (H_2, electricity,) for traffic and transportation has been suggested in order further to centralise the CO_2 emission points beyond the current percentage [70]. Otherwise, the assessment by Marchetti of cost and technical problems is grossly optimistic and hypothetical compared to the assessments below of **Baes c.s.** and **Steinberg c.s.** Finally, the Mediterranean Outflow into the North Atlantic does indeed sink to depths around 1200 m beyond Gibraltar. However, its distribution and mixing pattern within the North Atlantic and beyond warrants large-scale atmosphere/ocean ventilation of MOW within decades after leaving Gibraltar, notably in the Equatorial Atlantic region and along the coast of West Africa. At best, about half of the CO_2 thus injected would still be released into the atmosphere, some 50-200 years later.



36° N.

SALINITY ‰

April 19 - May 12, 1959, CHAIN stations 17-77.
North Carolina to Spain.
Mean latitude, 36° 15′ N.

0 500 Kilometers

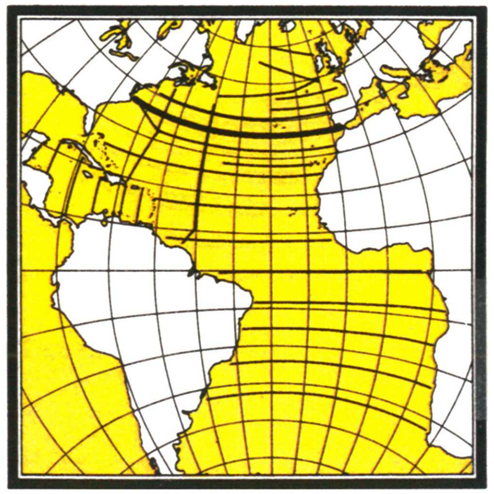


Figure 7.7 UPPER Vertical section in the North Atlantic Ocean running westward from Gibraltar along the 36° N

Pumping into the black abyss
Similarly, injection into the Iceland-Greenland (Denmark Strait) and Iceland-Scotland Overflow deep currents [121] would contribute to the deeper, and southward-flowing North Atlantic Deep Water (NADW) complex. Part of this complex is the Western Boundary Under Current (WBUC), flowing southward at great depth along the eastern seaboard of the USA. The WBUC is another deep-sea current, suitable for CO_2 injection. Part of this NADW or WBUC will, due to equatorial Atlantic upwelling, contact the atmosphere again; yet a large portion will remain at depth flowing southward towards the Antarctic Ocean. A substantial portion will indeed continue to flow around the Antarctic into the deep Pacific and Indian Oceans and will remain submerged for a period of up to 2000 years. Yet gradually, more and more of this water will also emerge at the surface and release its excess CO_2. The World Ocean Circulation Experiment (both field work and modelling) now starting will provide us with more reliable estimates of the time scales involved; yet on average the NADW will need several decades before reaching the surface again. Most of the CO_2 thus injected will be released into the atmosphere with a delay in the order of 200-500 years.

The Oak Ridge National Laboratory group around **C.F. Baes** produced a series of papers [6, 7, 8, 55], devising several schemes all based on initial collection by scrubbing power plant stacks with monoethanolamine (MEA) and transport of compressed (150 atm) CO_2 in pipelines (figure 7.8). Large US power plants account for only 30% of US CO_2 output, or 10% of global CO_2 emissions. Several options for final disposal in the oceans were suggested:

a. High-density solution in seawater; the reject stream would sink to the ocean floor.
b. Emitting pure, liquefied CO_2 at depths greater than 3000 m in order to be negatively buoyant (i.e. sinking) relative to ambient seawater. A large pool of liquefied CO_2 would remain dormant on the sea floor.
c. Dumping solidified blocks of CO_2 hydrate. The conversion to CO_2 hydrate requires considerable additional energy. The blocks would sink to the sea floor and remain there.
d. Dumping blocks of solidified CO_2 (dry ice). The conversion to dry ice requires considerable additional energy. The blocks would sink to the sea floor and remain there.

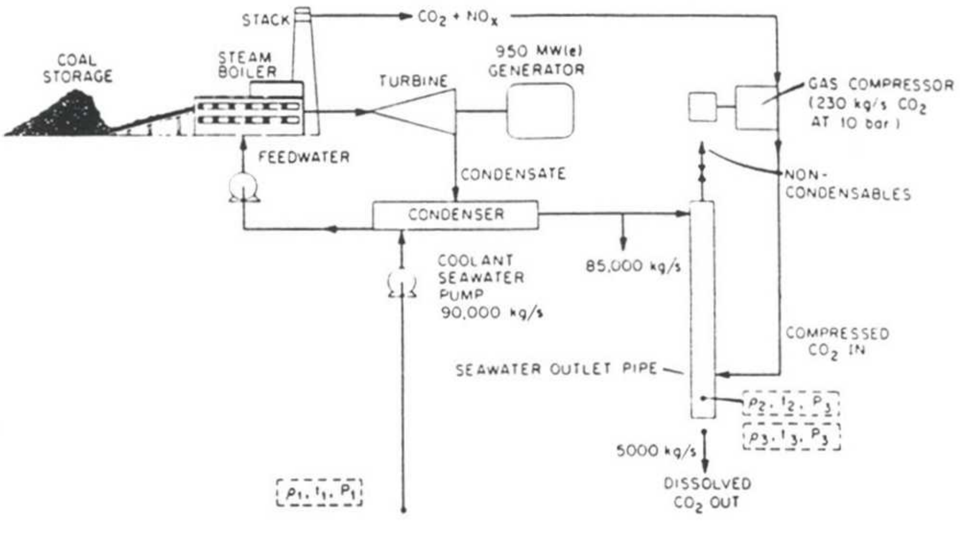


Figure 7.8 Flowsheet for a floating coal-fired power plant with CO_2 disposal to the deep (1,000-3,000 m ocean). Coal would be transported towards the plant with barges, and electricity transferred to land through cables. Taken from Baes c.s., [8]

Preferably all four physical states (phases) in discharge options a) through d) would provide long-term storage on the deep ocean floor. However, the passing ocean currents, which are undersaturated in CO_2 with respect to all of these four phases, would erode away the CO_2 piles, carrying along the erosion product in the form of CO_2 totally dissolved in seawater. Eventually, the deep water would reach the surface again and the CO_2 would escape into the atmosphere. In conclusion, all schemes of Baes c.s. would lead to a delay of several hundreds of years, as further worked out below when discussing **Hoffert et al.** and **Lysen** [54, 69].

Steinberg and his associates produced an exhaustive series of papers on solutions to the CO_2 problem [1, 11, 57, 100, 101, 102], some of them beyond imagination. For example, converting CO_2 into marketable products would yield a consumption of at best only 0.1-0.2% of CO_2 production. Also, these marketable products would within a very short time span again be released as CO_2. Their specific scheme on deep-ocean injection [1] appears the least unattractive and otherwise closely resembles the design, specifications and efficiency of the Baes et al. systems.

Only buying time

Hoffert and associates (1979) [53] tested the various deep-injection scenarios with a simple box diffusion model. The assumed (extremely high) input of 7000 Gt C over an initial time period of 150 years would be injected into the ocean in five different modes:

a. 100% into the atmosphere, none directly into the ocean
b. 50% into the atmosphere and 50 % into the ocean at 1500 m depth
c. 50% into the atmosphere and 50 % into the ocean at 4000 m depth
d. 100% at 1500 m depth
e. 100% at 4000 m depth

The outcome of the modelling as shown in Figure 7.9 further emphasises the buffer function of the oceans. The first option (no injection) is virtually identical to the greenhouse scenario of **Siegenthaler and Oeschger** [98]. By deep injection, the thermocline barrier between surface ocean and deep ocean is effectively bypassed, and in extreme option e), the normal renewal time of deep water of about 1,000 years is thus avoided when bringing CO_2 into the deep ocean. However, the same deep water renewal then also brings the injected CO_2 back up to the surface with the same 1,000-year mixing time and eventually after about 5,000 years, all five options converge to the same steady-state end value of about 1,150 x 10^{-6} atm CO_2 in the atmosphere, roughly four times higher than the pre-industrial (265±10) x 10^{-6} atm level [79] before about 1860.
We mentioned earlier that large, stationary power plants account for at most 25% of the current CO_2 production, i.e. the maximum effect of deep injection would lie somewhere in between option a and options b and c. Some 20-45% of the power output of such plants would be needed in the process, i.e. society would still have to reduce its electricity use accordingly. The peak value of the transient response in the year A.D. 2100 (figure 7.9) would exceed the 1,500x10^{-6} atm for scenario b or c.
Finally, it should be noted that the Siegenthaler & Oeschger (1978) scenario [98] for production, emission and fate of CO_2, as used by Hoffert et al. (1979), is among those with the highest CO_2 input functions. Most recent input predictions are considerably lower [131], and the resulting atmospheric CO_2 levels would also be much lower. For example, Trabalka et al. [112] would in A.D. 2075 arrive at about 1,600, 600 and 450 x 10^{-6} atm for a suite of high, standard and low production scenarios, all assuming 100% atmospheric emission.

Lysen (1989, [69]) was also invited to review the deep-sea disposal option. He observed that the input function of 7000 Gt of C in 150 years (1979) [54] might in fact be lower, partly as a result of policy measures towards reducing the burning of fossil fuels. He only assessed the final (5,000 years) steady-state value as a function of an integrated CO_2 input ranging from 200 to 7,000 Gt C., using a simplified time-independent version of the Hoffert c.s. model. For example, with a past input of about 400 Gt C (170 Gt C from fossil fuel, **Rotty and Masters**, 1985 [89]; upper limit of 150 Gt C from deforestation) and a future input of 1,000 Gt C, the integrated 1,400 Gt C addition to the ocean/atmosphere system yields a steady-state atmospheric CO_2 level of about 400 x 10^{-6} atm 5,000 years from now.

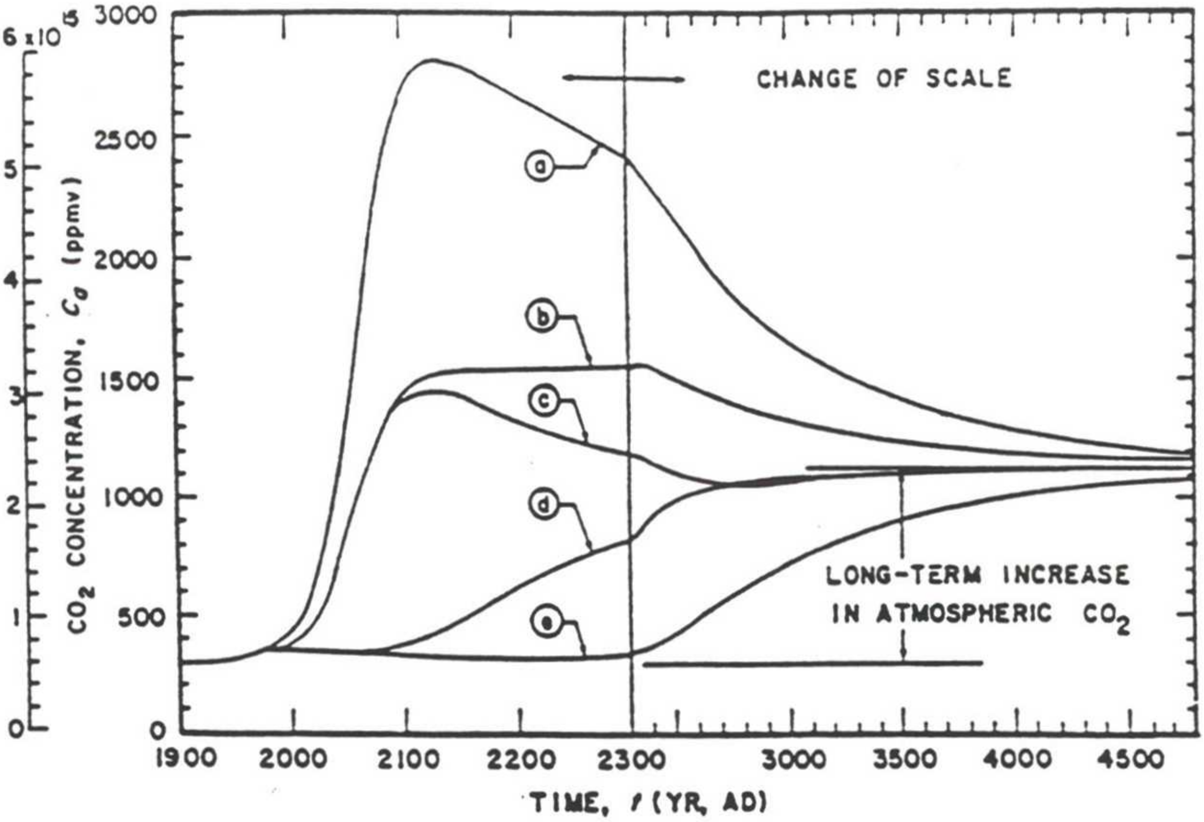


Figure 7.9 Model projections of atmospheric carbon dioxide variations, assuming entire fossil fuel CO_2 reserve is depleted as a logistic function of time:
a) 100% injected into the atmosphere;
b) 50% injected at 1500m depth into the ocean;
c) 50% injected at 4000m depth into the ocean;
d) 100% injected at 1500m depth into the ocean;
e) 100% injected at 4000m depth into the ocean.
NOTE: fivefold compression of timescale beyond A.D. 2300
Taken from Hoffert et al. [54].

The transient response has not been calculated, but it appears reasonable to assume that the peak value in the year A.D. 2100 will be reduced in a roughly proportional manner. When glancing at the Hoffert c.s. results (figure 7.9), but again realising that at best 25% (stationary plants) of CO_2 production would be injected into the deep sea, the peak, atmospheric CO_2 value in A.D. 2100 would probably still exceed 500×10^{-6} atm, roughly the typical doubling of atmospheric CO_2 commonly used as input function in General Circulation Models (GCM) for predicting global temperature (climate) response.

Ecological impact for the sea acceptable in itself

Uptake of CO_2 in seawater leads to a higher CO_2 content. This in turn will cause the concentration of $[CO_3^{2-}]$ to decrease and the acidity to increase (more acidity means lower p_H). Upon doubling of atmospheric CO_2, say in about A.D. 2040, the CO_2 content of oceanic surface waters will have increased by equilibration with the atmosphere, and consequently the p_H will have dropped. This will lead to shifts in the chemistry of seawater. For example, the availability of metals for interaction with the biota will in general increase. In the case of toxic metals (Cd, Cu), this may lead to suppression of growth and biological productivity. In the case of metals essential for the biota, e.g. Mn or Fe required for enzyme systems, the greater availability will lead to enhanced growth. Such feedbacks with dissolved substances may thus also affect the oceanic uptake of CO_2, an issue beyond the scope of this chapter. However, from this one illustration it is clear that the CO_2 greenhouse effect will, one way or another, also have its impact on the marine ecosystems. To what extent that impact can be predicted remains to be seen. Also, it will always remain debatable, even once proven, whether e.g. enhanced productivity is beneficial or detrimental. Here we will assume that any change is in itself unadvisable.

By pumping part of the CO_2 directly into the deep ocean, the environmental impact is shifted away from the surface ocean to the deep-sea ecosystem. There will be two effects:

1. slow dissolution of calcite deposits.
2. p_H shift, affecting biota living in deep waters or at the sea floor.

Dissolution of only a very small portion of the calcite deposits is considered rather harmless ecologically, and would also occur at a very slow rate. The p_H shift would again cause all kinds of shifts in chemistry of deep waters and sediments. The abundance of deep-sea ecosystems is, however, much lower than that in the surface ocean, i.e. the inevitable deep-sea shifts would be considered quantitatively less than the shifts in the ecosystem of the surface waters, in case no CO_2 were collected and pumped down.

In summary, it might be argued that pumping CO_2 down will be beneficial for avoiding of changes in the upper-ocean ecosystem.

7.2.3 Paying the bill

Baes c.s. estimate that the extraction, compression to 150 atm and transport over 40 km of CO_2 require as much as half of the energy produced, or only 1/3 if the coal is burnt in pure oxygen from an air separation plant (including the expenditure for running the plant). Alternatively, a plan was devised for building the whole power plant on a barge floating over the deep ocean, and for transporting coal, oil and electricity to and from the barge. Some 36% of the and for electrical output would be needed overall to run the barge plant itself.

Marland (1986) [72] summarises that the first two steps of all the above schemes, collection and transportation, have been investigated well and are in fact in full operation on a modest scale as commercial enterprises for using CO_2 to enhance recovery of petroleum from geological reservoirs [60, 38]. The most economical and practical methods, amine scrubbing and long-distance transport as liquefied CO_2, are operational today and are also well-understood in terms of efficiency. Some 32-45% of the combustion energy of coal would be required. Recent developments suggest more efficient operation of the MEA extraction step [14], requiring only about 15-25% of the overall energy input. This, combined with the expenditure for compression, transport etc., would make the overall energy loss somewhat lower, around 20-35%. The disposal of CO_2 into the deep sea is less well-documented, but will also require additional energy. For a more accurate assessment of cost, technical feasibility and calamity risks, one might also look at the installations of the offshore petroleum industry.

7.2.4 The best possible bypass for patient Europe

If Europe would decide on collecting CO_2 and pumping it into the deep sea, the original suggestion of disposal near Gibraltar in the outflowing Mediterranean Overflow water is the obvious choice. Europe currently contributes about 13% of the world's total fossil fuel CO_2 emission. Assuming that only 25% is produced by power plants, the European countries would at best dispose 4% of the global CO_2 emission at Gibraltar Straits. In fact it is unlikely that all European power plants will be tied into a CO_2 'drainpipe' in the foreseeable future.
However, after one or more decades, the Mediterranean Overflow Water will reach the surface again, and a large portion of the disposed CO_2 would be released back into the atmosphere. After 50-200 years, some 50% of the disposed CO_2 would enter the atmosphere anyway. In other words, the European countries would, with the 4% of the total CO_2 emission, only buy some time, at considerable expense.

Upon the remarkable but not very well-supported suggestion by Marchetti, (1975, [70]), several investigators have made an effort towards serious initial assessment of feasibility. From their combined theoretical studies, it now appears that at best, ocean injection of at most 30% of all fossil fuel CO_2 is feasible, at the expense of some 20-45% of the generated electricity, while keeping in mind that the scheme only provides a temporary delay of atmospheric CO_2 buildup. Europe alone would, in the most optimistic estimate, be able to reduce about 4% of the global fossil fuel CO_2 emission by deep-ocean dumping.
Otherwise; the collection and deep-sea disposal of CO_2 is and has never been considered a serious practical option [82, 138]. Only when other options (energy conservation, biomass burning, other energy sources, etc.) are even less attractive will some further study and pilot-plant experiments be relevant.

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8 The role of forests

(P.M. Esser and S.G.L. Michon)

This part of the study is focused on possibilities of binding CO_2 by reforestation, or the prevention of deforestation in the broadest sense of the word, respectively. Particularly long-term storage of carbon in biomass is mainly represented by forests.

With solar energy, green plants convert CO_2 and water into sugars and O_2. This process is called photosynthesis. The sugars are the components of cellulose, hemicellulose and lignin. 90 to 99% of trees and wood consist of these three components [8].
The proportion of the chemical elements constituting wood differs only slightly in the various species of wood. The average weight percentages of the elements (in dry wood) are 50% carbon, 43% oxygen, 6% hydrogen and 1% other [8].

The storage of carbon stored in forests and in wood can be realised in a number of different ways:

1. direct storage
   - reforestation and afforestation,
   - finding new applications of non tropical woods,
2. indirect storage
   - prevention of deforestation,
   - extension of the average lifetime of wood in service,
   - replacement of tropical wood by non tropical wood,
   - reuse of wood.

In this context, it should be remarked that the exact influence of the combination of acid rain and the increase of the level of CO_2 in the atmosphere on carbon binding is not yet known. Studies on this subject might be of considerable importance.
Air pollution and acid rain go together. It is probable that both will increase in the future. It is well known that acid rain is harmful to forests and that it causes a decrease in growth rate. This decrease in growth rate, however, does not affect the quality of the wood as timber. On the other hand, the increase of the level of CO_2 in the air may have a positive effect on the growth rate of trees [9].

8.1 Present situation of forest area and trade of wood

8.1.1 Forest area

The present total area of world's forest is approximately 3 Gha [13,14]. Two-thirds of this area is exploitable. In table 8.1 and figure 8.1, an overview of the distribution of the world's forests has been given. The largest areas of forest are found in the Soviet Union and Latin America (about 25%). North America and

Asia have somewhat less (about 16%). The total amount of carbon stored in this 3 Gha of forest is estimated at 435 Gt [19] to 475 Gt C [2].

The forest area in the developed countries has been stabilised at 1.6 Gha [14]. The area in the developing countries, however, is rapidly declining. It is estimated that 10 to 25 Mha of tropical forest is now vanishing each year [12,13]. This is equivalent to 2.3 - 5.6 Gt C. These values are based on an estimated carbon content of 225 t C/ha [2]. Only a part of this carbon is stored in wood (diameter > 7 cm).
The causes of the deforestation are [10]:

conversion of forest into farmland	79%
logging of trees for fuel wood	8%
logging of trees for the benefit of grazing cattle	6%
logging of trees for industrial wood	6%
infrastructure	1%

Table 8.1 presents the distribution of the forest area over the world.

Table 8.1 The distribution of the forest area over the world [13]

	Forest area (Mha)	
North America	531	
(US)		(267)
(Canada)		(264)
Latin America	740	
Africa	215	
Asia (excl. Japan)	470	
Japan	25	
Oceania	88	
Europe (excl. SU)	145	
(Northern Europe)		(52)
(EUR12)		(43)
(other European countries)		(50)
Soviet Union	792	
World	3006	

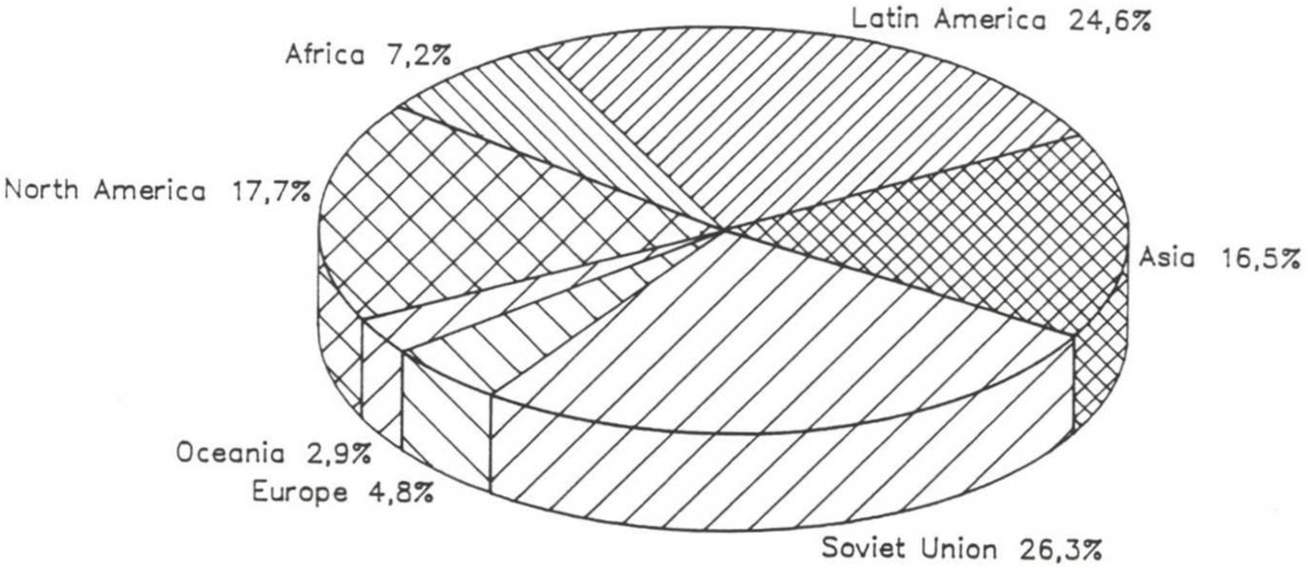

Figure 8.1 The distribution of the forest area over the world (total 3 Gha) [12]

The total forest area in EUR12 is 43 Mha [1, 5, 13]. This is only 1.4% of the total forest area. The carbon stored in these forests is estimated at 6.5 Gt.
The forests in EUR12 consist of coniferous woods (41%) and non-coniferous woods (59%) [5]. The most important timber species in EUR12 are: fir, pine, douglas fir, oak, beech and poplar [5]. The mean annual production of biomass of these timber species is 7.1 t C/ha/a. The individual production values per species are given in table 8.4.

8.1.2 Trade of wood

The total production of wood in the entire world is estimated at 3.3 Gm^3 per year [13]. This corresponds with 1 Gt C (0.2% of the total carbon stored in trees).

As far as the application of wood is concerned, the worldwide production can be subdivided into the following four categories [14]:

fuel wood	52%	(0.52 Gt C)	
sawn wood	29%	(0.29 Gt C)	0.48 Gt C
pulp	12%	(0.12 Gt C)	
other	7%	(0.07 Gt C)	

The total wood production for fuel is used within a year after it is produced. This implies that only 0.48 Gt C of the total production is stored in wood for a period longer than 1 year.

The total production of wood in EUR12 in 1988 was 126 Mm^3 (0.038 Gt C) [6]. This is 3.8% of the total world production (table 8.2). The production of wood from the separate EUR12 member countries and from the different tree species is given in table 8.3 [5].

Table 8.2 The production of timber

	Timber production (Mm^3)	Carbon stored (Gt)	Percentage of total stored in forest
World	3,300	1	0.02
EUR12	126	0.038	0.0008

Table 8.3 The production of wood of the separate EUR12 members and of the different species of trees [5]

TOTAL PRODUCTION OF WOOD

II C 1

PRODUCTION TOTALE DE BOIS

without bark 1000 m³ sans écorce

YEAR ANNÉE	EUR 12	EUR 10	B	DK	D	GR	E	F	IRL	I	L	NL	P	UK
CONIFEROUS RAW WOOD Firs, spruces, douglas firs														**BOIS BRUT DE CONIFERES** Sapins, epiceas, douglas
1980		27 294	1 128	938	16 508	282		5 502	314	1 155	100	207		1 160
1981		:	1 166	:	15 735	303		:	467	917	109	184		:
1982		:	:	:	15 453	297		:	583	1 051	97	156		:
1983		:	:	:	14 869	284		:	590	901	109	151		
1984		:	:	:	16 633	:		:	580	972	116	154		
Other coniferous														Autres coniferes
1980		17 523	275	219	5 462	358		8 567	196	553	11	403		1 479
1981		:	292	:	5 488	338		:	300	504	12	542		:
1982		:	:	:	5 751	334		:	378	573	14	487		
1983		:	:	:	4 222	402		:	378	377	11	498		
1984		:	:	:	4 922	:		:	372	417	9	501		
Total coniferous raw wood														Total de coniferes
1980		44 817	1 403	1 157	21 970	640		14 069	510	1 708	111	610		2 639
1981	57 299:	44 455	1 458	1 297	21 223	641	7 999:	13 786	767	1 421	121	726	4 845:	3 015
1982	:	:	:	2 611	21 204	631	9 270:	13 676	961	1 624	111	643	5 057:	3 084
1983	:	:	:	1 931	19 091	686	8 719:	15 227	968	1 278	120	649	5 364:	3 011
1984	:	:	:	1 623	21 555	:	8 316:	15 481	952	1 389	125	655	5 424:	2 970
NON-CONIFEROUS RAW WOOD Oaks														**BOIS BRUT DE FEUILLUS** Chenes
1980		10 313	248	74	1 477	934		5 003	11	1 789	39	53		685
1981		:	265	67	1 386	1 066		:	18	2 125	42	31		:
1982		:	:	59	1 217	955		:	18	1 868	41	30		:
1983		:	:	69	1 090	959		:	17	1 985	41	26		
1984		:	:	74	1 289	:		:	15	2 342	42	36		
Beeches														Hêtres
1980		14 124	333	558	6 606	479		4 987	11	650	137	43		320
1981		:	359	542	6 549	486		:	18	679	127	18		:
1982		:	:	534	6 334	492		:	18	662	135	18		:
1983		:	:	533	5 663	545		:	17	671	136	18		:
1984		:	:	474	6 047	:		:	15	779	129	25		:
Poplars														Peupliers
1980		:	243	–	:	118		2 069	–	2 412	–	160		45
1981		:	226	–	:	87		2 069	0	2 273	0	115		:
1982		:	:	:	:	136		:	0	2 124	0	105		:
1983		:	:	:	:	114		:	0	892	0	122		:
1984		:	:	:	:	:		:	0	850	0	123		:
Other non-coniferous														Autres feuillus
1980		7 849	99	136	274	401		4 196	2	2 430	5	44		262
1981		:	171	124	281	202		:	5	2 539	5	86		:
1982		:	:	123	246	383		:	5	2 288	4	91		:
1983		:	:	120	219	381		:	5	3 482	4	79		:
1984		:	:	141	259	:		:	5	3 802	4	173		:
Total non-coniferous raw wood														Total de feuillus
1980		37 333	923	768	8 357	1 932		16 255	24	7 281	181	300		1 312
1981	44 165:	36 188	975	733	8 216	1 841	5 242:	15 042	41	7 616	174	250	2 735:	1 300
1982	:	:	:	716	7 797	1 966	4 828:	14 666	41	7 026	180	244	2 735:	1 004
1983	:	:	:	722	6 972	1 999	5 731:	14 410	39	7 030	181	245	3 192:	895
1984	:	:	:	689	7 595	:	5 380:	14 752	35	7 773	175	258	3 800:	899
TOTAL RAW WOOD														**TOTAL BOIS BRUT**
1980	103 164:	82 150	2 326	1 925	30 327	2 572	12 484:	30 324	534	8 989	292	910	8 530	3 951
1981	101 464:	80 643	2 433	2 030	29 439	2 482	13 241:	28 828	808	9 037	295	976	7 580	4 315
1982	102 720:	80 830	2 645	3 327	29 001	2 597	14 098:	28 342	1 002	8 650	291	887	7 792	4 086
1983	101 200:	78 194:	2 740:	2 653	26 063	2 685	14 450:	29 637	1 007	8 308	301	894	8 556	3 906
1984	105 315:	82 395:	2 786:	2 312	29 150	2 683:	13 696:	30 233	987	9 162	300	913	9 224:	3 869

The total consumption of wood in EUR12 is 255 Mm^3 [6]. Thus, the net import of wood is 129 Mm^3. From these figures, EUR12 is the largest net importer of wood in the world.
The total import in EUR12 of tropical hardwoods in 1988 was 12.8 Mm^3. This is 20% of the total export by the developing countries. The consumption of tropical hardwoods in EUR12 is some 5% of the total consumption of wood in EUR12.

8.2 Binding carbon by reforestation and afforestation

Today, EUR12 is dealing with an overproduction of agricultural crops. It is estimated that, in EUR12, in the near future 20 to 30 Mha of farmland will be superfluous as a result of this overproduction [1]. From the foregoing it is obvious that a good alternative for farming would be forestry.
If all the extra farmland were to become forest, the total forest area in EUR12 would grow from the present 43 Mha to 63 to 73 Mha, implying a growth of 47-70%. However, in this context **energy farming** should also be considered as an option (see chapter 5).

Transforming farmland into forest in The Netherlands would cost 4300 ECU/ha [17]. On this basis, the costs for transforming farmland into forest in all of EUR12 would be 85 to 130 x 10^9 ECU.

For the six most important timber species in EUR12, and one cultivated (fast-growing) Eucalyptus species, some calculations were made on the possible contribution of forest and wood to the binding of carbon (table 8.4 [7, 11, 18]):
– the total amount of carbon in a mature forest;
– the annual production of carbon in timber; and
– the annual production of carbon in the total biomass.

The average amount of carbon stored in forests, consisting of the 7 species mentioned in table 8.4, is 148 t/ha (optimum growth). The carbon content of tropical rain forest averages 155 - 187 t/ha of standing biomass [12].
The entire covering of the 20 to 30 Mha of superfluous farmland in EUR12 with mature forest would theoretically imply the binding of 3.0 to 4.5 Gt C. However, this estimation is too optimistic for three reasons:

1. It is highly improbable that this entire area will actually be transformed into forest. Moreover, there are also lower estimates of available non-utilised farmland. Okken [15] e.g. estimated the total of superfluous farmland at 13 Mha (1.9 Gt C).
2. The production values calculated in table 8.4 are optimum values. In practice, for areas with average growing conditions, much lower values should be considered.
3. The carbon production values of agricultural crops growing on the farmland are not included here.

So, the afforestation of 13 x 10^6 ha of farmland in EUR12 would likely contribute directly 1 to 2 Gt C, i.e. 0.2 to 0.4% of the total carbon stored in forests.

The import of tropical hardwoods could be reduced, but simultaneously technologies for replacing these tropical woods with European woods would have to be developed. Reducing the import of tropical hardwoods would contribute to the protection of the tropical rain forest, and thus indirectly contribute to the binding of CO_2.

Table 8.4 Optimum values for carbon binding in wood (>7 cm), biomass and in mature forest per year for the six most important tree species in EUR12, and one fast-growing species [7, 11, 18]

	Softwoods			Hardwoods			
Tree species	**fir**	**pine**	**douglas**	**oak**	**beech**	**poplar**	**eucalypt globulus**
optimum carbon prod. (> 7 cm) (t/ha/a)	2.2	1.8	4.5	2.1	2.7	3.3	13.6
optimum carbon prod. biomass (t/ha/a)	6.0	3.8	11.3	5.2*	6.7	9.7	20.8
carbon in biomass in mature forest (t/ha)	172	87	174	152	249	99	104

* = Estimation, the same ratio as beech.

Botanical names

Fir = Picea abies
Pine = Pinus sylvestris
Douglas = Pseudotsuga Menziesii
Oak = Quercus Robur
Beech = Fagus sylvatica
Poplar = Populus robusta

The optimum carbon production per year (table 8.4) is calculated as follows:

(density of wood) x (50%) x (annual yield)

50% = weight percentage of carbon

The optimum carbon production of biomass per year is calculated as follows:

(carbon production) x (ratio)

The carbon stored in mature forest is calculated as follows:

$$\frac{\text{(woodmass at the end of a rotation)}}{2} \text{ x (density of wood) x (50\%)}^{*}$$

50% = weight percentage of carbon

8.3 Binding carbon by preventing deforestation

Saving the tropical forest has effects equivalent to the prevention of the conversion of carbon into CO_2.

The deforestation in the tropical areas is mainly due to the huge population stress in the developing countries. In the tropical areas, the total production of wood is 1.8 Gm^3/a. 80% of this quantity is fuel wood, and only 20% is used industrially [14][**]. In these countries, many people heavily depend on the forest:
– it is a source of fuel wood, needed for cooking,
– the wood is an important export product for many developing countries.

As mentioned before, an important factor in this context is the need for farmland for the inhabitants, both for the production of their own food and for export of beef (Brazil).
Thus, the problem of deforestation cannot be solved by only reducing the import of tropical hardwoods by developed countries. Simultaneously, the developed countries should start social and economic projects to stop, or at least to reduce deforestation. Some examples of projects that would be useful in this context are:

1. social
   - the introduction of more efficient ovens in developing countries, reducing the amount of fuel wood needed (a project of this nature has actually been executed by TU Eindhoven and TNO (1987).
   - the promotion of vegetarianism (especially in the developed countries), in order to reduce deforestation for cattle farming,

2. economic
   - investments in reforestation and afforestation (which may in part be financed from taxes to be paid per m^3 of tropical hardwood that has been cut);
   - investments in eco-tourism [4] (Promoting tropical forest parks for tourist purposes. With the revenues, land could be reforested and the tropical forest parks be maintained. The local people would be employed in tourist industry.);

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[*] Rotation: time interval between planting and logging

[**] Moreover, a considerable fraction of the 'fuel wood' is actually being burnt without even utilising the heat.

3. administrative
   - international agreements among developed and developing countries, constituting reforestation programs paid for by developed countries, at the same time restricting deforestation (only useful together with inspection procedures).

Wiersum and Ketner [19] calculated that 55 to 100 Mha of plantations is needed to cover the deficits of fuel wood, 20 to 40 Mha to cover the deficits of industrial wood and 130 Mha for degraded areas needing protective tree cover in the year 2000 in order to stop deforestation.
The World Watch Institute has calculated that in the next 10 years it is necessary to reforest 130 Mha of tropical land to cover the deficits of all wood and forest demands. The costs for such a project are estimated at US$ 50 x 10^9, or US$ 400 per ha. At the same time, deforestation would have to be reduced to 0 ha/year [16]. These plantations could be a solution to the deforestation problem in the tropics, simultaneously creating new carbon sinks.

8.4 Binding carbon in wood in service

The binding of carbon is also possible in wood in service. Annually, 1 Gt C is stored in wood (see 8.1.2). An increase in the storage of wood in service can be achieved in three different ways:
- extension of the average lifetime of wood in service;
- introducing applications of non tropical woods; and
- reuse of wood.

Wood can be used for many purposes (e.g. building of houses, furniture, paper and cardboard, see figure 8.2.). It can replace other materials like steel and plastics, which cause CO_2 production when being manufactured. Wood, on the contrary, is a CO_2 consuming material, and even if it is burnt for energy generation, an equivalent amount of fossil fuel is thus prevented from emitting its CO_2 into the atmosphere.

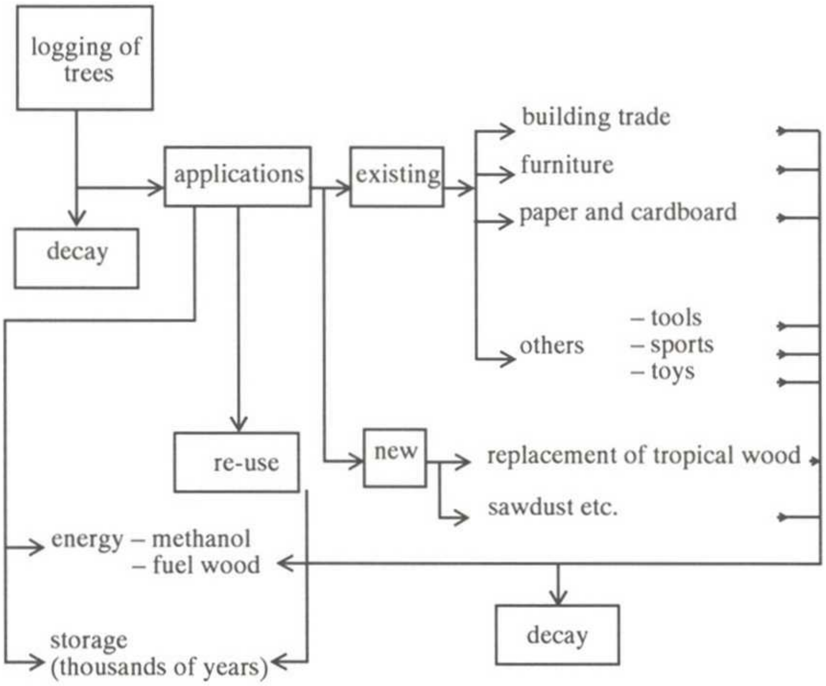

Figure 8.2 The flow of wood

Extension of the average lifetime of wood in service
It is obvious that the storage of carbon in wood for a longer period, for example 50 years instead of 25 years, may help to reduce the CO_2 problem. This can be achieved by:
- using preservatives; and
- improving technical constructions.

A longer service life of the wood in service will decrease the need to cut tropical forests. In the developed countries, a longer service life will lead to the use of wood in more and new purposes.

Nondurable woods can be treated with preservatives. However, wood preservatives are subject to discussion in several countries of EUR12 because of the environmental problems they entail. Studies are necessary, to investige the advantages (longer service lifetime) and disadvantages (emission of chemicals into the air, water and soil, and the use of energy) of the use of preservatives, also in relation to the binding of carbon.

Finding new applications of nontropical woods
Another way to promote carbon storage in wood is to develop new applications, or to encourage existing applications. An example is the building of timber-framed houses in Europe. These are, moreover, 10% cheaper than conventionally

built houses. The money that is saved could be invested in reforestation.
If, e.g. in EUR12, 100 x 10^6 timber-framed houses were built, for which per house 5 m^3 wood were needed, 0.15 Gt of C would be stored.

Reuse of wood
Wood that has been used for many different purposes, but ultimately has become waste wood, can be treated in three different ways:
a) it may be stored on a deposition site; and
b) it may be burnt in an incinerator (regaining the energy).

ad a) This will lead to the forming of deposition gas, which for 60% consists of CH_4. On a molecular basis, the greenhouse effect of CH_4 is 20 to 27 times greater than that of CO_2.

ad b) Using wood as a fuel is a much better proposition. In the developed countries, waste wood can be a substitute for fossil fuel. This process does still convert carbon into CO_2. However, through it an equivalent amount of fossil fuel is left out of the atmospheric carbon cycle. Also in developing countries, waste wood can be used as a substitute for fuel wood. This implies that less fuel wood would have to be cut, which would contribute to saving the tropical forest.

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9 Costs and effectiveness

(H. Bartelds, P.J.A. Van de Laak, E. Mot)*

In the preceding chapters, several *curative* options for confining and abating CO_2 from fossil fuel burning have been evaluated. Since some of these appeared to be less promising, their cost and effectiveness are not considered here. Further, it should be remembered that *preventive* options such as energy saving, renewables and nuclear energy are not the subject of this study. However, since in any conceivable EC policy these options will be considered together with the confining and abating of CO_2, they will be presented here as well (without going into any detail).
Thus, a total picture of all partial solutions to the problem is presented, resulting into a more complete evaluation in the next chapter.

In this chapter, the costs and effectiveness of the following options are calculated:

- Removing CO_2 from fossil fuel burning (9.1), as derived from chapter 4.
- Storage of CO_2 in aquifers and gas fields (9.2; chapter 6).
- Pumping CO_2 into the ocean near Gibraltar (9.3; chapter 7).
- Biological solutions, like afforestation, reforestation, energy farming (9.4; chapter 5 and 8).
- Options not considered earlier in this context, viz. the preventive options (9.5):
  - energy saving
  - renewables
  - nuclear energy.

The implementation of all options is bound to EC-territory, except for reforestation in tropical areas.
Finally, a summary of the financial consequences of the most promising options is presented (9.6). In this context, storage options imply mainly costs. Other options, however, imply benefits (avoided costs) as well. Thus "GROSS" and "NET" cost of the various options will be considered.
It should be emphasised that all calculations, and in particular those concerning the preventive options, have a very general character. The results are, moreover, very sensitive for slight variations in the assumptions. This holds for the net costs in particular, since these are often found by subtracting two figures of equal order of magnitude.
Hence, the only purpose of these calculations is to obtain a complete picture of *all* options for avoiding CO_2 emissions into the atmosphere, together with a first impression of the magnitude of the total financial consequences for the EC.

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* With contributions of A.G. Melman, Department of Heat and Refrigeration Technology, TNO.

9.1 Removing CO_2 from fossil fuel burning

The costs for prevention of CO_2 emissions by storage can be distinguished in:

- costs for binding and separating CO_2 from exhaust gas; and
- costs for transporting and injecting CO_2 (storage costs).

Before CO_2 can be stored in depleted gas fields, aquifers or in the ocean, it has to be concentrated. To this end, three methods were described in chapter 4:

1. Replacing a combustion process by a gasification process. The CO_2 recovery from the syngas stream can be as high as 98%.
2. Replacing combustion air with oxygen. The CO_2 content of the flue gas then varies between 80 and 95%.
3. CO_2 scrubbing. Six different techniques for scrubbing CO_2 from the flue gases are being developed. From these, only the absorption technique seems to be sufficiently mature for demonstration. With this technique, 90% of the CO_2 can be removed. The other techniques still need further research and development.

In all cases, complex additions to combustion installations will be required to collect CO_2.

The three techniques mentioned in chapter 4 for confining CO_2 emissions from flue gas result in the following costs:

ad 1. The IGCC process is still in the demonstration phase. According to Hendriks et al. [1], these costs are estimated at 11.1 ECU per ton CO_2.
ad 2. The production costs of oxygen are about 21.4 ECU per ton oxygen. This corresponds with 21.4 ECU per ton CO_2 avoided.
ad 3. The following costs can be derived from chapter 4: 27.4 ECU per ton CO_2 avoided (by pulverised-coal firing) and 22.2 ECU per ton CO_2 avoided (by natural gas firing), using CO_2 scrubbing technology.

According to table 2.2, in the European Communities 2734 Mt CO_2 are emitted every year. Current CO_2 emissions from all power stations are 801 x 10^6 tonnes of CO_2 per year. (see 9.2.1). Assuming an 85% effectivity of the CO_2-removal, we arrive at 680 x 10^6 tonnes of CO_2 per year. Furthermore, table 2.2 shows that 75% of these CO_2 emissions originate from coal-fired power stations, 14% from oil-fired and 11% from natural-gas-fired power stations.

The following costs for removing CO_2 from fossil-fuel-burning power stations in the European communities can be distinguished:

1. If all power stations would use the IGCC process: 680 x 10^6 x 11.1 = 7.6 x 10^9 ECU/a.
2. If combustion air would be replaced by oxygen: 680 x 10^6 x 21.4 = 14.6 x 10^9 ECU/a.
3. According to table 3.4, the CO_2 emission proportion of gas, oil and coal is 1 : 1.4 : 1.7 per unit of energy content. Further it is estimated that implementation of the absorption technique on oil-fired power stations will result in 24.8 ECU per ton CO_2 avoided, hence the average of the unit costs for gas and coal, respectively.

From this, the following costs can be calculated:
Coal-fired power stations : $0.75 \times 680 \times 10^6 \times 27.4 = 14.0 \times 10^9$ ECU/a.
Oil-fired power stations : $0.14 \times 680 \times 10^6 \times 24.8 = 2.4 \times 10^9$ ECU/a.
Gas-fired power stations : $0.11 \times 680 \times 10^6 \times 22.2 = 1.7 \times 10^9$ ECU/a.

Hence, if an absorption technique is applied in coal-, oil- and gasfired power stations the total costs are $14.0 + 2.4 + 1.7 = 18.1 \times 10^9$ ECU/a.

In order to avoid overoptimistic views it will be assumed here that costs for removing CO_2 emissions from power stations actually range between 14.6 and 18.1×10^9 ECU/a. (However, by introducing the IGCC process, these costs may decrease in due time). Further, the costs for transportation and injection (storage costs) should be added.

9.2 Storage of CO_2 in the subsurface

In chapter 6, the following alternatives for storage of CO_2 in the subsurface are distinguished:

- storage in (depleted) gas fields;
- storage in aquifers;
- storage in salt caverns.

9.2.1 Storage in gas fields

The following gas fields are located within a transportation distance (from power plants) of less than 300 km (figure 6.8 and Annex II). It is assumed that these gas fields have sufficient possibilities for storage of CO_2.

- C. and N. North Sea (offshore);
- Celtic Sea (offshore);
- Irish Sea (offshore);
- S. North Sea – North Germain Plains (offshore/onshore);
- Alpine foreland (onshore);
- Rhine Graben (onshore);
- Parisian Basin (onshore);
- Aquitaine Basin (onshore).

Table 9.1 Number of conventional power stations in EC12 and distances from gas fields

Distance (km)	Gasfields onshore	Gasfields offshore
< 10	22	
50	20	
100	36	1
150	4	19
200	25	3
Total	107	23

According to table 9.1, 78 conventional power stations are located within a range of 100 km from onshore or offshore gasfields.

Costs for storage of CO_2 in gas fields

It is assumed that the average capacity of power plants in EUR12 is about 600 MW. The yearly production of a 600 MW coal-fired power station is 2.8 x 10^6 tons of CO_2. In the European Communities, roughly 230 conventional power stations exist (Annex II). These correspond with a total annual production of 644 x 10^6 tons of CO_2. This is somewhat lower than the value of 801 x 10^6 tons of CO_2/a mentioned in table 2.2; this discrepancy may well be due to the fact that in Annex II only power plants over 300 MW have been indicated.

According to **Van der Harst** and **Van Nieuwland** [2], the storage costs (onshore) of a coal-fired 600 MW power plant with a CO_2 production of 450 ton/hr, 6300 hr/a in service and a CO_2 transportation distance of 100 km, amount to 3.2 ECU per ton CO_2. These costs concern transportation and injection. It is assumed that transportation costs are 1.6 ECU per ton CO_2 per 100 km and that injection costs are 1.6 ECU per ton CO_2 as well. This results in transportation and injection costs in onshore gas fields as indicated in table 9.2.

Table 9.2 Transportation and injection costs for storage of CO_2 in gas fields

Distance (km)	**Number of power plants**	**Total CO_2 emission (x 10^6 ton/a)**	**Transport costs (x 10^6 ECU/a)**	**Injection costs (x 10^6 ECU/a)**	**Total costs (x 10^6 ECU/a)**	**Costs/ ton CO_2 (ECUs per ton CO_2)**
onshore						
< 10	22	61.6	9.9	98.6	108.5	1.8
50	20	56	44.8	89.6	134.4	2.4
100	36	100.8	161.3	161.3	322.6	3.2
150	4	11.2	26.9	17.9	44.8	4.0
200	25	70	224.0	112	336	4.8
Total	107	299.6	446.9	479.4	946.3	3.2
offshore						
150	19	53.2	383.0	255.4	638.4	12

Average transportation and injection costs for this option are:

$\frac{946.3}{299.6} = 3.2$ ECU per ton CO_2.

In the above calculation it is assumed that all power stations are coal-fired. In reality, however, this holds for only 75% of the fossil-fuel-based power stations. The others use either oil or natural gas, hence produce less CO_2. This implies that both CO_2 emission reduction and storage costs are less. The actual emission reduction is

$$(107 \times 2.8 \times 0.75 + \frac{107 \times 2.8}{1.7} \times 0.14 + \frac{107 \times 2.8}{1.7} \times 0.11) \times 10^6 = 274.1 \times 10^6 tCO_2/a$$

This corresponds with $(1 - \frac{274.1}{299.6}) \times 100\% = 9\%$ reduction of storage costs.

Futhermore, in this calculation it is assumed that for every power plant a separate pipeline and compression plant are needed. In several regions in Europe, however, power plants are located rather near to each other. Hence, joint use of transport and injection facilities will lower the actual costs. To this end, a correction of 15% has been introduced.

The above results in a gross avoided CO_2 emission of 0.91 x 0.2996 = 0.27 Gt CO_2/a. The storage costs are approximately 0.91 x 0.85 x 0.9463 = 0.73 x10^9 ECU.

This results in $\frac{0.73}{0.91 \times 0.2996} = 2.7$ ECU per ton CO_2.

In case of transportation to offshore gas fields, the storage costs are estimated to be a factor of 3 higher than the costs onshore. Table 9.1 shows that most power stations are located at a distance of more than 150 km from offshore gas fields. The average transport and injection costs are 12 ECU per ton CO_2 (table 9.2). Since this is much more than other options which are nearer to plants, this option will not be considered further.

Total costs for removing CO_2 from fossil fuel burning and storage of CO_2 in gas fields

If CO_2 is removed from all power stations within a transport distance of 200 km from gas fields either by firing with oxygen or by applying the absorption technique, then a gross CO_2 reduction of 0.27 Gt/a would be realised. The net reduction will presumably be some 25% lower, hence 0.20 Gt CO_2/a, due to the energy, required for separation and transport. This would result in total costs of

$$\left(\frac{299.6 \times 0.91}{680} \times 14.6 + 0.2996 \times 0.91 \times 0.85 \times 3.2\right) \times 10^9 = (5.85 + 0.74) \times 10^9 = 6.6 \times 10^9 \mathrm{ECU/a}$$

(oxygen) and

$$\left(\frac{299.6 \times 0.91}{680} \times 18.1 + 0.74\right) \times 10^9 = (7.26 + 0.74) \times 10^9 = 8.0 \times 10^9 \mathrm{ECU/a}$$

(absorption technique). Or 33 ECU and 40 ECU per ton CO_2 avoided, respectively.
In the European Communities the storage potential of gas fields is approximately 28 Gton CO_2. This implies a storage capacity of some 110 years.

9.2.2 Storage in aquifers

As opposed to gas fields, aquifers can be used for storage immediately. However, in this case no existing infrastructure is available at all. Wells, pipelines and compressors will have to be installed, especially for disposal purposes. Therefore, storage costs for this alternative will be higher than in the case of gas fields.

In table 9.3, the average distance between conventional power stations in EUR12 and the position of aquifers is shown, as taken from figure 6.9 and Annex II. This table shows that about half of the European power stations are located within 50 km of an aquifer.

Table 9.3 Number of conventional power stations in EC12 and distances to the nearest aquifers

EC country	Total number of power stations	Average distance (km)						
		< 10	50	100	150	200	250	250
Denmark	11	11						
Netherlands	17	17						
Belgium	5		5					
Luxembourg	–							
Ireland	4				1		1	2
United Kingdom	39		25		10	4		
Germany	68		40		28			
France	21	9		4	8			
Italy	27		4			14		9
Spain	25				12	5		8
Portugal	(3)	(no aquifers)						
Greece	8							8
Total	228	37	74	4	59	23	1	27

Costs for storage of CO_2 in aquifers

It is assumed that the same transportation costs apply as those for the storage in depleted gas fields (1.6 ECU per ton of CO_2 per 100 km). However, the injection costs for aquifers will be higher, since new wells must be drilled (4 wells per 600 MW plant). It is assumed that these additional injection costs are approximately 0.4 ECU per ton CO_2. Thus, the injection costs for this alternative are 2.0 ECU per ton CO_2. In table 9.4, the transportation costs have been added to these injection costs.

Table 9.4 Transportation and injection costs for storage in aquifers

Distance (km)	Number of power plants	Total CO_2 emission (x 10^6 ton/a)	Transport costs (x 10^6 ECU/a)	Injection costs (x 10^6 ECU/a)	Total costs (x 10^6 ECU/a)	Costs/ ton CO_2 (ECUs per ton CO_2)
< 10	37	103.6	16.6	207.2	223.8	2.2
50	74	207.3	165.8	414.4	580.2	2.8
100	4	11.2	17.9	22.4	40.3	3.6
150	59	165.2	396.5	330.4	726.9	4.4
200	23	64.4	206.1	128.8	334.9	5.2
Total	197	551.6	802.9	1103.2	1906.1	

Average transportation and injection costs for this option are 3.5 ECU per ton CO_2. This is almost the same as those for gas fields. However, in the case of aquifers the injection costs are higher, and the transportation costs lower.

It was initially assumed that all power stations are coal-fired and that for each power plant a separate pipeline and compression plant are needed. Thus, a correction has been applied for power plants using oil or natural gas (9%) and for power plants connected to joint pipelines (15%).
This results in a gross avoided CO_2 emission of 0.50 Gt CO_2/a. The net emission reduction will presumably be some 25% lower, hence 0.38 Gt CO_2/a, due to the energy required for separating CO_2 from the flue gases, transport and injection.

The storage costs are approximately 1.47 x 10^9 ECU/a. This results in 3.8 ECU per ton CO_2.

Total costs for removing CO_2 from fossil fuel burning and storage of CO_2 in aquifers

If all power stations within a transport distance of 200 km from an aquifer were to remove CO_2, either with oxygen or with the absorption technique, then a CO_2 reduction of 0.38 Gt/a would be possible. This would entail total costs of 12.3 x 10^9 ECU (oxygen) and 14.9 x 10^9 ECU (absorption technique) per year, respectively, corresponding with 32 ECU and 39 ECU per ton CO_2.

In chapter 6, the minimum storage potential of aquifers was estimated at 101.7 to 406.6 Gton CO_2. This implies a storage capacity of 221 to 884 years.

From the cost survey, it is clear that storage costs are less than 10% of the total costs for abating and confining CO_2. The major costs are those for removing CO_2. Consequently, there is only little difference in cost between storage in gas fields and in aquifers. Moreover, though the actual storage costs for CO_2 in aquifers are somewhat higher than those for storage in gas fields, the location of power plants with respect to aquifers is more favourable. In Europe, 78 power plants are located within a range of 100 km from gas fields, while 111 power plants are within 50 km from aquifers.

9.2.3 Storage in salt caverns

Approximately ten salt domes can be found in The Netherlands. At a depth of 500 metres, the CO_2 storage potential would be 0.035 to 0.25 Mton per cavern. More than one cavern can be made in a dome. If on average 3 caverns can be made in a dome, then the total storage capacity in The Netherlands is 1 to 7.5 Mton. However, it is assumed that the volume of the salt domes in The Netherlands is a considerable percentage of those in the EC. If this percentage is e.g. 15%, then the total storage capacity in EUR12 would be 0.007 to 0.05 Gt. This is very low compared with gas fields and aquifers. Moreover, the storage costs are estimated at 4 ECU per ton CO_2, which is more than the storage costs for gas fields and aquifers. Therefore, this option is limited, and will not be considered further.

9.3 Pumping CO_2 down Gibraltar Falls

In this option, CO_2 is separated and collected from large point sources (power plants), transported and disposed into the ocean at Gibraltar. There the water is known to cascade down to about 1200 m depth and to spread laterally in the North Atlantic Ocean (chapter 7). This option is subject to the following limitations:

a. about half of the injected CO_2 would still be released into the atmosphere, some 50-200 years later;
b. extracting CO_2, compressing it to 150 bar and transporting it over 40 km requires a great deal of the energy produced. Overall energy loss is estimated at 20-35%, or even higher for long distances .

It is assumed that the transportation costs are the same as those for transportation of CO_2 to aquifers and gas fields: 1.6 ECU per ton CO_2 per 100 km. Furthermore, in the context of this rough estimate, injection costs are not taken into account.

Table 9.5 Transportation costs of CO_2 to Gibraltar Falls

Number of power stations	Distance from Gibraltar (km)	Transportation costs (ECU/ton of CO_2)
2	100	9
3	300	40.3
5	500	112

Table 9.5 shows that within a range of 100 km from Gibraltar, only 2 power stations are located, between 100 and 300 km 3 power stations, and between 300 and 500 km 5 power stations. If all power stations are 600 MW coal-fired power plants, the stations produce 2.8 x 10^6 ton CO_2 per power plant per year. Further it is assumed that the absorption technique is used.

Table 9.6 Costs for removing CO_2 from flue gases and transportation the CO_2 to Gibraltar Falls

Number of power stations	Reduction of CO_2 emissions (x 10^6 ton/a)	Costs for removing CO_2 (x 10^6 ECU/a)	Transportation costs (x 10^6 ECU/a)	Total costs (x 10^6 ECU/a)
2	5.6	153.4	9.0	162.4
3	8.4	230.2	40.3	270.5
5	14.0	383.2	112	495.2
Total 10	28	766.8	161.3	928.1

From table 9.6 it can be seen that the net CO_2 reduction with this option is 0.028 Gt/a. Subtracting 25% again, for energy due to separation, transport and injection gives 0.021/Gt CO_2/a. The costs for removing CO_2 from 10 power stations, located at a distance of less than 500 km from Gibraltar, and transporting CO_2 to Gibraltar Falls, are 0.93×10^9 /ECU/a, or 46 ECU per ton CO_2. If, instead of air, oxygen is used for combustion, the total costs are 0.76×10^9 ECU/a, or 38 ECU/ton CO_2.

Both amounts are in the same order as those for storage in gas fields or aquifers. However, the number of power stations available is relatively small. Further, transporting CO_2 over long distances will require much energy. And finally, power plants in the northern part of Spain are located nearer to aquifers. Therefore, the actual implementation of this option remains questionable.

9.4 Storage of CO_2 in biomass

In chapter 8, an outline has been presented of various ways of storing CO_2 in forests and in wood. Moreover, in chapter 5 the subject of energy farming was mentioned. In the present chapter, the costs and effectiveness of two options are **not** examined, viz. prevention of deforestation in tropical areas and storage of carbon in wood in service. This omission has been based on the following arguments:

Prevention of deforestation in tropical areas is a complex matter. It is estimated that about 10 to 15 x 10^6 ha of tropical forest vanishes each year [3,4]. According to figures based on FAO and others, the main structural cause of deforestation in tropical areas is the transformation of forests into agricultural areas by shifting cultivation (more than 60%) [5]. This also contributes to an accumulation of biomass. According to **Elliott and Booth** [6], the burning of forests currently accounts for some 25% of all man-made CO_2 emissions, or approximately 1.5 Gt C/a. Less than half of these emissions, or approximately 0.7 Gt C/a, accumulate in the atmosphere. According to **Otto** [5], rural development in tropical areas plays a crucial role in preventing deforestation. However, since it is very difficult to estimate costs and effectiveness of rural development programmes, this option is not further examined in the context of this study.

The total storage of carbon in wood in service is about 0.48 Gt C for a period longer than 1 year (sawn wood, pulp and other uses). Increasing the application of wooden constructions etc., and extension of their lifetime has only a small effect on the reduction of CO_2 emissions and is therefore not examined here.

Thus, costs and effectiveness have only been calculated for the following options:
- energy farming in Europe (9.4.1);
- afforestation in Europe (9.4.2), and
- afforestation and reforestation in tropical areas (9.4.3).

9.4.1 Energy farming in Europe

It is estimated (chapter 8, [7]) that in the near future in EUR12 20 to 30 x 10^6 ha of farmland will be superfluous as a result of overproduction. A good alternative for these agricultural surplus areas might be energy farming.

According to the Dutch National Council for Agricultural Research [8], the effectiveness of avoiding CO_2 through the use of agricultural products as fuels equals 60-70%. This figure holds for the whole chain of the production process, from winning and primary production to use. Moreover, the energy content of bioethanol is 50%, approximately, of that of petrol.

On the EC agricultural surplus area of 20 to 30 x 10^6 ha, it would be possible to produce 96 to 144 x 10^9 litres, or 2000-3000 PJ of bioethanol per year with conventional techniques. This is equivalent with 43 to 64 x 10^9 litres of petrol. Since 1 liter of petrol emits 2.9 kg of CO_2, it follows that by using 96 to 144 x 10^9 litres of bioethanol per year a maximum emission reduction of 0.12 – 0.19 Gt CO_2/a is possible. However, actually this reduction will be only 50%, approximately, hence 0.06 - 0.10 Gt CO_2/a, since ethanol production requires some 50% of the initial energy content of the biomass.

According to **Elliott and Booth** [6] about 9 Mt of fuel ethanol was produced at a cost of 8.7 ECU per GJ in Brazil in 1989. On that basis, in Europe the production of 2000-3000 PJ would result in total costs of 17 to 26 x 10^9 ECU. In the USA, some 2 x 10^6 ton of fuel ethanol was produced in 1987 at a price of 16 ECU per GJ. In Europe this would result in a total cost of 32 to 48 x 10^9 ECU , or 510 ECU per ton CO_2 gross. Presumabably, USA cost estimates are more relevant for the EC than those from Brazil. Assuming *production costs* (government take and taxes excluded) of petrol of 0.1 ECU/liter, the saving of 43 to 64 x 10^9 litres of petrol implies 4 to 6 × 10^9 ECU of savings. Subtracting this amount from the costs of bioethanol production leads to 28 to 42 x 10^9 ECU/a of net costs. From these figures it may be concluded that the emission reduction by introducing bioethanol would cost about 450 ECU per ton CO_2 net. Though this amount is relatively high, it should be realised that using agricultural surplus areas for energy farming implies considerable secondary financial benefits. On a European level there is a surplus of cereals. This surplus is now sold on the world market with the help of export subsidies. Not only export subsidies, but also additional costs for storage and other services, such as administration, are connected with the cereal policy. The costs that could thus be saved 1989 are estimated at 5.3 x 10^9 ECU [8].
An additional benefit would originate from avoiding the so-called fallow premium [8]. In The Netherlands, this premium is 792 ECU per hectare. Paying a fallow premium for 20 to 30 x 10^6 ha of agricultural surplus area would cost 15.8 to 23.8 x 10^9 ECU per year. Together with the prementioned export subsidies, this amounts to 21 to 29 x 10^9 ECU per year. On that basis, the production of biomass for energy fuels could become relatively attractive.

However the above may actually imply an overestimation of the benefits, since the price of land in The Netherlands is high, which results in a high fallow premium.
In the final calculations, these secondary financial benefits are **not** considered.

9.4.2 Afforestation in Europe

Another optional destination for the agricultural surplus area of 20 to 30 x 10^6 ha is afforestation. The mean annual production of biomass of the most important timber species in EUR12 (fir, pine, douglas fir, oak, beech and poplar) is 7.1 t C/a. From this figure, it follows that by transforming agricultural areas into forests, a carbon sink is created of 142 to 213 Mt C per year or 0.5-0.8 Gt CO_2 per year.

According to **Wolf and Janssen** [9], however, changes in land use have a considerably lower effect on the reduction of CO_2 emissions. They calculated that for The Netherlands, the transformation of agricultural land into forest would actually result in a net accumulation of 0.56 t C/ha.a. Based on this figure, only 11.2 to 16.8 x 10^6 ton C/a would accumulate on 20 to 30 x 10^6 hectares. This corresponds with 0.04-0.06 Gt CO_2 per year.

The average time before these timber species become mature ranges between 35 and 150 years; after such a period, the net accumulation of biomass becomes zero.

For afforestation the following costs can be distinguished:

- development costs, and
- management cost.

Mohren and **Klein Goldewijk** [10] have calculated costs and accumulation of CO_2 through forestry in The Netherlands, on the basis of annuity. Calculations were made for pine, douglas fir, oak and poplar (table 9.7).

Table 9.7 Production costs of four timber species on annuity basis

Timber species	Costs/ha.a (ECU)	Years of rotation
Pine	51 - 60	100
Douglas fir	43	100
Oak	137	150
Poplar	155 - 200	35

Source: Mohren and Klein Goldewijk [10]

Based on the figures of table 9.7, the transformation of agricultural land into forest in Europe on a scale of 20 to 30 x 10^6 ha would result in total costs of 1.0 to 1.8 x 10^9 ECU/a (pine), 0.9 to 1.3 x 10^9 ECU/a (douglas fir), 2.7 to 4.1 x 10^9 ECU/a (oak) and 3.1 to 6 x 10^9 ECU/a (poplar). This corresponds with 23 - 100 ECU per ton of CO_2 avoided.

9.4.3 Afforestation in tropical areas

In mature tropical forests production and consumption of CO_2 are in balance. Only on the rich soils there may be a small further accumulation of

carbon. This implies that mature tropical forests do not have a major impact on the reduction of CO_2 in the atmosphere.
According to the World Watch Institute, it is necessary to reforest 130 x 10^6 hectares of tropical land to cover the deficits of all wood and forest demands in the next 10 years. This corresponds with 13 x 10^6 ha/a. The costs for such a project are estimated at 35.7 x 10^9 ECU or 3.6 x 10^9 ECU/a [5]. In Europe the mean annual production of biomass is 7.1 t C/ha.a. For tropical areas, the mean annual production of biomass is much smaller, since average tropical soils are very poor. This makes reforestation in tropical areas extremely difficult.

If it is assumed that the mean annual production of biomass in tropical areas is only 10% of the production of biomass in Europe, reforestation of 13 x 10^6 ha would result in an accumulation of 9.2 Mt C/a, or 0.03 Gt CO_2/a. However this is an underestimation, since on Eucalyptus plantations on rich soils the mean annual accumulation of carbon is much higher than in Europe. Eucalyptus, however, covers only a minor percentage of the total tropical forest.
On the other hand, the accumulation of biomass is only temporary; after these tropical forests become mature (which is assumed to happen in 15 to 50 years), the net accumulation of biomass will be zero. Further, a correction is necessary for tropical forests vanishing every year. Taking the many uncertainties into account, it is estimated that the net effect of all aspects may be a sink in the order of 0.03 Gt CO_2 per year. The costs are estimated at 3.6 x 10^9 ECU per year, corresponding with 120 ECU per ton CO_2.

9.5 Energy saving, renewables and nuclear energy

9.5.1 Energy saving

a. Gross costs of energy saving

In the European Communities in 1987, primary energy consumption was 45,700 PJ. It is estimated that currently about 46,500 PJ are consumed. In The Netherlands, 2,760 PJ of primary energy was consumed in 1987; today, this may be 2,800 PJ.
In The Netherlands, in the next ten years, a 20% savings in energy is thought to be possible (560 PJ/a)[*]. This corresponds with a total reduction of 42 Mt CO_2. It is assumed that a total reduction of 42 Mt CO_2 in the year 2000 will be maintained continuously through replacement investment. The necessary investments amount to 15 x 10^9 ECU in the period 1990-2000 [11]. Assuming capital dependent costs of 14% (annuity, maintenance, etc.) implies costs of 2.1 x 10^9 ECU/a, approximately.

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[*] It is noteworthy that some recent studies [13,14] have shown that the technical potential for energy conservation in the EC in the long run is considerably higher.

If these figures from The Netherlands are extrapolated to the European Communities [15], this would result in total savings of 9,300 PJ/a for the European Communities in the year 2000, implying a reduction of 0.698 Gt CO_2/a. To this end, a total investment of 249 x 10^9 ECU in the period 1990-2000, leading to annual costs of 34.9 x 10^9 ECU per year is required. This corresponds with 50.0 ECU per ton CO_2 avoided.

b. Credits

(i) Savings in costs of fossil fuels

We will assume that 10% of the savings is electricity. Taking credits for avoided energy costs into account as well, on the basis of average costs of 2.5 ECU/GJ thermally and, (assuming a conversion efficiency of 40%) of
2.5/0.40 = 6.25 ECU/GJ electrically, we arrive at average savings of
(0.9 x 2.5) + (0.1 x 6.25) = 2.88 ECU/GJ for the energy mix. In total these avoided costs are 2.88 x 9300 x 10^6 = 26.8 x 10^9 ECU/a.

(ii) Savings in investments

If electricity is produced during 6000 h/a, this implies a production capacity of (930×10^{12})/(6000 x 3600) = 43 x 10^6 kW.
Estimating investments in power plants on 150 ECU/kW.a, this leads to investment savings of 6.5 x 10^9 ECU/a.

c. Net costs of CO_2 abatement[*]

From the aforegoing it is concluded that the net costs for CO_2 abatement by energy saving are only (34.9 - 26.8 - 6.5) x 10^9 = 1.6 x 10^9 ECU/a, or
2.3 ECU/ton CO_2 avoided.

Moreover, it should be noted that energy saving implies other positive effects as well, such as reduction of acidification and the saving of resources.

9.5.2 Renewables

a. Gross costs of renewables

In The Netherlands, the objective is a production of renewable energy in 2010, equivalent with 150 PJ of fossil fuel (primary energy). This is about 5% of the current energy consumption [11]. This effort would imply a growth of 90 PJ, to be maintained continuously through replacement investments. The necessary investments are 2.6 x 10^9 ECU. Capital dependent costs are estimated on 14% per annum; this corresponds with 0.36 x 10^9 ECU/a, approximately.

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[*] In this case the sensitivity for initial assumptions is extremely large. 1% point change in annuity, for example, results into a change of 3 ECU/ton CO_2, approximately.

In the European Communities today, about 84% of the energy production is based on fossil energy, and 14% on nuclear energy; 2% stems from renewables (930 PJ). This percentage also holds for The Netherlands. Extrapolation of the Dutch efforts in this respect to an EC-level, 5% from renewables in 2010, results into an energy production of 2,325 PJ from renewables, hence the equivalent of 1395 PJ of fossil fuel additionally [15] (of course, there will be variations in the actual mix for each country).
This would result in a reduction of 0.105 Gt CO_2/a, involving costs of
$0.36 (1395/90) \times 10^9 = 5.58 \times 10^9$ ECU/a, corresponding with 53.1 ECU per ton CO_2 avoided.

b. Credits

(i) Savings in costs of fossil fuels

In this case, the avoided fossil fuel costs are $2.5 \times 1.395 \times 10^9 = 3.49 \times 10^9$ ECU/a.

(ii) Saving in investments

We assume that 25% of the renewable energy is electricity (wind, water, photovoltaic solar), and 75% thermal (geothermal, waste, thermal solar). This implies that $0.25 \times 1395 = 349$ PJ thermal energy does not have to be converted into electricity. If the conversion efficiency is 40%, $0.40 \times 349 = 140$ PJ_e is avoided. At a production time of 6000 h/a this equals
$(140 \times 10^{12})/(6000 \times 3600) = 6.5 \times 10^6$ kW of installed power. With investment costs of 150 ECU/kW.a this implies 0.98×10^9 ECU/a of avoided investments.

c. Net costs of CO_2 abatement

From the aforegoing it can be seen that the net costs of CO_2 abatement of this option are $(5.58 - 3.49 - 0.98) \times 10^9 = 1.11 \times 10^9$ ECU/a, or 10.6 ECU/ton CO_2.

According to the Center for Energy Conservation and Environmental Technology [12], the potential contribution of wind energy in The Netherlands from the continental shell, within a range of 50-90 kilometres from the coast, could result in an power production of about 30,000 MW. If, moreover, sea areas are used at a distance of over 100 kilometres, then a maximal energy production of 45,000 MW is feasible. This would be equivalent to 75 conventional 600 MW power stations! The costs of wind energy are estimated at a minimum of 7.3 ECU per GJ. The costs for the total power production of 45,000 MW is (at least) 2.2×10^9 ECU per year. Replacing coal-fired power stations with this amount of energy production would result in a reduction of 0.21 Gt/a. This is also 10.5 ECU per ton CO_2 avoided. (This should, however, rather be seen as a coincidence than as a confirmation of the accuracy of the figures presented.

9.5.3 Nuclear energy

a. Gross costs of nuclear energy

Electricity produced with light water reactors would cost approximately 0.04 ECU/kWh [12]. Replacing a 600 MW coal-fired power plant with a nuclear power plant (6000 hours/a in use) would correspond with a reduction of 3.2 Mt CO_2/a [15]. A 600 MW nuclear power station would then cost 144 x 10^6 ECU/a. This concerns exploitation costs only. Costs for storage of nuclear waste and for dismantling of nuclear power stations have been omitted. If these costs are considered too, the total costs are considerably higher. To include these additional costs, a correction factor of 25% has been applied.

Replacing 20% of the conventional power in Europe (20% of 232 GW = 46.4 GW [15]) with nuclear power would imply an emission reduction of 0.25 Gton/a. This would cost 13.9 x 10^9 ECU/a, or 56 ECU/ton CO_2.

b. Credits

(i) Savings in costs of fossil fuels

In this case, the benefits are the avoided fossil fuel costs of 2.5 ECU/GJ, entirely converted into electricity with an efficiency of 40%, hence 6.25 ECU/GJ_e. Assuming again a production of 6000 h/a, these savings are 46.4 x 6000 x 3600 x 6.25 = 6.3 x 10^9 ECU/a.

(ii) Savings in investments

Since the 46.4 GW mentioned in 9.5.3a are all electricity, the avoided investments (on the basis of 150 ECU/kW.a) are 46.4 x 150 x 10^6 = 7.0 x 10^9 ECU/a.

c. Net costs of CO_2 abatement

From the aforegoing it can be seen that the net costs for CO_2, abatement are (13.9 - 6.3 - 7.0) x 10^9 = 0.6 x 10^9 ECU/a, or 0.6/0.25 = 2.4 ECU/ton CO_2.

9.6 Summary of financial consequences of the various options

Table 9.8 gives a summary of the various options for abating, confining and preventing CO_2 emissions with respect to maximum feasible CO_2 emission reduction per option, its total costs, costs per ton CO_2 avoided and the number of years the option remains intact. Of course, these figures only give an indication of the order of magnitude of potential reduction and costs of options for abating, confining and prevention of CO_2 emissions.

Table 9.8 Summary table of options for reducting CO_2 from fossil fuel burning, including their financial consequences. The "GROSS" columns indicate the total costs; in the "NET" columns the financial benefits due to avoided energy production are subtracted from the gross amount.

		GROSS		NET		
Options	**CO_2 reduction (Gt/a)**	**Total costs (x 10^9 ECU/a)**	**Costs/ ton CO_2 (ECU)**	**Total costs (x 10^9 ECU/a)**	**Costs/ ton CO_2 (ECU)**	**Number of of years**
Abating and confining						
1. Removing CO_2 and storage in gas fields	0.20	6.6 - 8.0	33 - 40	6.6 - 8.0	33 - 40	110
2. Removing CO_2 and storage in aquifers	0.38	12.3 - 14.9	32 - 39	12.3 - 14.9	32 - 39	220 - 880
3. Removing CO_2 and pumping it down Gibraltar Falls	0.021 1)	0.76 - 0.93	38 - 46	0.8 - 0.9	38 - 46	no limit
4. Energy farming	0.06 - 0.10	32 - 48	510	28 - 42	450	no limit
5. Afforestation in Europe	0.04 - 0.06	1 - 6	23 - 100	1 - 6	23 - 100	35 - 150
6. Afforestation and reforestation in tropical areas	0.03	3.6	120	3.6	120	15 - 50
Prevention						
7. Energy saving	0.698	34.9	50.0	1.6	2.3	no limit
8. Renewables	0.105	5.58	53.1	1.11	10.6	no limit
9. Nuclear energy	0.25	13.9	56	0.6	2.4	30 2)

1) It is estimated that in 50-200 years, 50% of the CO2 will still be emitted into the atmosphere
2) Proven reserves

The nine options selected in this table may now be summarised as follows:

ad 1 Removing CO_2 from fossil fuel burning in power stations, followed by storage in gas fields

By separating CO_2 from all fossil fuel fired power stations within a transport distance of 200 km from gas fields, either by combustion with oxygen or by an absorption technique, a net CO_2 reduction of 0.20 Gt CO_2/a is possible. This would cost of 6.6 x 10^9 ECU/a (oxygen) and 8.0 x 10^9 ECU/a (absorption technique), corresponding with 33 ECU and 40 ECU per ton CO_2 per year, respectively. The option is valid for a period of 110 years.

ad 2 Removing CO_2 from fossil fuel burning in power stations, followed by storage in aquifers

Removing CO_2 as above from all power stations within a transport distance of 200 km from aquifers would make possible a net CO_2 reduction of 0.38 Gt CO_2/a, at a total cost of 12.3 x 10^9 ECU/a (oxygen) and 14.9 x 10^9 ECU/a (absorption technique) per year, respectively. This corresponds with 32 ECU and 39 ECU per ton CO_2 per year, respectively. The option is valid for a time span of 220-880 years; further research is needed in order to obtain more certainty.

ad 3 Removing CO_2 from fossil fuel burning in power stations, followed by pumping down Gibraltar Falls

For this option, only those power stations in Spain and Portugal are considered which are located at a transport distance of less than 500 km from Gibraltar. This concerns 10 power stations. If the average capacity of these power stations is 600 MW, and if these are coal-fired power stations, a net reduction of CO_2 emissions is possible of 0.021 Gt CO_2/a. The total costs for removing and transporting CO_2 to Gibraltar Falls for these 10 power stations are estimated at 0.8 to 0.9 x 10^9 ECU/a. This corresponds with 38 to 46 ECU per ton CO_2 avoided.

ad 4 Energy farming in Europe

On the EC agricultural surplus area of 20 to 30 x 10^6 ha, it would be possible to produce 96 to 144 x 10^9 litres bioethanol with conventional techniques. Thus a net maximum emission reduction is possible of 0.06-0.10 Gt/a. The costs are estimated to be 32 to 48 x 10^9 ECU/a, on the basis of data from the USA, corresponding with 510 ECU/ton CO_2. If avoided petrol costs are also taken into account, the costs are 4 x 10^9 ECU/a lower, leading to 450 ECU/ton CO_2, approximately. Though these amounts are high, this option does deserve attention, since avoided export subsidies for cereals and the fallow premium for agricultural surplus areas should be taken into account.

ad 5 Afforestation in Europe

The transformation of agricultural land into forest would result in a net accumulation of around 560 kg C/ha.a. Based on this figure, on the 20 to 30 x 10^6 hectares mentioned above 11 to 17 Mt C per year will accumulate. This corresponds with 0.04-0.06 Gt CO_2/a. The transformation of agricultural land into forest in Europe on this scale would entail a total cost of 1 to 6 x 10^9 ECU/a, and correspond with 23 to 100 ECU per ton CO_2 avoided.

Note: Obviously, a choice between ad 4 and ad 5 will have to be made

ad 6 Afforestation and reforestation in tropical areas

If it is assumed that the mean annual production of biomass in tropical areas is only10% of the production of biomass in Europe, then reforestation of 13 x 10^6 ha per year would result in an annual accumulation of 9.2 Mt of carbon per year. This corresponds with 0.03 Gt CO_2/a. However, this accumulation has a temporary character, because after these tropical forests become mature the net accumulation of biomass becomes zero. The costs are estimated at 3.6 x 10^9 ECU/a. This corresponds with 120 ECU per ton CO_2 avoided.

ad 7 Energy saving

An energy saving objective of 2% per year over 10 years in the European Communities would ultimately result in a reduction of 0.698 Gt CO_2/a. For this energy saving objective, an investment of 34.9 x 10^9 ECU/a is estimated. This corresponds with 50.0 ECU per ton CO_2 avoided. If, however, the avoided cost of energy production and related investments are taken into account, the net cost is only 2.3 ECU/ton CO_2.

ad 8 Renewables

The European Communities' goal of enlarging the contribution of renewables in 2010 to the level of 5% of current energy consumption, would imply a growth of 70 PJ per year. This would cumulatively result in a CO_2 emission reduction of 0.105 Gt/a. The costs are estimated at 5.58×10^9 ECU/a. This corresponds with 53.1 ECU per ton CO_2 avoided. If the avoided cost of conventional energy production and related investments are taken into account, the net costs are only 1.11×10^9 ECU/a, or 10.6 ECU/ton CO_2.

ad 9 Nuclear energy

It is estimated that in the long run the total costs of a 600 MW nuclear power plant would amount to 144×10^6 ECU/a. To this amount, 25% is added for costs of storage of nuclear waste and dismantling of nuclear power plants. This percentage is, however, still very uncertain. Replacing a 600 MW coal-fired power plant with a nuclear power plant would result in a reduction of 3.2 Mt CO_2/a.

Replacing 20% of the fossil fuel power stations with nuclear stations would then cost 13.9×10^9 ECU/a, and lead to an emission reduction of 0.25 Gt CO_2/a, or 56 ECU/ton CO_2.

If the avoided costs of conventional energy production and related investments are subtracted, we arrive at net costs of 0.6×10^9 ECU/a, or 2.4 ECU/ton CO_2.

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10 Integration and evaluation

(E. Mot)

In the preceding chapters, the basic options for abating and confining CO_2 from fossil fuel burning in EUR12 have been analysed. In the first section of this chapter (10.1), the figures presented earlier will be integrated in order to obtain a total overview of the CO_2 situation in EUR12.
Next, a critical consideration of these results will be presented (10.2).

10.1 Integration

Some 13% of the global CO_2 emissions stem from EUR12; in section 2.2, this emission was estimated to be 0.745 Gt C/a.
It has been shown that the possibilities to reduce CO_2 emission by influencing the fossil fuel mix are limited (chapter 3). One of the reasons is that switching to natural gas implies an increased leakage of methane, which entails per molecule a greenhouse effect up to 27 times that of CO_2. Moreover, the global gas reserves are limited. Options for removing CO_2 from flue gases from point sources (read: power plants) are available, though not yet implemented. In this context, firing by oxygen instead of air, and absorption techniques, are most promising (chapter 4). These techniques have to be applied before injecting the CO_2 into the subsurface or the ocean. Also for useful application of CO_2, it is necessary to separate it from flue gases. From chapter 5 it can, however, be seen that for all present applications together, on a world level, still only a small fraction of the CO_2 emitted by fossil fuel burning could be utilised. So, even apart from the fact that CO_2 from flue gases generally contains more impurities than allowed, this option is simply not practical.
The only exception which can be foreseen in this respect is energy farming, by which CO_2 is transformed into biomass with the help of solar energy. This biomass is applied as an energy carrier, hence somehow oxydised into CO_2 (and H_2O) again. The net result is actually the use of solar energy, preventing an equivalent amount of fossil energy from being used. For the implementation of energy farming in EUR12, the availability of some 25 x 10^6 ha of redundant farmland is an interesting coincidence.
Large-scale implementation of energy farming is still in its infancy – except in Brazil, where sugar cane is used for the production of bioethanol. There are, however, a number of other options, which are today in their initial stage of investigation. In this context, in particular the development of methods for utilising algae may be important, since they bind carbon at a significantly higher rate than most other plants.

Injection of CO_2 from large point sources, mainly power plants, into aquifers and depleted gas fields is feasible (chapter 6).
Since, however, the presence of aquifers is a rule and that of gas fields an exception, the average distance from power plant to aquifers is shorter.
In order to obtain a first impression of these distances, the locations of fossil fuel power plants, as given in Annex II, have been plotted on the aquifer map of figure 6.9. The result is shown in fig. 10.1. It should be reminded, though,

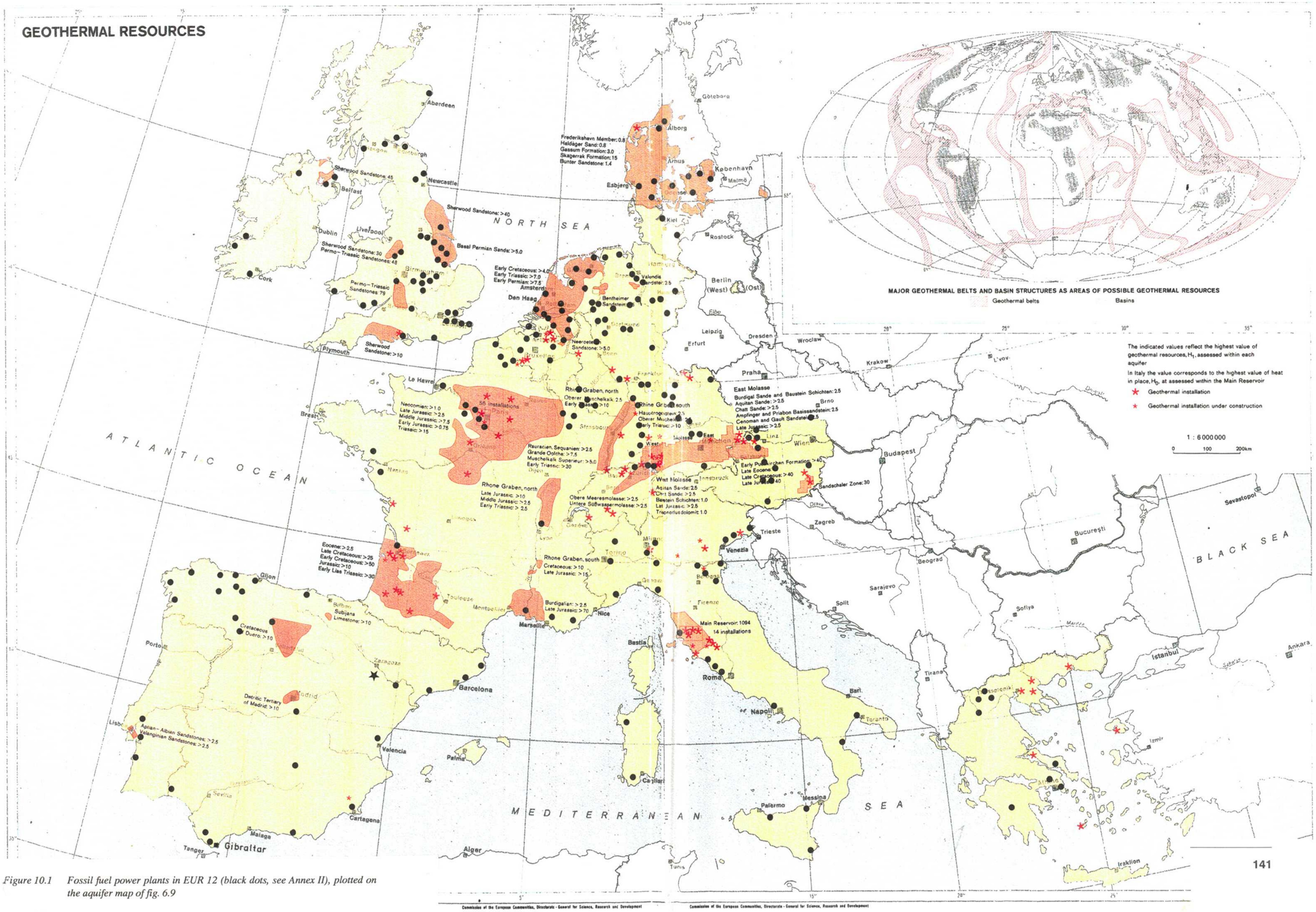

Figure 10.1 *Fossil fuel power plants in EUR 12 (black dots, see Annex II), plotted on the aquifer map of fig. 6.9*

In table 10.1, corrections for the relevant of overlaps have been carried out, on the basis of rough estimates. More specifically, the feasible CO_2 reduction by storage is reduced by 20% for gas fields and by 15% for aquifers. For energy farming and afforestation in Europe, the minimum figures from table 9.8 have been maintained. All other values are now taken as averages, and expressed in Gt C.

Table 10.1 Survey of feasible options of CO_2 abatement, confinement and prevention, that could be implemented simultaneously

			Feasible				
			GROSS		**NET**		
Options	**CO_2 [1] reduction ($Gt\ CO_2/a$)**	**CO_2 reduction (Gt C/a)**	**Total costs (10^9ECU/a)**	**Costs/ ton C (ECUs)**	**Total costs (10^9ECU/a)**	**Costs/ ton C (ECUs)**	**Number of years**
Abating and confining							
1. Removing CO_2 and storage in gas fields	0.16 [1]	0.044	5.84	133	5.84	133	110
2. Removing CO_2 and storage in aquifers	0.32 [1]	0.087	11.56	133	11.56	133	670
3. Removing CO_2 and pumping it down Gibraltar Falls	0.021	0.006	0.85	142	0.85	142	no limit
4. Energy farming	0.06 [1]	0.016	30	1900	26.25	1600	no limit
5. Afforestation in Europe	0.04 [1]	0.011	2.8	250	2.8	250	95
6. Afforestation and reforestation in tropical areas	0.03	0.008	3.6	450	3.6	450	35
Prevention							
7. Energy saving	0.698	0.190	34.9	183	1.6	8.4	no limit
8. Renewables	0.105	0.029	5.58	193	1.11	38.2	no limit
9. Nuclear energy	0.25	0.068	13.9	205	0.6	8.8	30
Total		0.459	109.03		54.21		

1) In order to avoid overlap, these figures have been lowered with respect to table 9.8

Comparing the total emission of 0.745 Gt C/a (section 2.2) with the calculated reduction of 0.459 Gt C/a from table 10.1 leads to a decrease of

$$\frac{0.459}{0.745} \times 100\% = 61.6\%$$

Hence, it can be seen that roughly

62% of the total C emission of EUR12 might be avoided for about 109×10^9 ECU/year gross, or 54×10^9 ECU/year net.

This implies average costs of $\frac{109.03}{0.459}$ = 238 ECU/ton C gross or,

$\frac{54.21}{0.459}$ = 118 ECU/ton C net, (65 ECU/ton CO_2 gross or,)

32 ECU/ton CO_2 net, respectively

10.2 Evaluation

It is obvious that the many uncertainties formulated in the preceding chapters, culminating in the quantitative estimates of table 10.1, require a critical evaluation.

In this context, it seems reasonable to begin with the observation that the analyses presented have the character of a **'snapshot'**. It is a static picture, indicating what basic possibilities exist for decreasing CO_2 emissions.

Actually, this picture should be used as a basis for a **scenario study** in which, starting from the real momentary situation in each field of action, a time path is plotted in order to evaluate what may be realised in the course of, say, the next 25 years. These time paths should indicate the interactions of a number of essential variables, such as world population, use of energy per capita in various parts of the world, etc. And, of course, ECU's.....

In this context, a logical starting point might be the rearrangement of table 10.1 in terms of increasing GROSS and NET costs per ton C avoided. The results are presented in table 10.2 and 10.3, respectively. Figure 10.2 shows these results graphically.

Table 10.2 Survey of feasible options of CO_2 abatement, confinement and prevention, that could be implemented simultaneously, placed in a sequence of increasing GROSS costs/unit C (0.745 Gt C/a = 100%)

					Gross			
Options	**CO_2 reduction ($Gt\ CO_2/a$)**	**CO_2 reduction (Gt C/a)**	**CO_2 reduction %**	**CO_2 reduction % cumulatively**	**Total costs (10^9 ECU/a)**	**Costs cumulatively (10^9 ECU/a)**	**Costs/ ton C (ECU)**	**Number of years**
– Removing CO_2 and storage in aquifers	0.32	0.087	12	12	11.56	11.6	133	670
– Removing CO_2 and storage in gas fields	0.16	0.044	6	18	5.84	17.4	133	110
– Removing CO_2 and pumping down Gibraltar Falls	0.021	0.006	1	19	0.85	18.3	142	no limit
– Energy saving	0.698	0.190	26	45	34.9	53.2	183	no limit
– Renewables	0.105	0.029	4	49	5.58	58.7	193	no limit
– Nuclear energy	0.25	0.068	9	58	13.9	72.6	205	30
– Afforestation in Europe	0.04	0.011	1	59	2.8	75.4	250	95
– Afforestation and reforestation in tropical areas	0.03	0.008	1	60	3.6	79.0	450	35
– Energy farming	0.06	0.016	2	62	30	109.0	1900	no limit
Total		0.459	62	62	109.03			

Table 10.3 Survey of feasible options of CO_2 abatement, confinement and prevention, that could be implemented simultaneously, placed in a sequence of increasing NET costs/unit C (0.745 Gt C/a = 100%)

					Nett			
Options	**CO_2 reduction ($Gt\ CO_2/a$)**	**CO_2 reduction (Gt C/a)**	**CO_2 reduction %**	**CO_2 reduction % cumulatively**	**Total costs (10^9 ECU/a)**	**Costs cumulatively (10^9 ECU/a)**	**Costs/ ton C (ECU)**	**Number of years**
– Energy saving	0.698	0.190	26	26	1.6	1.6	8.4	no limit
– Nuclear energy	0.25	0.068	9	35	0.6	2.2	8.8	30
– Renewables	0.105	0.029	4	39	1.11	3.3	38.2	no limit
– Removing CO_2 and storage in aquifers	0.32	0.087	12	51	11.56	14.9	133	670
– Removing CO_2 and storage in gas fields	0.16	0.044	6	57	5.84	20.7	133	110
– Removing CO_2 and pumping down Gibraltar Falls	0.021	0.006	1	58	0.85	21.6	142	no limit
– Afforestation in Europe	0.04	0.011	1	59	2.8	24.4	250	95
– Afforestation and reforestation in tropical areas	0.03	0.008	1	60	3.6	28.0	450	35
– Energy farming	0.06	0.016	2	62	26.25	54.2	1600	no limit
Total		0.459	62	62	54.21			

Thus a picture is presented, implying a first, rough indication of the sequence of priority in which this problem might be approached in actual practice.

It should, however, be stressed that this picture in not 'true' in a number of ways. First, it has already been indicated that there is little agreement about the future developments and the costs of most of the options presented here, and that in some extreme cases literature sources show differences of well over a factor of 10.
Second, it should be realised thtat each option mentioned here has in fact been built up from a series of suboptions, for which a picture similar to figure 10.2 could be drawn. It is obvious that the cheapest versions of these suboptions, hence the most profitable forms of renewable energy, of energy saving, etc. should be implemented in the first place. Finding and quantifying these options requires more detailed research.
Third, it should be remarked that, actually, the options presented here are, to a large extent, not comparable, due to all kinds of effects that are not taken into account here.
Energy saving and renewables, for instance, also decrease acidification and help save natural resources; nuclear reactors imply certain environmental risks and uranium reserves are limited. The logical next step in this context would be the implementation of breeder reactors which, however, lack public acceptance. Storage options require additional energy, forests may promote tourism, etc.

With these severe restrictions in mind, the picture of figure 10.2 might constitute the end of this study. However, in the context of this problem, which may be classified as one of the most fundamental ones mankind has ever come across, a number of more basic remarks are relevant.

The first one is that, though the 60% reduction of CO_2 emission calculated is quite high compared with estimates from other studies, it still constitutes only 30% of the reduction of all greenhouse gases. This will probably not be enough to prevent climate change, through it will cause some retardation of climatological effects. Therefore, abating the greenhouse effect should not focus on CO_2 only. It seems logical that further calculations are made in order to arrive at a rational choice between abating CO_2 to a large extent and the abatement of other greenhouse gases, notably CH_4, N_2O and CFCs, in order to arrive at an optimum abatement strategy for the greenhouse effect, hence a maximum reduction of CO_2 emission *equivalents* at minimum costs.

A second remark concerns the CO_2 fraction of the greenhouse problem.
Large, fundamental problems require large, fundamental solutions. Therefore, it is noteworthy that all options presented here somehow imply a continuation, or at most an adaption of the present trend.

Hence, in order to cope with this problem, the possibilities for arriving at a **breach of trend** should also be taken into consideration. In that context, the amount of 55×10^9 ECU/a net, required for abating 60% of the CO_2 emission in EUR12, may be considered an opportunity for investment, because it is only economic logic that any solution significantly cheaper deserves a chance.

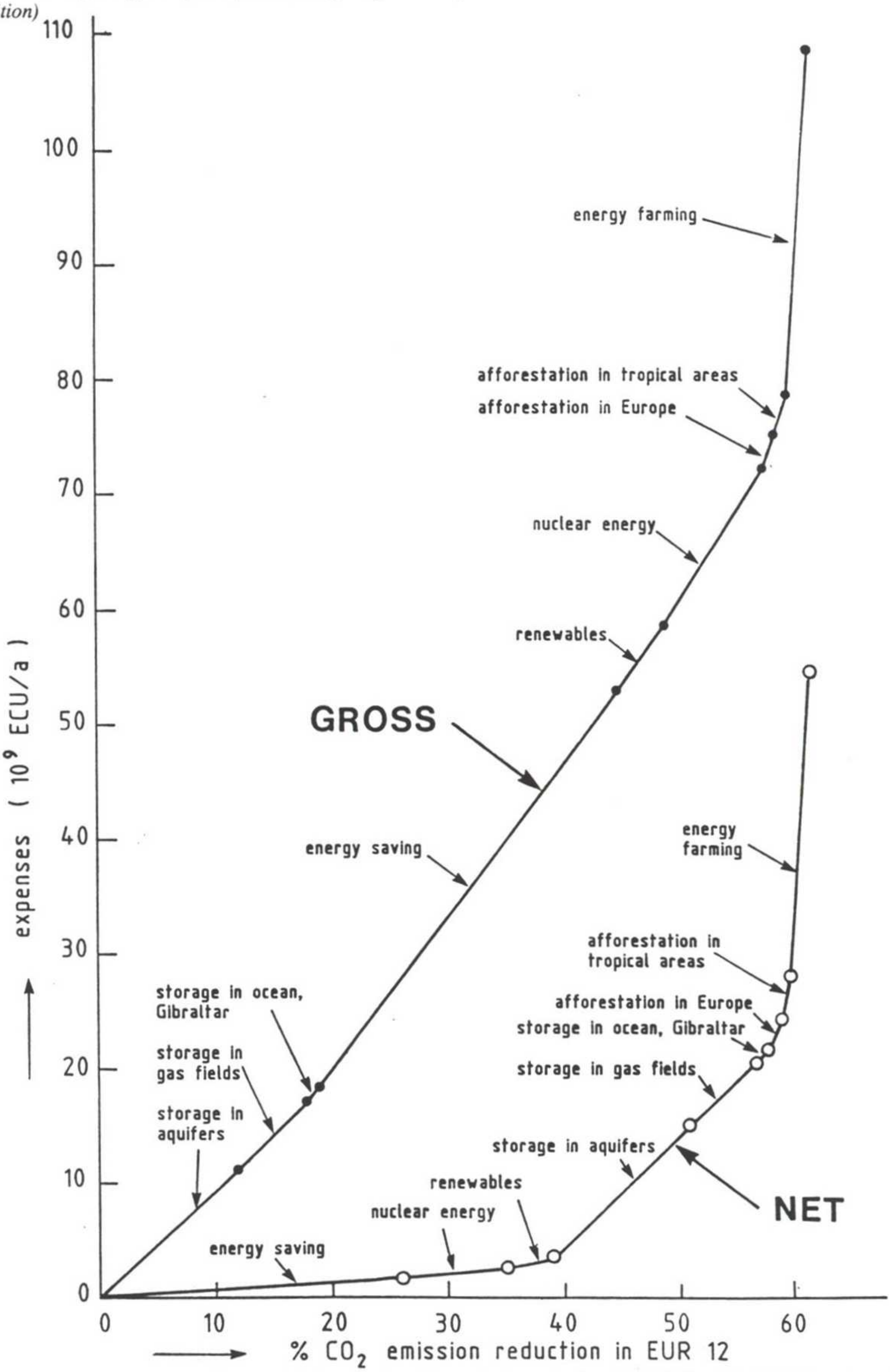

Figure 10.2 Options for CO_2 emission reduction in EUR12, NET/GROSS costs and effectiveness

This statement will be clarified with three examples.
None of these will be worked out in detail; all three serve only the purpose of indicating that the CO_2 problem is presently in the stage of premature thinking. Though no time should be wasted – because we are already late – very fundamental, basic decisions on how to proceed still have to be made.

Breach of trend no 1: Wind energy
From figure 10.2, it can be seen that renewables are a relatively attractive method for CO_2 emission prevention. However, in The Netherlands, and probably also in other EC-countries, it is usual to think of renewables in terms of *millions* of ECU's and of nuclear in terms of *milliards* of ECU's. What would, for example, be the consequence, if our efforts on wind energy are increased by a factor of 1,000 – or perhaps 'only' by a factor of 100? (In this context the option of large wind energy parks at sea, mentioned in 9.5.2, constitutes an interesting suggestion).
Certainly, we will see a forest of wind turbines, wherever we look. But accepting that is part of breaking the trend.....

Breach of trend no 2: Inherently safe nuclear breeding reactors
In 9.5.3 it was supposed that, in the framework of CO_2 prevention, 20% of the fossil fuel power stations were replaced by nuclear reactors. Taking the present public resistance against nuclear energy into account, this is certainly not a realistic proposition.
But if populations and governments would become convinced that they have to choose between the risks of nuclear energy and the certainty of an accelerated climate change, things might change.
In this context, the development of inherently safe nuclear reactors, also of the breeding type, a noteworthy development. In these reactors, accident prevention is integrated as much as possible into the basic design.
Moreover, it is known that well over 95% of reactor accidents are due to human errors. This probably implies that improvements in safety are feasible by further transferring human tasks to more fail-safe computer systems.

Breach of trend no 3: Controlling world population growth
This is definitely the most challenging, most difficult problem facing mankind. In figure 1.4, the expected increase in world population is shown. A large majority of this increase occurs in developing countries and it is clear that its increased contribution to the CO_2 emissions will be of great importance in the near future[*].
Little or no success can be claimed from historical efforts to control birthrates.
In the sixties, men in India were offered transistor radios as a reward for sterilisation. The effect was very limited.
Programs for distribution of contraceptives in developing countries failed as well – and it may well be concluded that this direct approach does not work.
It is noteworthy, though, that strong population increase today is a typical problem in developing areas, and that birthrate decreases with increasing prosperity. In this context, an important background is definitely the absence of governmental care

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[*] In this context it should be noted that the present world population of 5×10^9 people also produces 0.7 to 1.1 Gt C/a of CO_2 by exhalation. Though this quantity is not negligible in comparison with the 5.5 Gt C/a of CO_2 from fossil fuel burning, it should **not** be considered here, as it is part of the biological C cycle and does not stem from fossil sources.

for the elderly in most developing countries. Thus the offspring receives the role of old-age insurance.
Hence, increasing prosperity of third world countries will most probably lead to a decreased birthrate. However, it will also lead to an increased (fossil) CO_2 output per capita. Moreover, it has proved to be almost impossible to persuade developing countries to use renewables, to save energy, etc. – as soon as these cost more than the conventional (fossil) option.
This situation may well lead to the conclusion that part of our development work should be directed towards leaving the application of technologically simple renewables to the developing countries, thus minimising their use of fossil fuels, and simulaneously strongly emphasising renewables and nuclear energy in the developed world.

Three breaches of trend have been presented. None of these is realistic.
Yet, they serve the purpose of indicating that to the various options of CO_2 abatement, confinement and prevention presented in this study, other, more basic views have to be added and implemented. Further, it is obvious that the fervent controversy over renewables **or** nuclear energy should be ended as soon as possible, because in coping with the CO_2 problem, we will most probably need both.
Finally, any scenario study on this subject should probably be composed of elements from this study and aspects of 'breaches of trend', like those presented here.

11 Conclusions and recommendations

11.1 Conclusions

In this early stage of thinking on the CO_2 problem, the discrepancies on financial and other quantitative estimates between various investigators are considerable.
Though this investigation has been carried out on the basis of the best available knowledge, this emphasises both the uncertainty of many figures presented and the need for further research, in order to set out an EC policy on the subject. With this uncertainty in mind, the following conclusions can be drawn:

1. Simultaneously implementing all conceivable options of CO_2 abatement, confinement and prevention could avoid roughly **60% of the CO_2 emissions** from the European Community. This would cost about **110 milliard ECU/a, GROSS, or 55 milliard ECU/a NET** (that is, taking the benefits of avoided energy production into account).

2. In the context of CO_2 emission reduction, **point and diffuse sources** have to be distinguished. Point sources are mainly power plants. They cause some 25% of the total emission. Diffuse sources are traffic and transport, industry and built-up areas.

3. The effect of **influencing the fuel** mix is limited, amongst others since switching from oil and coal to natural gas would imply increased methane leakage. Further, the gas reserves are limited.

4. **Separation of CO_2** from point sources may best be realised by firing with oxygen, or with the help of an absorption technique. Both options are expensive and require some 20 to 30% additional energy. They are, however, a prerequisite for storage of CO_2 in the subsurface or ocean. In the future, though, improved separation technologies will be expected.

5. For **abating CO_2** from point sources (mainly power plants), storage in aquifers and in depleted gas fields are prospective options. The costs of these two options are similar. Storage in depleted gas fields has the additional advantage of improved gas recovery.

6. Though the **oceans** play a crucial role in the global carbon cycle, the possibilities for speeding up their carbon uptake are limited. For the EC, the only feasible option seems injection of CO_2 near Gibraltar, where it is transported by a current into the Atlantic Ocean to a depth of 1200 m. About 50% are, however, expected to be released again in 50 to 200 years.

7. For **confining CO_2**, 20 million to 30 million ha of redundant farmland available in the EC may be utilised either for afforestation or for energy farming. Both options are expensive, but imply positive side effects.

8. **Reforestation** and in particular prevention of deforestation in tropical areas is also a relevant tool for CO_2 confinement. This option is moreover of great importance in the context of development aid.

9. For **prevention** of CO_2 emissions, energy saving, nuclear energy and renewables are the basic options. Economically, they are the most attractive way of avoiding CO_2 emissions into the atmosphere. Energy saving and nuclear have the largest impact, particularly if their NET costs are considered.

10. Further, more drastic CO_2 emission reduction could only be brought about by implementing fundamental **breaches of trend**, e.g. large-scale implementation of wind energy and/or nuclear breeding reactors, together with an integrated, global approach to the problem of increasing world population.

11. A much stronger **emphasis on non-fossil options in the developed world**, simultaneous stimulating the application of technologically simple renewables in developing countries, thus minimising their use of fossil fuels, seems a logical policy for the near future.

11.2 Recommendations

11.2.1 General recommendations

1. On the basis of this study, a **scenario study** should be carried out, in which the development of the parameters relevant for CO_2 emission reduction are plotted as a function of time, for e.g. the next 25 years.

2. Simultaneously, **EC policy decisions** should be made on crucial matters like the future use of redundant farmland, renewable energy, nuclear energy, the role of the EC in the context of the tropical rain forests and in controlling world population.

3. A policy development study of the **optimum mix of** abating, confining and preventing **all relevant greenhouse gases**, viz. CO_2, CH_4, N_2O and CFCs, should be carried out.

11.2.2 Recommendations regarding specific issues

1. The start of a **demonstration project on CO_2 removal options,** preferably at a gas-fired power station, is recommended. In this context, absorption techniques should play an important role.

2. The further development of of **membrane separation techniques** is recommended for the development of new CO_2 removal technologies

3. Further investigations on **cryogenic scrubbing** are recommended as well.

4. It is recommended to study the combustion of fossil fuels with **oxygen as an oxidant** (instead of air) to produce CO_2 rich flue gases.

5. Research into the various options of **energy farming** is necessary, and in particular into the possible contribution of certain algae species, either freshwater or marine, in large tanks, ponds or bioreactors.

6. Investigation into the future use of **redundant farmland** is necessary, in particular regarding the basic choice between energy farming and afforestation.

7. Additional research into the possibility of **storing CO_2 in aquifers** is recommended.

8. Basic research into the options for preserving the **tropical rain forest** is of prime importance for CO_2 confinement, but also in the context of development aid. Parallel to this, actions on the subject of reforestation are very relevant.

12 Authentication

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4. CARBON CYCLE

Carbon dioxide (CO_2) is not a pollutant in the conventional sense; it is a normal component of the atmosphere and it is essential to the growth of plants, being a primary raw material for photosynthesis. However, man-made CO_2 emissions, mainly from fossil fuel combustion, have resulted in a gradual increase in the concentration of CO_2 from the historical level of around 300 parts per million. There is now a general consensus that increasing concentrations of the so-called *greenhouse gases* (including CO_2 as well as chlorofluorocarbons, ozone, methane and nitrous oxide) will cause a significant warming of the earth's climate within the next fifty years (the *greenhouse effect*). The magnitude of this warming is uncertain, but even modest warming would have disruptive effects. There is therefore strong interest, both at Community level and at the world level in policies directed towards the control of emissions of all greenhouse gases.

The figures presented here are the first published statistics for CO_2 emissions at Community level; they have been calculated by EUROSTAT from EUROSTAT's own energy balance sheets, following the internationally-accepted methodology of the US Carbon Dioxide Information and Analysis Centre (CDIAC) (see notes).

In general, CO_2 emissions in the EC countries, as in the USA and Japan, reached a peak in the nineteen-seventies and have been stable or declining since then. This is the result of fairly stable oil consumption following the oil supply crises of the nineteen-seventies, combined with declining coal consumption and increasing use of natural gas, which generates much less CO_2 per unit of energy. However, EC countries are still responsible for 13% of world CO_2 emissions from fossil fuels.

Notes

- EUROSTAT estimates for CO_2 emissions exclude emissions from gas flaring and from cement production, which together account for less than 5% of CO_2 emissions.
- EUROSTAT estimated the non-oxidized fractions of gas, liquid and solid fuels using balance sheet data on specific products; this estimate was made separately for each country and each year. CDIAC used an overall average for each class of fuel; this makes very little difference to the overall results, but the EUROSTAT method, which takes advantage of the more detailed input data available for EC countries, should be more accurate.
- to complete the tables, CDIAC data have been used as follows: World totals; USA; Japan; Greece 1960-1970; Spain 1960-1975; Portugal 1960-1975. The World total for 1987 is extrapolated from values for 1985-86.

Documentation

Estimates of CO_2 emissions from fossil fuel burning and cement manufacturing, based on the United Nations energy statistics and the US Bureau of Mines cement manufacturing data. Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

4.1

CO2 emissions: natural gas

1 000 000 t C

	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
EUR12	5.283	9.071	37.269	87.541	105.367	103.084	98.694	103.078	108.496	113.675	115.438	123.045
Belgique/Belgie	0.034	0.040	2.061	5.016	5.499	5.052	4.153	4.378	4.520	4.525	4.027	4.544
Danmark	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.062	0.357	0.649	0.824
BR Deutschland	0.414	1.543	7.907	21.549	27.899	26.523	23.879	24.595	25.318	25.625	25.532	28.351
Ellas	0.000	0.000	0.000	0.000	0.000	0.000	0.034	0.038	0.039	0.037	0.049	0.055
Espana	0.000	0.002	0.045	0.693	1.098	1.213	1.319	1.348	1.285	1.483	1.610	1.799
France	1.474	2.494	4.993	9.613	13.164	13.176	12.797	13.613	14.168	14.823	14.895	15.393
Ireland	0.000	0.000	0.000	0.000	0.391	0.634	0.975	1.046	1.109	1.151	0.780	0.756
Italia	3.141	3.695	6.321	11.162	13.905	13.474	13.553	13.908	16.338	16.748	17.787	19.817
Luxembourg	0.000	0.000	0.007	0.217	0.268	0.205	0.172	0.164	0.176	0.191	0.190	0.218
Nederland	0.179	0.831	9.518	19.478	18.831	17.902	17.063	18.126	19.010	19.940	20.074	20.732
Portugal	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
United Kingdom	0.042	0.465	6.418	19.812	24.312	24.905	24.748	25.862	26.471	28.795	29.845	30.556
USA	180.422	228.034	312.070	285.997	272.505	264.246	245.390	233.785	241.457	236.710	222.577	235.156
Japan	0.437	0.985	2.095	4.682	13.082	13.262	13.577	14.560	19.568	21.010	22.132	23.063

4.2

CO2 emissions: liquid fuels

1 000 000 t C

	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
EUR12	115.574	232.779	379.319	407.399	424.271	389.301	371.321	357.110	372.005	361.301	367.459	372.571
Belgique/Belgie	4.949	10.282	17.739	17.173	17.952	15.873	15.023	13.391	12.725	13.166	15.485	15.061
Danmark	3.676	7.375	13.712	12.091	10.691	9.306	8.835	8.399	8.336	8.762	8.435	7.969
BR Deutschland	23.803	56.824	94.675	96.557	98.291	87.181	83.773	82.269	93.123	95.013	96.757	94.690
Ellas	1.490	2.466	4.376	6.730	9.341	8.715	8.820	8.516	8.315	8.768	8.575	9.089
Espana	3.885	8.666	17.886	31.328	38.118	35.116	33.374	32.447	30.125	28.549	28.940	29.318
France	20.172	39.069	68.090	81.465	83.885	74.455	69.411	66.269	64.734	62.381	62.430	64.700
Ireland	0.857	1.732	3.027	4.039	4.546	4.107	3.612	3.429	3.150	3.348	3.868	3.578
Italia	15.347	34.730	62.061	67.895	72.401	71.152	66.914	64.939	61.222	61.753	61.637	67.617
Luxembourg	0.171	0.639	1.016	1.073	0.891	0.855	0.840	0.810	0.807	0.875	0.953	1.084
Nederland	7.457	15.251	20.503	15.743	20.340	18.937	15.865	14.631	14.446	13.838	15.484	15.746
Portugal	1.435	2.064	2.568	4.520	6.555	6.561	7.060	7.169	6.985	6.347	6.675	6.123
United Kingdom	32.333	53.682	73.667	68.785	61.260	57.042	57.794	54.840	68.037	58.501	58.220	57.576
USA	349.790	406.597	514.822	565.124	581.029	533.085	502.245	500.064	507.096	506.568	531.079	544.285
Japan	22.002	54.846	129.270	161.176	166.995	156.214	151.463	149.061	157.097	142.754	142.733	143.185

4.3

CO2 emissions: solid fuels

1 000 000 t C

	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
EUR12	347.040	326.384	278.222	213.538	247.751	248.782	244.840	241.545	229.805	249.939	242.341	240.558
Belgique/Belgie	16.810	16.254	13.736	9.414	11.369	11.605	11.413	9.723	10.716	10.241	9.165	8.978
Danmark	3.901	3.502	2.368	2.223	6.087	5.135	6.117	5.774	5.990	7.787	7.610	7.852
BR Deutschland	114.733	105.705	94.676	73.417	85.930	87.184	84.921	85.845	88.007	86.276	82.019	78.155
Ellas	0.831	1.699	1.523	3.061	3.299	3.752	4.018	5.025	5.520	6.415	6.670	7.165
Espana	8.759	9.485	9.991	11.304	15.654	18.515	18.662	18.362	19.028	20.633	19.287	18.813
France	46.790	45.529	37.335	26.282	32.420	29.774	29.353	26.478	25.662	25.557	21.423	19.899
Ireland	1.750	1.636	1.783	1.320	1.770	1.764	1.882	2.021	2.602	2.728	2.984	3.773
Italia	7.954	8.573	9.260	8.406	11.513	13.083	13.750	12.821	14.590	15.707	14.726	13.943
Luxembourg	3.166	2.833	2.753	2.091	1.940	1.592	1.444	1.341	1.509	1.496	1.362	1.104
Nederland	11.201	9.737	5.257	2.505	4.229	3.872	5.398	5.326	6.914	6.828	6.761	7.115
Portugal	0.650	0.880	0.831	0.452	0.449	0.388	0.335	0.444	0.388	0.689	1.170	1.640
United Kingdom	130.495	120.551	98.709	73.064	73.091	72.119	67.547	68.384	48.880	65.581	69.164	72.122
USA	253.437	301.107	322.436	317.558	394.640	403.000	390.091	405.462	427.795	448.009	437.742	434.489
Japan	38.403	45.759	63.301	58.899	62.821	68.902	68.529	65.235	76.928	80.474	76.337	75.205

4.4

Per capita CO2 emissions: natural gas

t C

	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
EUR12	0.019	0.031	0.123	0.281	0.331	0.323	0.309	0.322	0.338	0.353	0.358	0.380
Belgique/Belgie	0.004	0.004	0.214	0.512	0.558	0.513	0.421	0.444	0.459	0.459	0.408	0.460
Danmark	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.070	0.127	0.161
BR Deutschland	0.007	0.026	0.130	0.349	0.453	0.430	0.387	0.400	0.414	0.420	0.418	0.463
Ellas	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.004	0.004	0.004	0.005	0.006
Espana	0.000	0.000	0.001	0.020	0.029	0.032	0.035	0.035	0.034	0.039	0.042	0.046
France	0.032	0.051	0.098	0.182	0.244	0.243	0.235	0.249	0.258	0.269	0.269	0.277
Ireland	0.000	0.000	0.000	0.000	0.115	0.184	0.280	0.299	0.314	0.325	0.220	0.213
Italia	0.063	0.071	0.117	0.201	0.246	0.238	0.239	0.245	0.287	0.293	0.311	0.346
Luxembourg	0.000	0.000	0.021	0.601	0.734	0.560	0.471	0.448	0.481	0.521	0.515	0.585
Nederland	0.016	0.068	0.730	1.425	1.331	1.256	1.192	1.262	1.318	1.376	1.378	1.414
Portugal	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
United Kingdom	0.001	0.009	0.115	0.352	0.432	0.442	0.440	0.459	0.469	0.509	0.526	0.537
USA	0.999	1.174	1.522	1.324	1.197	1.149	1.056	0.997	1.020	0.989	0.921	0.964
Japan	0.005	0.010	0.020	0.042	0.112	0.113	0.115	0.122	0.153	0.174	0.182	0.189

4.5

Per capita CO2 emissions: liquid fuels

t C

	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
EUR12	0.413	0.794	1.250	1.306	1.335	1.220	1.161	1.114	1.158	1.122	1.138	1.151
Belgique/Belgie	0.543	1.088	1.841	1.753	1.823	1.611	1.524	1.359	1.291	1.336	1.570	1.526
Danmark	0.802	1.550	2.782	2.389	2.087	1.817	1.726	1.642	1.631	1.713	1.647	1.558
BR Deutschland	0.429	0.969	1.561	1.562	1.597	1.413	1.359	1.339	1.522	1.557	1.584	1.547
Ellas	0.179	0.288	0.498	0.744	0.969	0.896	0.901	0.865	0.840	0.883	0.861	0.910
Espana	0.128	0.270	0.530	0.882	1.020	0.930	0.879	0.850	0.786	0.741	0.748	0.755
France	0.442	0.801	1.341	1.546	1.557	1.374	1.274	1.211	1.178	1.131	1.127	1.163
Ireland	0.303	0.602	1.026	1.271	1.337	1.193	1.038	0.979	0.893	0.946	1.092	1.010
Italia	0.306	0.666	1.153	1.225	1.283	1.259	1.181	1.143	1.074	1.081	1.077	1.179
Luxembourg	0.543	1.920	2.989	2.976	2.441	2.339	2.299	2.217	2.204	2.382	2.580	2.913
Nederland	0.649	1.240	1.573	1.152	1.437	1.329	1.108	1.018	1.002	0.955	1.063	1.074
Portugal	0.160	0.226	0.284	0.497	0.671	0.666	0.711	0.716	0.692	0.625	0.654	0.597
United Kingdom	0.617	0.988	1.324	1.223	1.088	1.012	1.026	0.973	1.205	1.033	1.026	1.011
USA	1.936	2.087	2.511	2.617	2.551	2.318	2.162	2.132	2.143	2.113	2.198	2.231
Japan	0.236	0.560	1.250	1.445	1.430	1.328	1.279	1.250	1.309	1.182	1.175	1.173

4.6

Per capita CO2 emissions: solid fuels

t C

	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
EUR12	1.241	1.113	0.917	0.685	0.779	0.780	0.765	0.753	0.715	0.776	0.751	0.743
Belgique/Belgie	1.843	1.720	1.425	0.961	1.155	1.178	1.158	0.987	1.087	1.039	0.929	0.910
Danmark	0.851	0.736	0.481	0.439	1.188	1.003	1.195	1.129	1.172	1.523	1.486	1.531
BR Deutschland	2.070	1.803	1.561	1.187	1.396	1.413	1.378	1.398	1.439	1.414	1.343	1.277
Ellas	0.100	0.199	0.173	0.338	0.342	0.386	0.410	0.510	0.558	0.646	0.669	0.717
Espana	0.288	0.296	0.296	0.318	0.419	0.490	0.491	0.481	0.496	0.536	0.499	0.484
France	1.024	0.934	0.735	0.499	0.602	0.550	0.539	0.484	0.467	0.463	0.387	0.358
Ireland	0.618	0.569	0.604	0.415	0.520	0.512	0.541	0.577	0.737	0.771	0.843	1.065
Italia	0.158	0.165	0.172	0.152	0.204	0.232	0.243	0.226	0.256	0.275	0.257	0.243
Luxembourg	10.055	8.507	8.101	5.799	5.316	4.354	3.951	3.667	4.122	4.073	3.685	2.968
Nederland	0.975	0.792	0.403	0.183	0.299	0.272	0.377	0.371	0.479	0.471	0.464	0.485
Portugal	0.073	0.096	0.092	0.050	0.046	0.039	0.034	0.044	0.038	0.068	0.115	0.160
United Kingdom	2.492	2.218	1.774	1.299	1.293	1.280	1.200	1.214	0.866	1.158	1.218	1.267
USA	1.403	1.550	1.572	1.470	1.733	1.752	1.679	1.729	1.808	1.872	1.812	1.781
Japan	0.412	0.467	0.612	0.528	0.538	0.586	0.579	0.547	0.641	0.666	0.628	0.616

4.7

CO2 emissions: all fossil fuels

1 000 000 t C

	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
EUR12	467.897	568.233	694.810	708.478	777.389	741.167	714.855	701.733	710.307	724.915	725.238	736.174
Belgique/Belgie	21.792	26.576	33.535	31.603	34.821	32.530	30.589	27.493	27.961	27.931	28.678	28.582
Danmark	7.576	10.876	16.080	14.314	16.778	14.441	14.952	14.173	14.388	16.907	16.694	16.665
BR Deutschland	138.950	164.072	197.258	191.522	212.120	200.889	192.573	192.710	206.448	206.915	204.308	201.195
Ellas	2.321	4.165	5.899	9.791	12.640	12.467	12.872	13.579	13.874	15.220	15.294	16.310
Espana	12.644	18.153	27.922	43.325	54.870	54.845	53.354	52.158	50.438	50.665	49.837	49.930
France	68.436	87.092	110.418	117.360	129.470	117.405	111.561	106.361	104.563	102.761	98.748	99.991
Ireland	2.607	3.368	4.810	5.359	6.706	6.504	6.469	6.496	6.861	7.227	7.632	8.107
Italia	26.442	46.998	77.642	87.463	97.818	97.708	94.217	91.668	92.150	94.208	94.149	101.378
Luxembourg	3.337	3.472	3.776	3.380	3.098	2.651	2.456	2.315	2.493	2.562	2.505	2.406
Nederland	18.837	25.819	35.278	37.727	43.400	40.711	38.326	38.082	40.370	40.606	42.320	43.592
Portugal	2.085	2.944	3.399	4.972	7.005	6.949	7.396	7.613	7.373	7.036	7.344	7.764
United Kingdom	162.870	174.698	178.794	161.662	158.663	154.066	150.089	149.086	143.387	152.878	157.228	160.254
USA	783.649	934.738	1 149.328	1 168.679	1 248.174	1 200.331	1 137.726	1 139.301	1 176.348	1 190.287	1 191.398	1 213.930
Japan	60.842	101.590	194.666	224.757	242.898	238.378	233.569	228.856	253.593	244.238	241.202	241.453

4.8

Per capita CO2 emissions: all fossil fuels

t C

	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
EUR12	1.673	1.937	2.290	2.271	2.445	2.323	2.235	2.189	2.211	2.252	2.247	2.274
Belgique/Belgie	2.390	2.813	3.480	3.227	3.536	3.302	3.104	2.790	2.837	2.833	2.908	2.896
Danmark	1.654	2.286	3.262	2.829	3.275	2.820	2.922	2.771	2.815	3.306	3.260	3.250
BR Deutschland	2.507	2.799	3.252	3.098	3.445	3.257	3.124	3.137	3.375	3.391	3.346	3.288
Ellas	0.279	0.487	0.671	1.082	1.311	1.281	1.315	1.379	1.402	1.532	1.535	1.633
Espana	0.415	0.566	0.827	1.220	1.468	1.453	1.405	1.366	1.315	1.316	1.289	1.286
France	1.498	1.786	2.175	2.227	2.403	2.167	2.048	1.943	1.903	1.863	1.783	1.797
Ireland	0.921	1.171	1.630	1.687	1.972	1.889	1.859	1.854	1.944	2.041	2.156	2.288
Italia	0.527	0.902	1.443	1.578	1.733	1.729	1.663	1.613	1.617	1.649	1.645	1.768
Luxembourg	10.598	10.427	11.111	9.375	8.491	7.252	6.720	6.332	6.807	6.976	6.780	6.466
Nederland	1.640	2.100	2.706	2.761	3.067	2.857	2.678	2.651	2.799	2.802	2.904	2.973
Portugal	0.233	0.322	0.376	0.547	0.717	0.705	0.745	0.761	0.731	0.693	0.768	0.757
United Kingdom	3.110	3.214	3.214	2.875	2.817	2.734	2.666	2.646	2.540	2.700	2.770	2.315
USA	4.337	4.811	5.605	5.411	5.481	5.218	4.897	4.859	4.971	4.974	4.931	4.977
Japan	0.652	1.037	1.883	2.015	2.080	2.026	1.972	1.919	2.113	2.023	1.985	1.978

4.9

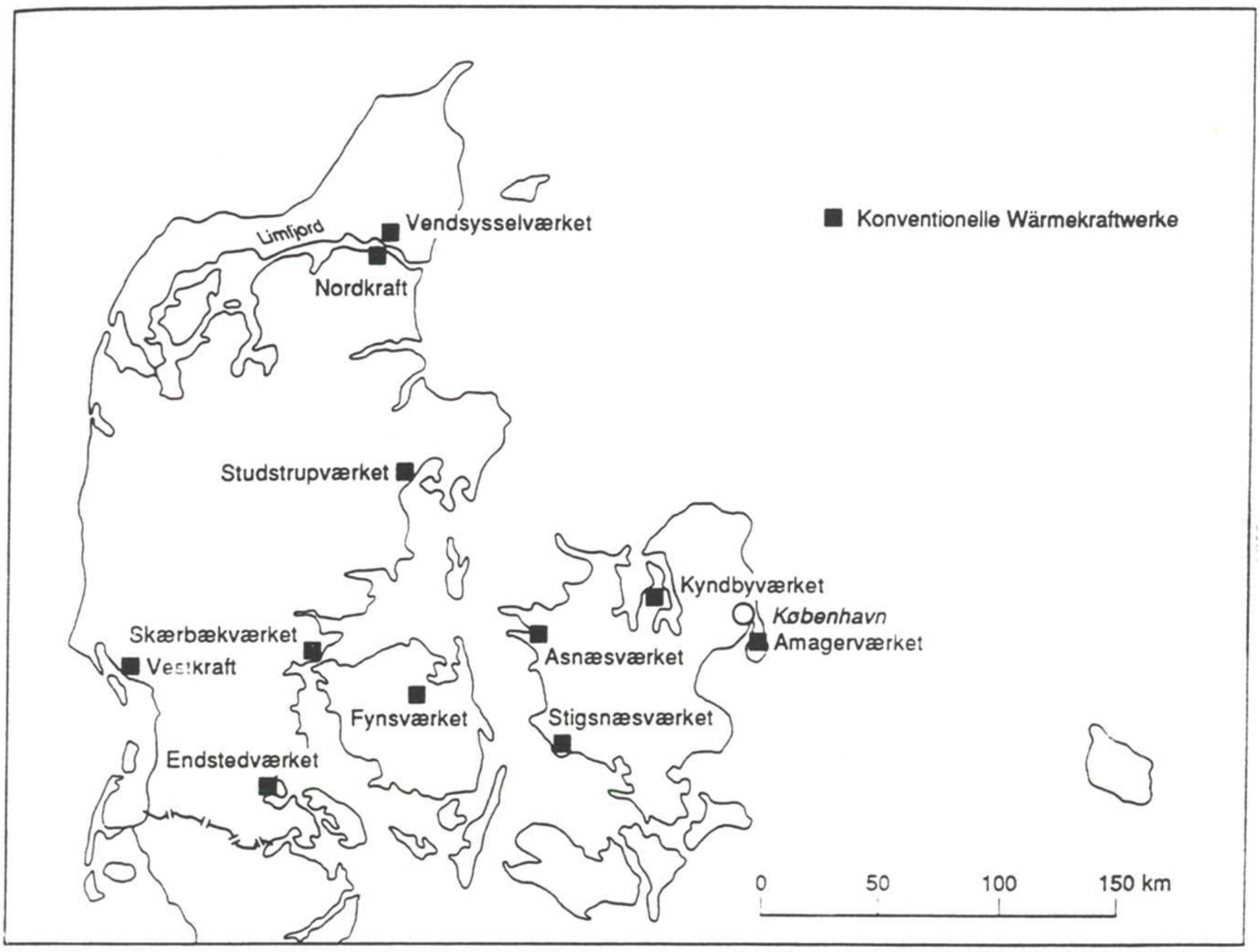
CO2 emissions from fossil fuels: global contribution of EC Member States

- 1 000 000 t C

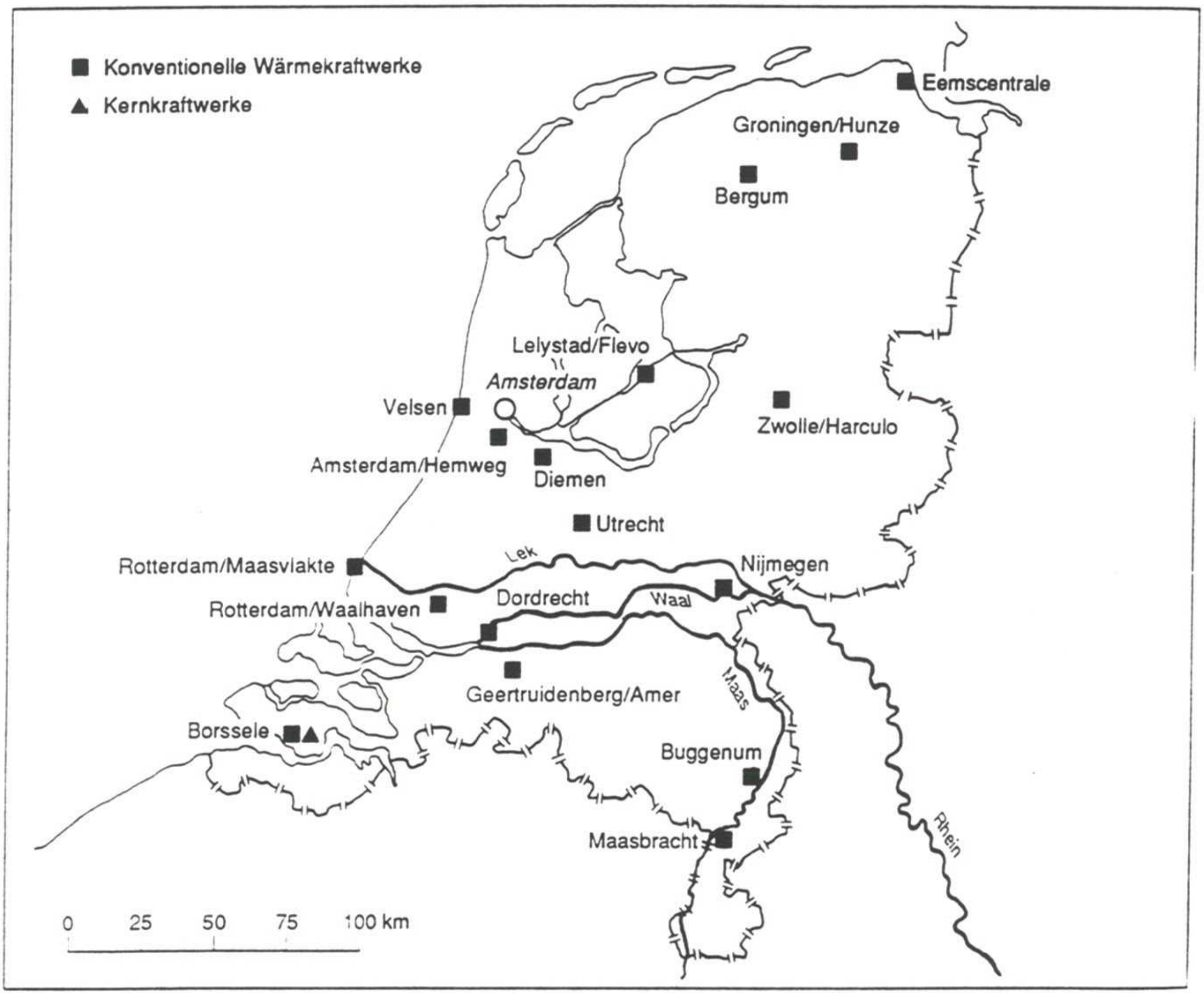
	1960	1965	1970	1975	1980	1981	1982	1983	1984	1985	1986	1987
World total	2 504.000	3 040.000	3 924.000	4 437.000	5 051.000	4 934.000	4 898.000	4 839.000	5 063.000	5 162.000	5 374.000	5 594.707
EUR12	467.897	568.233	694.810	708.478	777.389	741.167	714.855	701.733	710.307	724.915	725.238	736.174
	18.7%	18.7%	17.7%	16.0%	15.4%	15.0%	14.6%	14.4%	14.0%	14.0%	13.5%	13.2%

Annex II Power plants in Europe (Von Brecht, 1988)

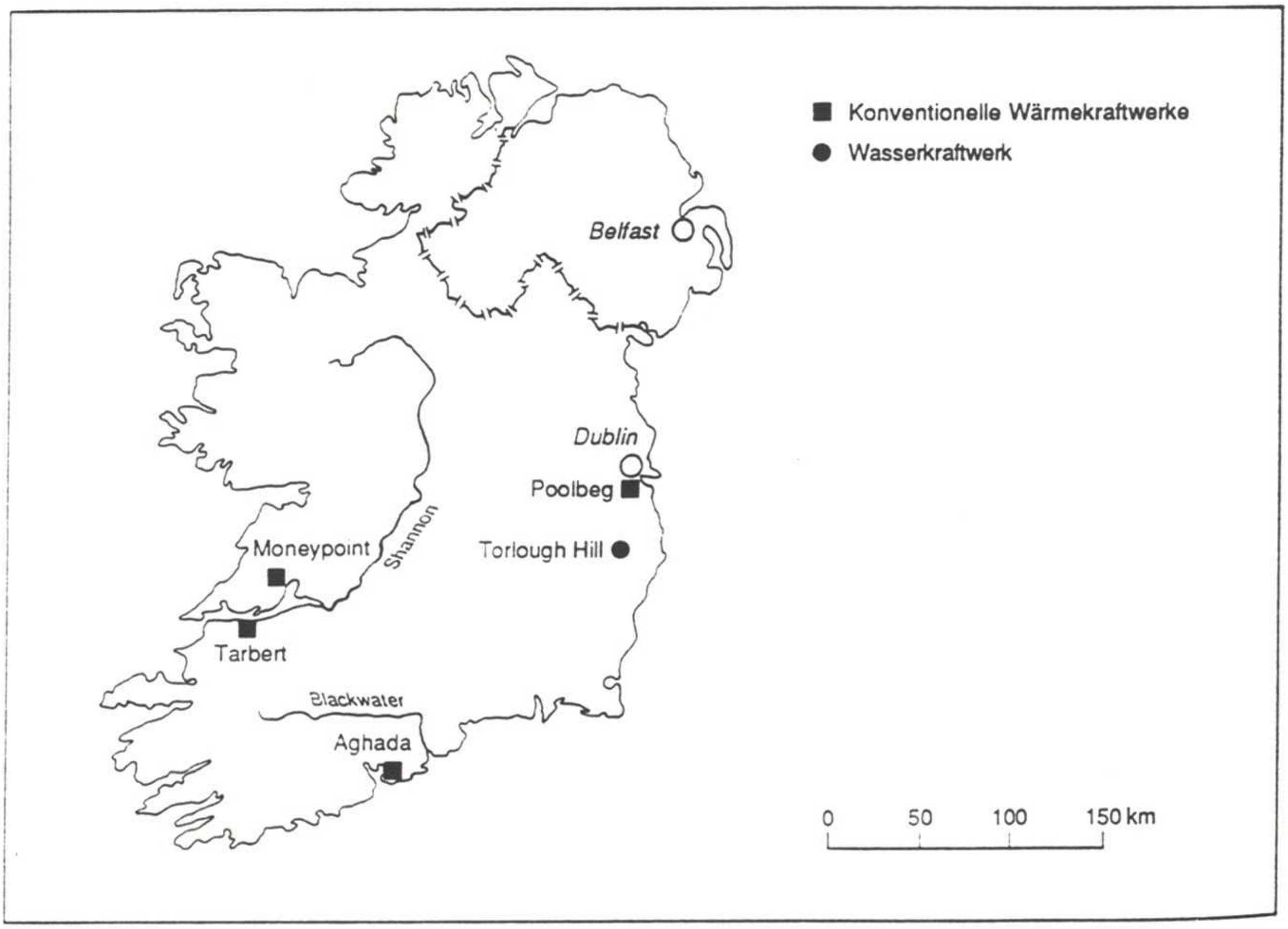
POWER PLANTS IN DANMARK (CAPACITY > 300 MW)



POWER PLANTS IN THE NETHERLANDS (CAPACITY > 300 MW)



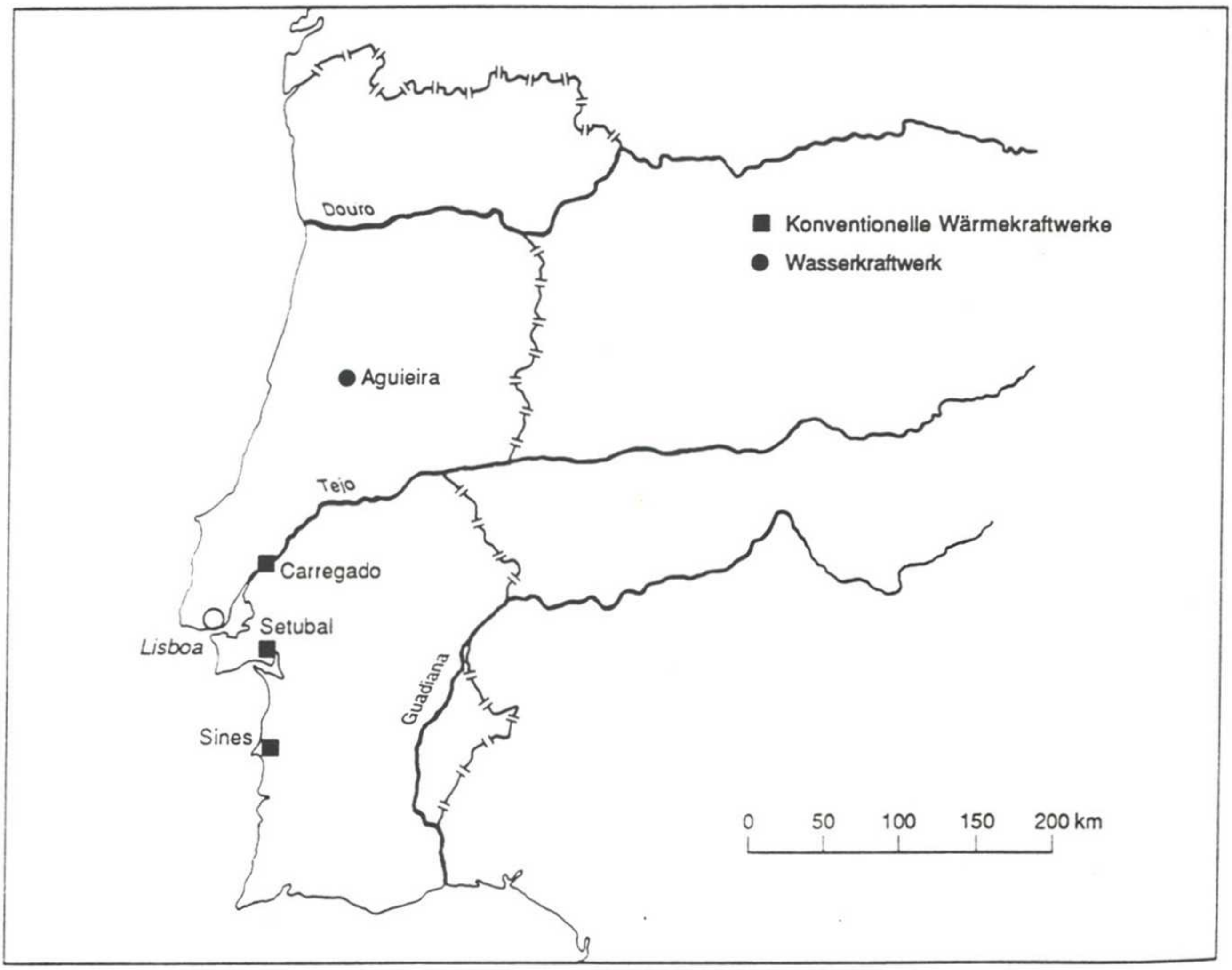
POWER PLANTS IN IRELAND (CAPACITY > 300 MW)



POWER PLANTS IN SPAIN (CAPACITY > 300 MW)

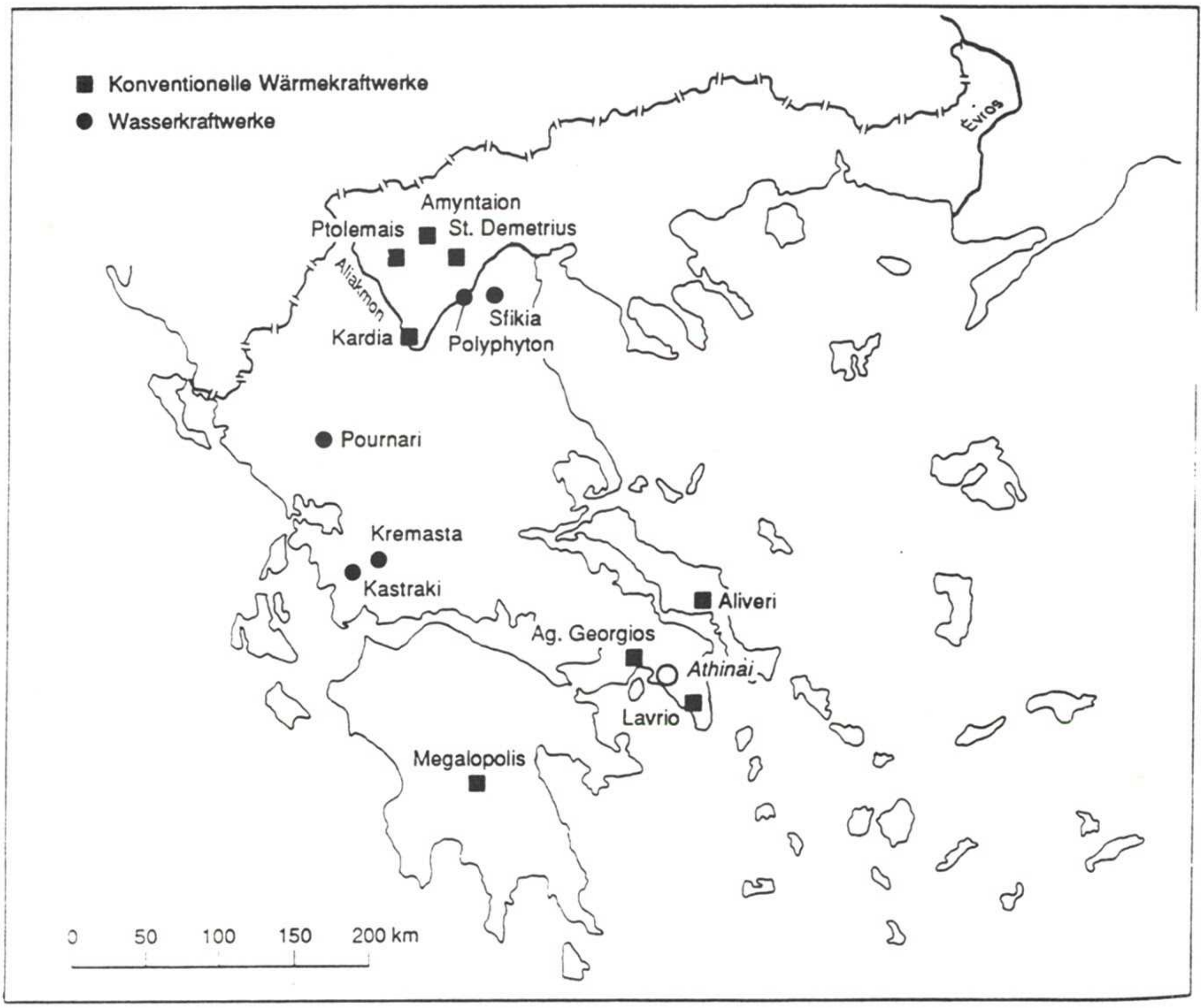
POWER PLANTS IN ITALY (CAPACITY > 300 MW)

POWER PLANTS IN PORTUGAL (CAPACITY > 300 MW)

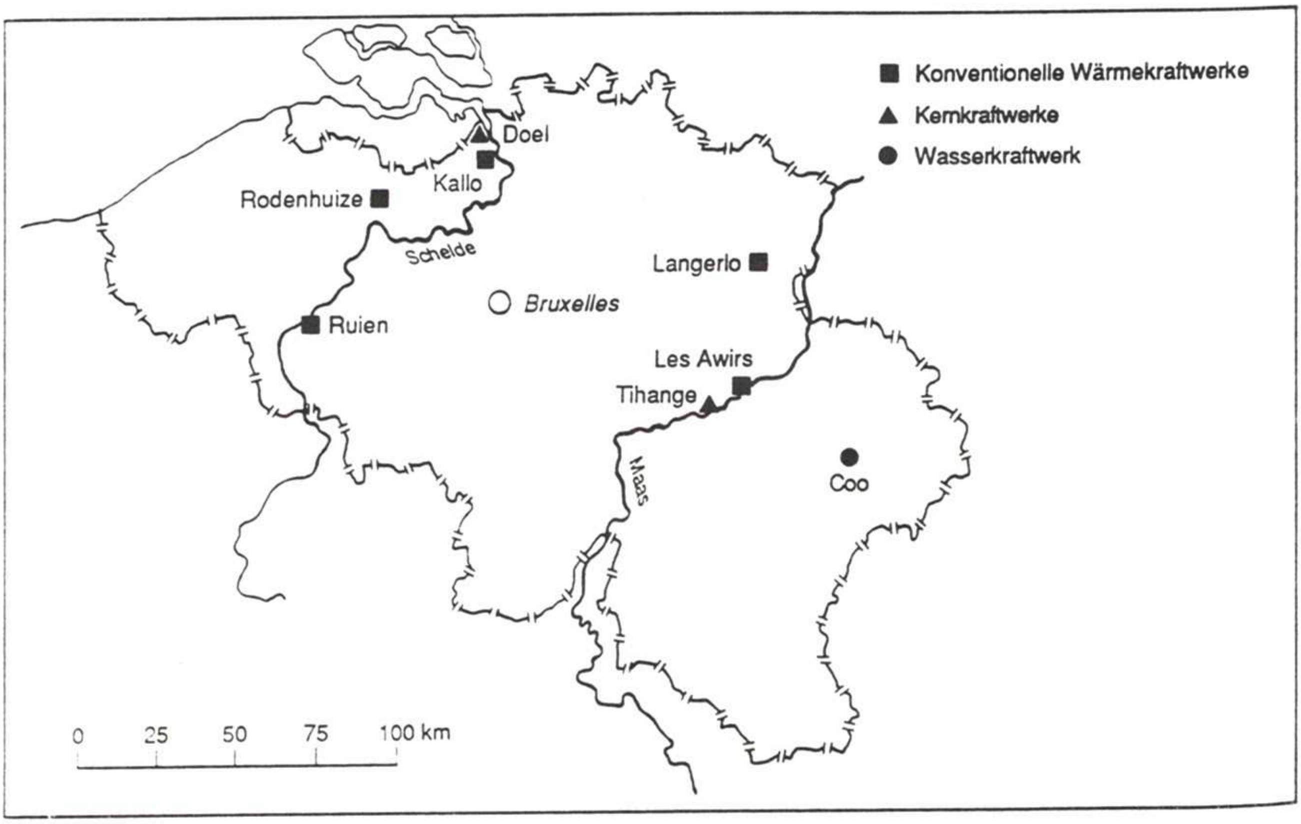


POWER PLANTS IN THE UK (CAPACITY > 300 MW)

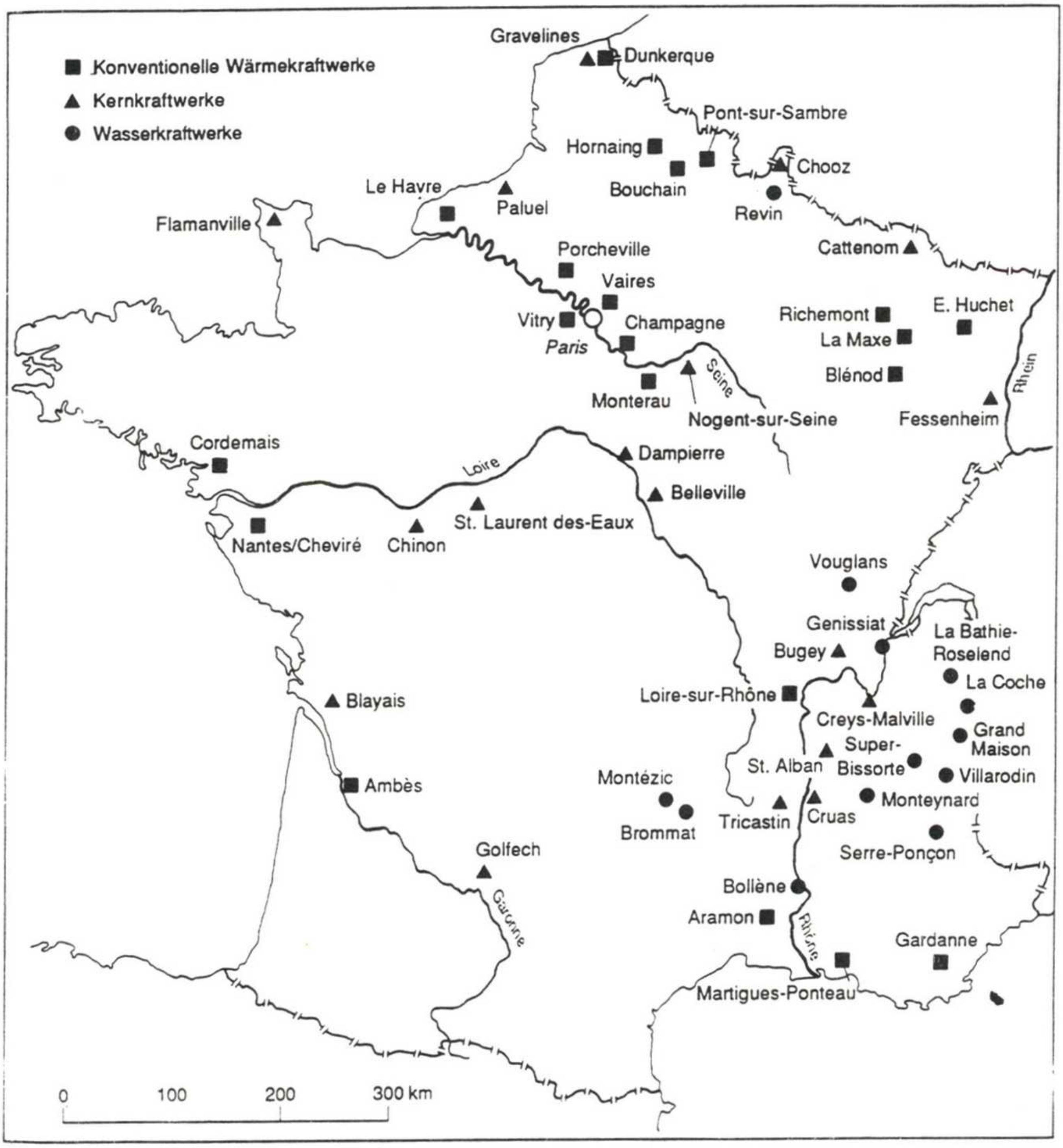
POWER PLANTS IN GREECE (CAPACITY > 300 MW)

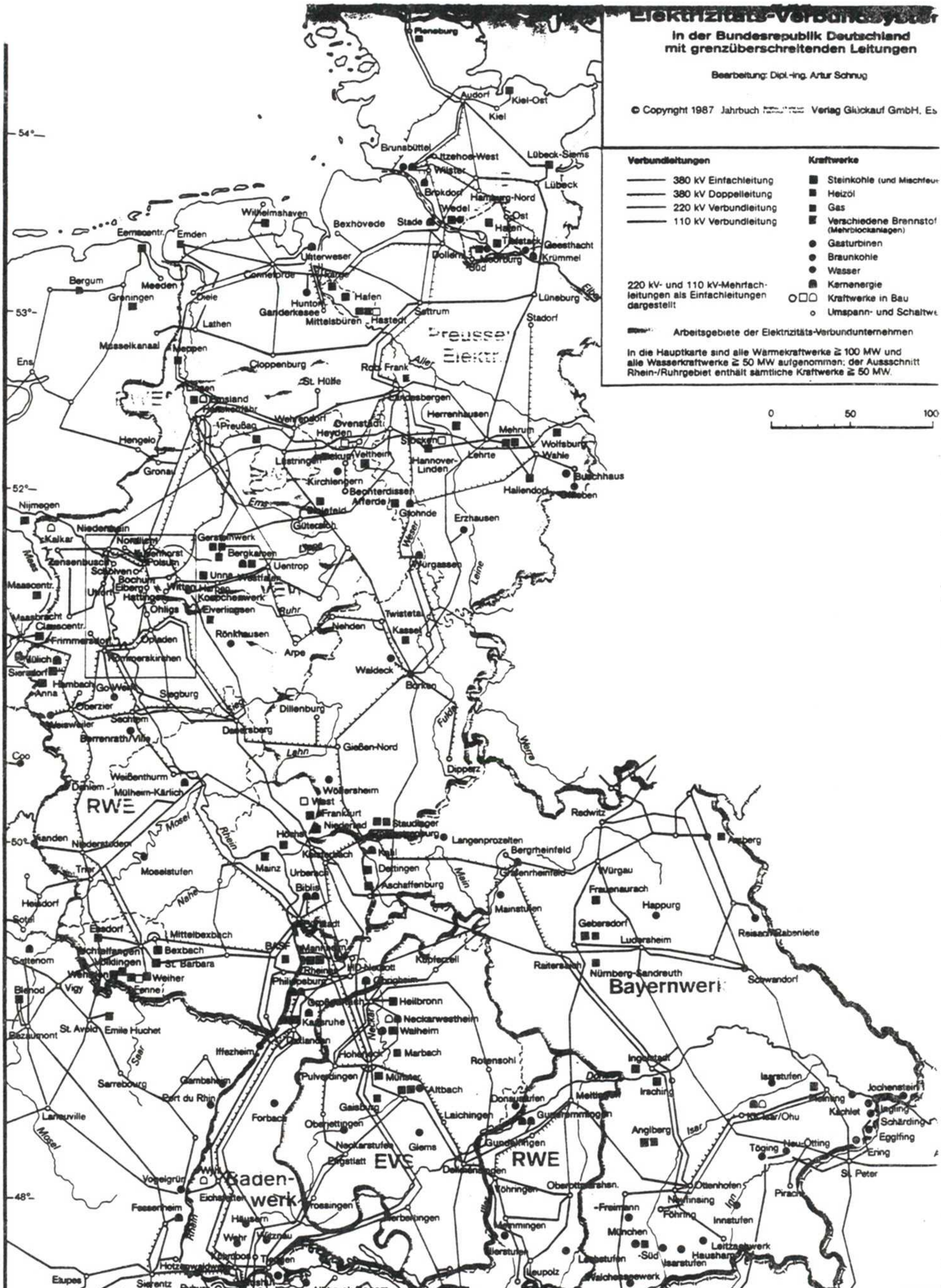


POWER PLANTS IN BELGIUM (CAPACITY > 300 MW



POWER PLANTS IN FRANCE (CAPACITY > 300 MW)





Elektrizitäts-Verbundsyst

in der Bundesrepublik Deutschland mit grenzüberschreitenden Leitungen

Bearbeitung: Dipl.-Ing. Artur Schnug

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