Ministry of Transport, Public Works and Water Management

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National Institute for Coastal and Marine Management/*RIKZ*

# Sequestration of carbon dioxide ($CO_2$) in the Dutch part of the North Sea

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# Preface

This study was commissioned (RIKZ 2002/05639, 17 May 2002) by H. Kersten and N. Ouibrahim (Directie Noordzee).

Objective:
To write a bilingual (Dutch and English) popular scientific report on the possible effects (on the seabed and organisms) and consequences of dumping and sequestering carbon dioxide ($CO_2$) on and in the seabed of the Dutch Continental Shelf (known in the Netherlands by the acronym NCP).

To issue advice based on this information to Directie Noordzee about the scientific, social and political consequences of dumping $CO_2$ in the Dutch part of the North Sea, so that Directie Noordzee can determine what stance to adopt for the London Dumping Convention.

# Contents

# 1 Introduction

### 1.1 Greenhouse effect

During the last 420,000 years the average $CO_2$ concentration on earth has varied between 180 and 280 particles per million per volume (ppmv). However, since the industrial revolution, more and more $CO_2$ has ended up in the atmosphere as a result of the increasing use of fossil fuels; the current concentration is 370 ppmv. Furthermore, it is estimated that if nothing changes, by 2100 this concentration will be approximately 750 ppmv. It is thus assumed that the $CO_2$ concentration in the atmosphere will rise to an unacceptable level in the next 500 years, as this rise will lead to a global strengthening of the greenhouse effect and associated climate change.

One of the results of the 1997 Kyoto Climate Conference was the commitment by all EU countries to reduce annual emissions of greenhouse gases (including $CO_2$) in the period 2008-2012 by eight percent with respect to the 1990 level. In 1998, the Netherlands agreed to this under certain conditions, and the joint objective was translated into a national reduction of six percent with respect to the 1990 level, to be achieved in the period 2008-2012.

### 1.2 Sources

The average worldwide anthropogenic emission of $CO_2$ is approximately 7.4 gigatons C per year (1997). This will rise to 26 GtC/year by 2100 (1 gigaton is 109 ton). The total emission of $CO_2$ for the Netherlands in 2000 was 50 Mt C (106 ton).

Sources of $CO_2$ include: power stations, industry, homes, traffic and transport, agriculture and horticulture, gas and oil extraction. The emissions of v by large point sources, such as heavy industry and power generation represent about a third of total worldwide anthropogenic emissions; in the Netherlands this accounts for about 56 percent.

Reducing the concentration of $CO_2$ in the atmosphere can be achieved in various ways, for instance by economising on energy use or by producing more materials in which carbon is sequestered for a long period of time (e.g. plastic and wood). In the short term, possible options include sequestering $CO_2$ in seawater and in the ground or the seabed under conditions that prevent its uncontrolled leakage back into the atmosphere.

Two important $CO_2$ releasing processes can be distinguished: burning of organic matter and separation of $CO_2$ from other gasses. By nature, natural gas contains up to 70% $CO_2$, which must be removed before the gas can be used by the consumer. Sequestration of $CO_2$ in seawater or bottom needs pure $CO_2$. From a technical point of view it is possible to separate $CO_2$ from other gasses. However, this process needs energy and consequently an additional release of $CO_2$. It is estimated that about 30% more $CO_2$ is produced in this purifying process. A complete

Life Cycle Analysis, comparing the efficiency of different matter and energy fluxes, is net yet performed.

In addition it is remarkable that in the literature studied, only the sources, path and fate of $CO_2$ as a gas is followed, and little is mentioned about the fate of other (greenhouse) gasses (e.g. nitrogen and sulphur oxides).

This memorandum evaluates the pros and cons of sequestering carbon in the sea and the possible associated risks.

# 2 Background

## 2.1 Seawater and carbon dioxide

By nature, $CO_2$ dissolves easily in water and particularly in seawater. This is because seawater has a higher acidity (pH) than fresh water. In seawater 1% of the $CO_2$ is present as $CO_2$ gas and more than 90% is present as bicarbonate. Additionally, warm water is in principle able to hold less gas than cold water. The solubility of $CO_2$ in deep and cold ocean water is twice the solubility in warmer surface water. The relatively warm surface water of the sea is saturated with $CO_2$, but the cold, deep water contains less $CO_2$ than it could potentially hold. The accelerated addition of atmospheric carbon dioxide to seawater does little to change the amount of carbon dioxide in seawater. Most of the $CO_2$ on earth is already in the oceans (38,000 GtC). If all fossil fuels were burnt and all the $CO_2$ this produced were taken up by the oceans, the amount of $CO_2$ would rise to 40,000 GtC.

It is assumed that in a thousand years, 85% of the current anthropogenic emissions to the atmosphere will be taken up by the oceans by natural processes. There are however, three ways of accelerating the sequestration of anthropogenic $CO_2$ in the sea.

- Adding $CO_2$ to seawater (for instance by means of direct injection);
- Increasing the production of algae by applying fertiliser;
- Storing $CO_2$ in the seabed in aquifers and gas and oil fields.

## 2.2 Adding carbon dioxide to seawater

Marchetti (1977) was the first to suggest injecting $CO_2$ into the deep, cold layers of the ocean. This water is not saturated with $CO_2$ and retains $CO_2$ for a very long time. $CO_2$ dissolves well in the relatively cold water of the Atlantic Ocean that sinks in the north and results in the thermohaline circulation of seawater southwards towards the South Pole. The water eventually surfaces again in the Indian and Pacific Oceans to flow back along the surface to the Atlantic Ocean. The time between sinking and rising to the surface again is estimated to be 1000 years. Studies using models have demonstrated that there are also locations in the ocean where the deep water surfaces within 100 years. In order to sequester $CO_2$ in seawater it is necessary to inject it at a depth of at least 1500 metres. At depths below 3000 metres the $CO_2$ is denser than the water and it will remain there as a layer of $CO_2$. It is assumed that this layer is isolated from the water above by carbon dioxide hydrates ($CO_2.5,75H_2O$).

It is technically possible to insert $CO_2$ in seawater at great depths. This can be done by allowing solid blocks of $CO_2$ to sink from ships or platforms. The estimated cost of energy (generating electricity) would in such case become 50-100% higher than is presently the case. The greatest costs would result from separating and purifying the carbon dioxide.

### 2.3 Fertilising

Algae in seawater naturally sequester $CO_2$ in organic material (50GtC/j), most of which is mineralised in the water phase (by being converted to $CO_2$). A small portion of the mass of algae that is produced (a maximum of one third) sinks to the ocean floor, where it is buried. This process from production to burial is called the biological pump.

In large parts of the oceans algae are unable to grow optimally; their production is hampered by a lack of nutrients. Adding macronutrients such as nitrates and phosphates (i.e. fertilising the oceans) and also adding essential microelements such as iron, would enable more algae to grow and more carbon to be sequestered in the deep ocean layers.

### 2.4 Carbon dioxide in aquifers

$CO_2$ can be sequestered in the porous water-bearing layers or aquifers that lie more than 800 metres below the earth's surface. The overlying layers of clay or salt prevent the $CO_2$ from escaping.
The most suitable aquifers in Western Europe are in central and southern England and in a ridge that stretches from Belgium and the Netherlands through Germany to Poland. It is assumed that the layers below the North Sea are also suitable. There are sufficient layers of this type in the Netherlands. Calculations show that at least 1500 megatons of $CO_2$ could be stored in them.

### 2.5 Carbon dioxide in gas and oil fields

There are no technical restrictions to sequester $CO_2$ in gas and oil fields. Compared to aquifers, oil and gas fields have the advantage that their geological proportions are better known. Gas fields at a depth of 2000 - 3000 metres are preferable over oil fields, as these fields have already proven that they can hold gas for very long periods of time. The gas is usually located in sandstone that is sealed at the top by salt formations. An added advantage of injecting $CO_2$ in existing gas fields is that it enhances the production of methane gas by flushing it out.

Various gas fields naturally contain so much $CO_2$ that the $CO_2$ first needs to be removed before it is possible to use them. In a large-scale project at the Norwegian Sleipner gas field, $CO_2$ that has been stripped of gas is injected in a saltwater layer at a depth of 1000 metres. There are no technical obstacles to injecting $CO_2$ in gas and oil fields. Production from the oil fields in the North Sea usually takes place by injecting water or by loss of pressure. As a result, 40-50% of the oil is often left behind. It is possible to achieve a greater gas and oil yield and a higher production capacity by injecting $CO_2$ during the production process.

# 3 Impact op het mariene ecosysteem

Many statements on the long-term behaviour of sequestered $CO_2$ are based on studies using models that have been tailored to particular situations and are still insufficiently calibrated and validated. Japan. Norway and America have agreed in 1997 to collaborate in (field) research to assess the possible consequences of $CO_2$ sequestration. Since than, Canada, Australia and Switzerland joint this international project. It is to be expected that an enormous amount of information about the possible risks will be released the coming next years from these projects.

## 3.1 Carbon dioxide in seawater

Inserting more $CO_2$ into seawater would mean that the acidity would rise (a lower pH value). It has been calculated that the current pH of seawater has already fallen by 0.1 unit owing to the absorption of anthropogenic $CO_2$. The pH in the deep ocean water is fairly constant. When $CO_2$ is injected the pH falls by about 1 unit in an area of several kilometres around the point of injection. It is expected that this will certainly have an influence on the organisms present there: their reproduction and growth may be slowed down. As a result of the lowering of the pH, calcite ($CaCO_3$) in the ocean sediments can dissolve. This may have a considerable impact on the calcium metabolism of organisms that use calcium to build shells or skeletons. Changes in pH also affect the bioavailability of metals for organisms, as a result of which symptoms of toxicity may occur.

If $CO_2$ is inserted into the oceans at great depths, it will remain suspended as a layer above the bed and will not mix well with water. Beneath this layer, organisms will die from a lack of oxygen. This will also certainly change the microbiological processes in the seabed.

Inserting solid carbon dioxide will greatly lower the temperature locally and this may cause organisms to die. Additionally, the release of $CO_2$ causes bubbles, which may interfere with the sonar communication between marine organisms. Moreover, insufficient account has been taken of the fact that after 100 – 1000 years the injected $CO_2$ will rise to the surface again and some will re-enter the atmosphere.

There are important reservations with regard to fertilising the sea with the aim of sequestering atmospheric carbon for a longer period of time. The assumption is that the fertilising substances will be applied in a pure form. In the first place, very little is known about the short and long term impact of fertilisation on the structure and dynamics of marine ecosystems. Fertilisation can lead to eutrophication, with the possible effect of local oxygen deprivation and uncontrolled (toxic) algal blooms. It is likely that fertilisation will lead to an unpredictably higher fish production. Additionally, modelling studies have shown that the amount of $CO_2$ that can be sequestered in the oceans in this way is likely to be smaller than expected.

### 3.2 Carbon dioxide in the bottom

From an administrative, technical, economical, social and environmental point of view it is assumed that existing installations will be used to pump $CO_2$ in the bottom layers. It is technically possible to inject $CO_2$ in aquifers, and international projects and experiments are being planned or conducted worldwide (see table 2). However, the ecological risks are not yet very well known and the isolating capacity of these layers still needs to be proven by location specific research.

Injection of $CO_2$ in the bottom can cause earthquakes, as shown in America and France (up to 1.5 on the scale of Richter). In its necessary here to consider that for instance in the Netherlands 128 earthquakes were recorded in 1986 caused by the pressure decrease by the mining of gas in the northern part of the Netherlands.

The ecological consequences of injecting $CO_2$ in exhausted and existing gas and oil fields are still unknown. A number of trial projects are already being conducted, but here, however, the main focus lies on technical feasibility rather than on the ecological consequences. It is assumed that when $CO_2$ is injected in deeper layers it will remain underground for a very long time. In the Netherlands it is assumed that it must always be possible to re-access the $CO_2$ in the deep layers in a controlled way. Using models it has been calculated that after 8000 years, 90-98% of the injected $CO_2$ will still be in the reservoir. Leakage of injected $CO_2$ through cracks caused by the contraction of the depleted gas and oil fields is assumed to be minimal. Any subsidence can be partially balanced or countered by injecting $CO_2$ into exhausted or existing gas and oil fields.

In general it can be concluded that the impact of the long-term effects of storing $CO_2$ in seawater or in the seabed on the structure and function of marine ecosystems and on biogeochemical cycles is insufficiently known. It is expected that the impact will be largest in the case of direct injection in the water and also in the case of increasing the uptake of $CO_2$ (by fertilising, for example ).

# 4 Feasibility for the Dutch continental shelf (NCP)

Direct injection of $CO_2$ in seawater is not an option for the Dutch Continental Shelf (NCP) in the North Sea, as the sea is too shallow.

It is technically feasible to store large amounts of $CO_2$ for long periods in aquifers and in old and existing gas and oil fields on the NCP. Existing oil and gas fields are to be preferred, as $CO_2$ injection increases the yield of gas.

It has been calculated that at least 10,000 megatons of $CO_2$ can be sequestered in gas and oil fields in the Netherlands. Groningen alone has a sequestration capacity of 6,500 megatons of $CO_2$, but this will only become available around 2040. A feasibility study has shown that annually 30% of the $CO_2$ emission from point sources in the Rijnmond (industry and a power station), at IJmuiden (industry) and in the Eems estuary (a power station) can be combined and sequestered in nearby fields and aquifers. Though the fields in the Netherlands and the North Sea are capable of sequestering the $CO_2$ production from power stations for 30 years, it must be taken into account that the current policy in the Netherlands is aimed at storing gas in old gas fields.
At the same time it looks like there is a preference to sequester $CO_2$ in the Netherlands in the sea bottom, because it is to be expected that more protests will appear by sequestration on land.

The present calculations fro the feasibility of the Dutch continental Shelf are based on generic (model) calculations. Further studies must take in to account location specific characteristics of the aquifers and gas fields.

# 5 Political considerations

There are legal and political obstacles that obstruct the injection of $CO_2$ in the oceans.

- The principle of caution dictates that no change may be made to the environment without all the consequences being known.
- According to the Protocol of the 1996 London Convention, with the exception of a few substances it is not permitted to dump substances from ships and platforms.
- The UN Convention of the Law of the Sea compels coastal states to regulate and control the discharge through pipes within their exclusive economic zone.

Against these legal and political obstacles it can be argued that the principle of caution equally applies to the rising $CO_2$ concentration in the atmosphere. It must also be taken into consideration that $CO_2$ is a natural product and that injecting $CO_2$ accelerates the natural process of $CO_2$ uptake by the oceans, thus reducing the possible risks of climate change.

It is necessary to take account of the current zoning plans in the Netherlands, and of Dutch legislation: the Land Protection Act, the building and mooring permits in the Environmental Management Act, and the Surface Water Pollution Act. Last but not least, there must be support from the Dutch public.

Recently a small scale field experiment to inject $CO_2$ in sea water was cancelled in Norway under pressure of Greenpeace and WWF.

The solutions for the problem that this memorandum has discussed are end-of-pipe; in other words, they aim to treat the symptoms. The preference in Dutch policy is for long-term solutions that deal with the causes of $CO_2$ emissions; examples are economising on energy use, using sustainable energy and climate-neutral energy carriers, and chemical sequestering.

# 6 Conclusions

- Sequestration of $CO_2$ is an end of pipe solution with hardly any change at the emission side.
- Long-term solutions that deal with the causes of $CO_2$ emission are preferred.
- Present assessments are based on studies using models that have been tailored to particular situations and are still insufficiently calibrated and validated.
- Assessment and field studies are up to now mainly focussed on the technical feasibility and not yet on the ecological consequences.
- Some large scale field experiments reveal that, from a technical point of view, large amounts of $CO_2$ can be sequestered in seawater and in the sea bottom (aquifers, oil and gas fields).
- Relatively minor attention is paid to the possible effects of the release of a $CO_2$ cloud by accidents during transport and storage.
- The North Sea is too shallow to store for a long time $CO_2$ in seawater
- Storage of large amounts of $CO_2$ by fertilising the (North)sea is technical difficult and the ecological consequences can not be estimated.
- It is possible to store 30% of the released $CO_2$ for the coming 30 years in the Netherlands in aquifers and gas fields under the land and sea bottom.
- In the Netherlands there is a prevalence to store $CO_2$ in the sea bottom.
- Little is known about the ecological consequences of sequestration of $CO_2$ in aquifers, oil and gas fields. The risks, when existing installations are used, are estimated to be small.
- A life cycle analysis is necessary to map the energy and mass fluxes during the whole process of purification, transport and storage.
- The ministry of Economical Affairs in the Netherlands has started a project office to study the feasibility of sequestration of $CO_2$. It is recommended that Directie Noordzee, as administrator of the North Sea, will be involved in this organisation.
- The support from the Dutch public for the sequestration of $CO_2$ in sea water/bottom must be enlarged.

# 7 Recommendations for further research

Following an extensive feasibility study a project office for sequestration research is founded by the ministry of Economical Affairs in the Netherlands. This office will coordinate field experiments and will stimulate international collaboration.
In the literature many recommendations for further research are mentioned: there are still many technical and ecological questions open. A few are already addressed in running projects. If these answers are know in a few years it will be much easier to select research questions for the Dutch risk assessment.

In general, it is necessary to collect more knowledge of the biogeochemical processes in the oceans, as it is not known how much $CO_2$ can be sequestered in the oceans before the structure and function of the marine ecosystem is disturbed.

Additionally, it is worth looking to other options for durably storing $CO_2$ besides sequestering. Examples include the production of methanol from $CO_2$. A number of basic chemicals for the chemical industry, such as ethylene, are already being made from $CO_2$.

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# 10 Risk table

Summary of the pros and cons and the possible risk, split up to technical, geochemical and ecological effects, for different options to sequester $CO_2$ in sea water/bottom. Indicated are also the storage capacity in the Netherlands. XXXXX indicated strength of the risk. Text in the risk boxes describe the preconditions of effects.

| **Options** | **Capacity (Mton)** | **Pros and Cons** | | **risk** | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | **Large** | | | | **small** |
| Injection in sea water | | Energy price up by 100-150% | Technical<br>Geochemical<br>Ecological | <br><1500m<br>pH, <O2 | | | <br>>3000m | XXXXX |
| Fertilising | | Pollution by metals, hormones and organic matter. Changes in biogeochemical cycles | Technical<br>Geochemical<br>Ecological | <br><br>XXXXX | <br>XXXXX | | XXXXX | |
| Aquifers | 4700 (land)<br>1100 (sea) | Earthquakes | Technical<br>Geochemical<br>Ecological | | | | <br>XXXXX<br>XXXXX | >800m |
| Oil and gas fields<br>gas fields | 10000 (land)<br>975 (sea) | Greater yields -<br>of oil and gas<br>Less subsidence<br>and earthquakes | Technical<br>Geochemical<br>Ecological | | | <br>X olie X | <br>X gas X<br>XXXXX<br>XXXXX | XXXXX |

# 11 Overview of fields experiments (not exhaustive)

| Naam | country | | year | area | remarks |
|---|---|---|---|---|---|
| Sleipner West | Norway | aquifer | 1996 | North Sea | First field experiment carbon dioxide from gas filed in aquifer |
| Natuna | Indonesia | aquifer | | sea, west of Borneo | |
| Kona coast | Hawaii | Sea water | 2001 | ocean | |
| Pennzoail's SACRO | America, west Texas | Oil field | 1972 | land | First field experiment carbon dioxide in oil field |
| | Japan | Sea water | 1997 | sea | Running for 5 years |
| Alberta Basin | Cananda | | | | Feasibility study |
| IRONEX | | Iron fertilizer | 1993 | Pacific | |
| San Juan Basin | | carbon layers | | | Demonstration project |
| Black Warrior Basin | America, Alabama | carbon layers | | | Demonstration project |
| Monterer Bay | America | Sea water | 1998 | ocean | |
| Sharon Ridge | America, Texas | Oil field | | land | Enhanced oil production |
| Rangely | America, Colorado | Oil field | | land | Enhanced oil production |
| Enid | America, Oklahoma | Oil field | | land | Enhanced oil production |
| Weyburn | Canada, Saskatchewan | Oil field | | land | Enhanced oil production |