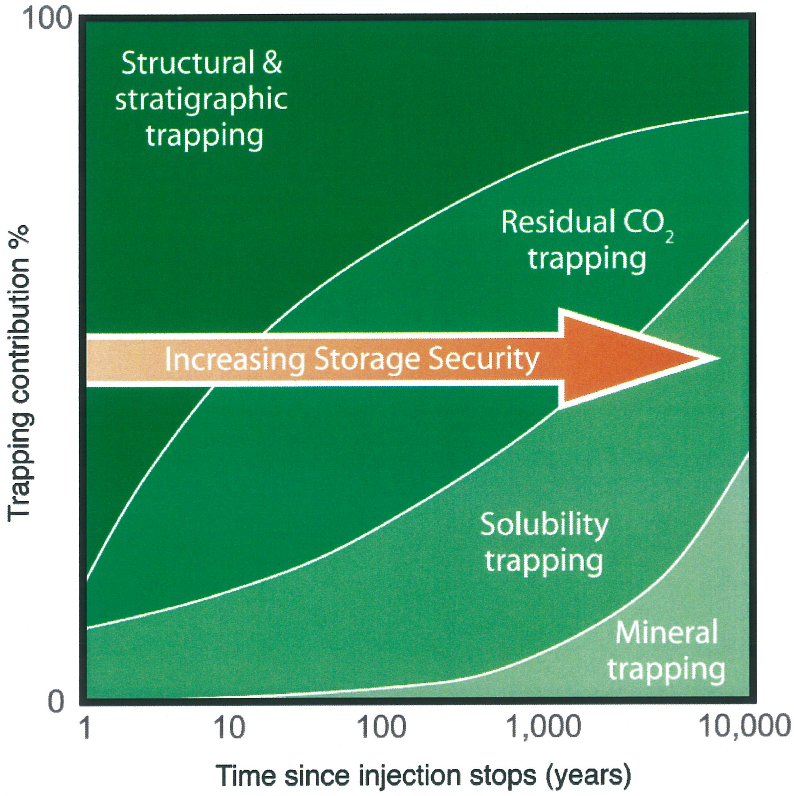

AMESCO
Generic Environmental Impact Study on CO_2 Storage

AMESCO Steering committee:
NAM, SEQ, Nogepa,
Essent, Electrabel, Eneco
Province Groningen, Friesland, Drenthe, South Holland, Ministery of VROM, State Supervision of Mines
1 July 2007
Final Report
9S0742

CE Delft

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ROYAL HASKONING

HASKONING NEDERLAND B.V.
ENVIRONMENT

Chopinlaan 12
P.O. Box 8064
Groningen 9702 KB
The Netherlands
+31 (0)50 521 42 14 Telephone
+31 (0)50 526 14 53 Fax
info@groningen.royalhaskoning.com E-mail
www.royalhaskoning.com Internet
Arnhem 09122561 CoC

Document title	AMESCO Generic Environmental Impact Study on CO_2 Storage
Document short title	AMESCO
Status	Final Report
Date	1 July 2007
Project number	9S0742
Client	AMESCO Steering committee: NAM, SEQ, Nogepa, Essent, Electrabel, Eneco Province Groningen, Friesland, Drenthe, South Holland, Ministry of VROM, State Supervision of Mines
Reference	9S0742/R04/ETH/Gron

Drafted by	H. Croezen, R. van Eijs, M. Vosbeek, S. Hagedoorn, T. Wildenborg, M. Goldsworthy, E.Th. Holleman
Approved by	drs. E.Th. Holleman
Date/initials approval	16-07-2007

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APPENDIX FIGURES

Abbreviations

AMESCO	Algemene Milieu Effecten Studie CO_2 Opslag
CATO	CO_2 Afvang, Transport en Opslag, a research program in the Netherlands
CCS	carbon dioxide capture and storage
CDM / JI measures	Joint Implementation and Clean Development Mechanisms
CO_2	carbon dioxide
EGR	Enhanced Gas Recovery
EIA	Environmental Impact Assessment (MER)
ESPOO	Convention on EIA in a Transboundary Context
ETS	Emission Trading Scheme
IEA-CSLF	International Energy Agency, Carbon Sequestration Leadership Forum
GESTO	Geological Storage of CO_2, a European initiative
GHG	Greenhouse gas
IPCC	The Intergovernmental Panel on Climate Change of the United Nations
MAC	Maximum Allowable Concentration
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
PAM	Policies and Measures
PBL	Planetary Boundary Layer
SBSTA	Subsidiary Body for Scientific and Technological Advice
UNFCC	United Nations Framework Convention on Climate Change

Policies and permits

EC	European Commission
EMA	Environmental Management Act
EU	European Union
LAP	Landelijk Afvalbeheer Plan
MA	Mining Act
Min. EA	Ministry of Economic Affairs
Min. VROM	Ministry of Housing, Spatial Planning and Environmental Affairs
OV	Omgevingsvergunning
NMP	Nationaal Milieu Plan
POP	Provinciaal Omgeving Plan
SEA	Strategische Milieu Boordeling (Strategic EIA)
SMB	Strategic Environmental Assessment
SPA	Spatial Planning Act

Involved participants from the Steering committee and project team

Steering Committee

M. Kuijper	NAM
D. Drenth	SEQ
Y. van den Berg	Nogepa
A. van Harten	Provincie Drenthe
R. Deems	Provincie Fryslân
L. Slangen	Provincie Groningen
A. Bosma	Provincie Zuid Holland
R. Vrolijk	Eneco
H. Paes	Electrabel
H. Mous	Essent
J. de Jonge	Essent
H. Spiegeler	Ministerie van VROM
H. Roest	Staatstoezicht op de Mijnen
B. Scheffer	Staatstoezicht op de Mijnen

Projectteam

E. Holleman	Royal Haskoning
S. Bos	Royal Haskoning
M. Vosbeek	Ecofys
S. Hagedoorn	Ecofys
C. Hendriks	Ecofys
T. Wildenborg	TNO
R. van Eijs	TNO
Christian Bos	TNO
Tjirk Benedictus	TNO
Filip Neele	TNO
H. Croezen	CE
K. Rensma	CE
M. Goldsworthy	Golder Associates

This report is the result of a combined effort by all mentioned to present as good as possible the current knowledge and insights in CO_2 injection and storage. Therefore the report does not reflect the specific individual meaning of participants or their organisation. This can differ on some parts of the text. It should also not be read as a scientific report, but as a comprehensive overview of the current state-of-the-art situation of CO_2 injection and storage in the Netherlands.

PREFACE

Status of the report

This reports aims to supply background information on CO_2 storage in the Netherlands for a broad group of stakeholders. By bringing together the information from the scientific world and discussing relevant policies, it is intended to make clear what the realistic options are for storing CO_2 in Dutch onshore reservoirs. The international information is also reviewed and interpreted for the Dutch situation.

Since the start of the project in the summer of 2006 the attention from the media and politics to climate change and the possibilities of CO_2 storage has increased. Contributing to this have been the extreme weather in the Netherlands, the IPCC reports in the early part of 2007 and also the Al Gore movie.

We have tried to stay up to date, but due to rapid developments some parts of the report may be superseded in due course by new information or policies. Despite this, we believe that the report, in combination with all the background articles that have been made available through the AMESCO-project website, will be useful as:

- State-of-the-art document
- Guideline for EIAs
- Definition of gaps in knowledge
- Suggestions for filling the gaps

This report has been written cooperatively by a group of authors from five different companies. Instead of writing an article each and connecting the different articles with a general introduction and summary, we have combined our knowledge and experience and written the complete report as a team. There has been intense feedback from different groups of stakeholders in workshops, in bilateral communication and through the organizations in the Steering Committee. The report can therefore be seen as the state-of-the-art knowledge from a broad range of involved parties.

Special features of CO_2 storage

What makes CO_2 storage from the perspective of environmental impact so special? First there is the mechanism in which a global impact (increase of greenhouse gases) is reduced by local measures (storage of CO_2 in gas reservoirs). The storage of CO_2 may have some local impact, and possibly even result in a risk to the environment. These have to be weighed against the global benefit of a reduction of greenhouse gases. Apart from this difference in spatial scale there is a difference in the timescale. In a conventional EIA the impacts are described which can reasonably be expected in the coming years. However the CO_2 storage is intended to be for a very long time; there is no intention to recover it. There is little experience with describing impacts with a potential timescale of hundreds of years, and maybe more.

Using the findings of this report in a project-specific EIA

This report is intended to be used as a background document for a project-specific EIA. It is expected that for each new CO_2 storage project a specific EIA will be required. Both the initiators and the authorities can use the findings from this report to agree upon the required detail and extent of the specific EIA. The following table gives an indication of the possible use of information from this report in an EIA. The relevant information and conclusions are summarized at the end of each chapter.

Chapter	Project specific EIA document	Finding in AMESCO report
1	Introduction to initiative	
2	Purpose and background	Chapter 2 for general background on CO_2 storage Chapter 8 for selection of a reservoir
3	Legal and policy aspects	Chapter 4
4	Description of initiative	Chapter 3 for technical aspects Chapter 6 for geographical information
5	Alternatives and variants	Chapter 8 for suggestions
6	Environmental impact	Chapter 5 for general impact issues Chapter 7 specific leakage impacts
7	Conclusions	
8	EIA procedure	Chapter 4 for permits
9	Gaps in information and monitoring	Chapter 9 for monitoring Chapter 10 for the response plan Chapter 11 for possible gaps

In presenting this document we intend to make a valuable contribution to the discussion about how CO_2 storage can be used in the Netherlands to reduce the emission of greenhouse gases.

Evert Holleman – Royal Haskoning
Mariëlle Vosbeek – Ecofys
Harry Croezen – CE
Ton Wildenborg and Rob van Eijs – TNO
Martin Goldsworthy – Golder Associates

SUMMARY

1. INTRODUCTION

1.1 Reason for the project

Concern about human impact on climate

At the moment climate change is a 'hot topic' in the social-political debate in several industrialized countries. General consensus has been reached among scientists and politicians about the fact that mankind is very likely changing the global climate. Fossil fuel consumption, agriculture, chemical processes and waste disposal are all contributing to the emission of the greenhouse gas carbon dioxide (CO_2).

In order to keep the consequences of climate change such as changing weather patterns and sea level rising under control, temperature rising should be kept under 2°C in the next century. This requires a reduction of 50% with regard to 1990 levels in 2050.

CO_2 storage is a spear head in greenhouse gas mitigation policies

CO_2-storage is regarded globally as one of the most promising technical measures that can be applied for realizing the drastic reduction in anthropogenic greenhouse gas emissions that is required in the next decades.

In the Netherlands CO_2-storage has been defined as one of the spear heads in climate policy and its development and introduction in the Netherlands is actively supported by the government, by means of covenants and subsidies for CO_2 capture and storage pilot projects.

Relevance and potential of CO_2 storage for the Netherlands

Storage of CO_2 is possible in depleted oil- and gas fields. For the Netherlands CO_2-storage seems a realistic and promising option. The Dutch deep subsurface contains more than 100 gas fields in which natural gas has been stored for millions of years, proving the intrinsic integrity of these fields. The total onshore storage capacity in gasfields is estimated at a maximum amount of 1 600 Mtonnes (excluding the ´Groningen´ field, Slochteren[1]). Current concentrated greenhouse gas emissions from large industrial point sources amount to approximately 70 Mtonnes, which means that theoretically a maximum storage capacity is available for all current industrial point emissions for about 20 years. This storage capacity will allow for a transitional situation in which CO_2-storage is utilized for reduction while reducing carbon intensity of our society and developing alternative carbon free energy sources.

Lack of actual experiences and knowledge

Several Dutch companies and governmental organizations have expressed the wish to initiate schemes for Carbon dioxide Capture and Storage (CCS). This has led to a discussion on how to judge the potential effects of such activities on the environment. However, CO_2-storage is a relatively new activity. No dedicated legislation, specific policy and examples of precedents of Environmental Impact Assessment (EIA) have been formulated on this topic so far to give guidance to initiators, permitting authorities and stakeholders. For this reason a broad group of parties (private, governmental and

[1] This field has an additional capacity of approximately 7 300 Mtonnes CO_2.

institutional) initiated this study on the general environmental impacts of underground, onshore CO_2 storage called AMESCO (Algemene Milieu Effecten Studie CO_2 Opslag).

1.2 Aim of the project

The AMESCO study aims to supply environmental background information on CO_2 storage in the Netherlands for the broad group of initiators mentioned above and other stakeholders. By bringing together the information from the scientific world, companies and authorities and by analyzing relevant policies it is intended to eludicate:

- which are the possible environmental effects of CO_2 injection and storage;
- which are the possibilities for risk reduction or mitigation;
- which existing legislation is of relevance for CO_2 storage in the deep surface;
- where are the gaps in knowledge and legislation with regard to CO_2 storage.

The report produced during the AMESCO study should be seen as a broad answer to the four questions mentioned above. In specific projects the report can be used as a background document during permitting procedures. This background information has to be supplemented with location specific information. The report can also be used as input for an environmental impact assessment (EIA).

1.3 Scope

For practical reasons the AMESCO study was performed with the following scope limitations:

1. Focus on potential impacts and risks resulting from the storage of CO_2.
2. Only consider CO_2 storage in gas reservoirs.
3. Only consider onshore projects.
4. Only consider permanent storage.
5. Consider alternative options for CO_2 storage in gas reservoirs; but not other forms of CO_2 emission reduction.

The scope is limited to depleted gas fields, from which the economically recoverable resources have already been taken. Oil and gas reservoirs have demonstrated their suitability by holding hydrocarbon compounds for millions of years. Since oil fields often still contain a large quantity of oil, and in many cases water, the gas fields look more suitable in the short-term. The number of gas fields in the Netherlands is also much larger than the number of oil fields. Gas fields in general have a low pressure at the end of their lifetime and a high recovery rate[2], which makes them more suitable for CO_2 storage than aquifers.

1.4 Reading guide

This report presents a summary of the in the AMESCO study obtained information. To give laymen some insight in the subject Chapter 2 provides a broad description of CO_2 storage in depleted gas fields. Chapter 3 presents a broad overview of the environmental burden and risks related to CO_2 storage. This chapter also provides the reader with information on health effects as a consequence of exposure to possibly

[2] High recovery rate: a high percentage of the original existing gas has been extracted.

leaked CO_2 and gives measures to reduce the risk on CO_2 leakage. An overview of relevant legislation and gaps in this legislation is presented in Chapter 4. Finally, Chapter 5 shortly discusses the anticipated future activities.

2. INJECTION AND STORAGE, A BROAD TECHNICAL DESCRIPTION

2.1 Lay out of the CO_2 storage location

Much of the technology applied in CO_2 injection in gas reservoirs is standard technology in the oil and gas industry. However, the description in the paragraphs below is partly hypothetical since experiences with permanent CO_2 storage in the deep surface are limited[3].

The description below is based on current operational procedures common in Dutch gas industry and global oil industry and on requirements in Dutch mining regulations. In the text indications are given where operational experiences lack and legislation has not been defined yet.

Main issues in this paragraph:
- **Applied technology and operational procedures are largely standard in gas and oil industry;**
- **Monitoring strategies are still under development;**
- **Wells abandoned and sealed decades ago, are without adjustments possibly unsuitable for permanent CO_2 storage.**

In general a system for CO_2 storage in a depleted gas reservoir consists of three different parts

These are:

- Surface facilities.
- Sub-surface facilities, through which injection takes place.
- Reservoir.

More detailed information is provided in Table 1 and Figure 1.

Table 1. Different CO_2 storage facility parts

		Common in oil and gas industry?
Surface facilities	Paved terrain, Pump or compressor, Monitoring equipment, Wellhead ('Christmas tree')	Yes
Sub-surface (Bore hole, well)	Cementing, steel casing, steel tubing	Yes
Reservoir	Reservoir rock, cap rock, side barriers, existing residue gases	Yes

3 There are example projects of CO_2 injection in the deep surface such as K12B, in Salah (Algeria) and Sleipner. However, there is still no experience with abandoning and after care.

The aboveground part of the location will look comparable to a gas production location without a gas treatment plant. The subsurface part may differ compared to gas production as far as quality standards of the materials applied in tubing, casing and cementing are concerned.

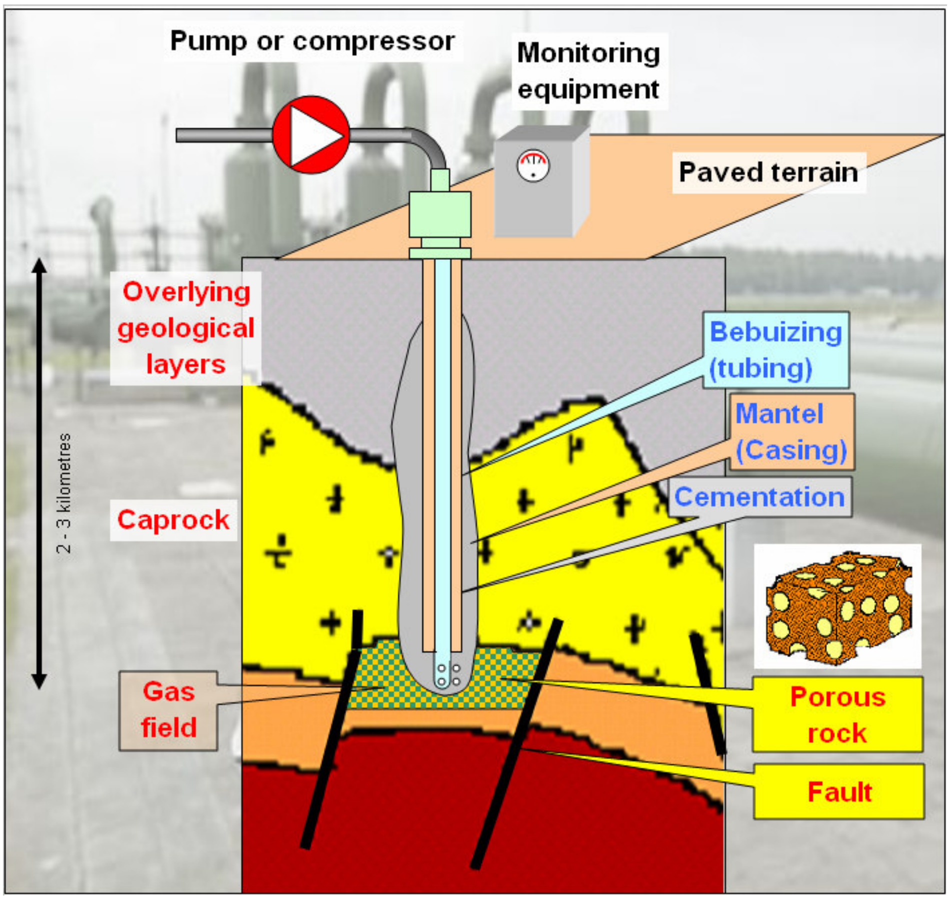
The location will go through four phases:

- Construction.
- Operation/injection.
- Abandonment and sealing of wells.
- Post abandonment.

CO_2 is supplied by pipeline
CO_2 will be supplied in a supercritical state - compressed to such a pressure that it behaves comparable to a liquid - and will be injected in the reservoir along a bore hole. The supplied CO_2 will have been dried (water removal) to prevent possible corrosion in pipeline and injection well. Injected CO_2 might contain impurities and inert gases, depending from the CO_2 source (source fuel and capture technology). Sources yielding pure CO_2 are for example ammonia and hydrogen plants and ethanol production. Pipeline transport and injection in a geological reservoir (gas field, oilfield) of supercritical CO_2 is a common technology in the oil and gas industry[4].

[4] CO_2 is applied for improving oil recovery (enhanced oil recovery or EOR) since the early 1970's. High pressure CO_2 is used to push oil out of the reservoir. The technique is currently applied primarily in North America, Libya and Venezuela and utilized in the production of approximately 3% of total global crude oil production. Injection rates amount to 40 Mtonnes annually in the USA and pipeline networks of 2,500 kilometers length are applied to transport the CO_2 to Texas from more inland located natural subsurface CO_2 gas reservoirs.

Figure 1. Structure of a CO_2 storage location (based on 'Basiskennis olie en gas', an internal NAM handbook)



Injection pressure and injection volume, an indication

In accordance with the mining act, Injection pressure will be such that risks on crack formation is minimized. The pressure in the reservoir will ultimately be comparable to the pressure of the gas that was originally present in the reservoir. First indications of injection rates based on desk top studies and reservoir simulations range from 0.2-0.5 Mtonne/year. For comparison, a modern 1,000 MW_e coal fired power plant produces 5.0-5.5 Mtonnes CO_2 annually. Therefore storage of CO_2 will require multiple injection well.

Emission figures and facts:

- Total annual Dutch greenhouse gas emission amounts to 220 Mtonnes CO_2-eq.
- Of this total, approximately 70 Mtonnes CO_2/year is emitted by large industrial point sources.
- A modern coal fired base load power station emits approximately 5 Mtonnes per year.

Compared to this:

- Total storage capacity in onshore gasfields is approximately 1.600 Mtonnes.
- Storage capacity per gas field ranges from 5 to tens of Mtonnes.
- Injection rates are 0,2-0,5 Mtonnes per year, per well.

Monitoring: many suitable technologies
Specific, location tuned, technologies for monitoring the process of CO_2 injection, the conditions within the reservoir and the integrity of the boreholes are available. Examples are:

- Direct measurements by means of registration of pressure, temperature and flow in wellhead and tubing.
- Indirect measurements by means of several geophysical technologies such as:
  - Measuring resistance of soil and lower geographic layers (out of the borehole);
  - Measuring above surface concentrations of CO_2 and upward emissions from the soil;
  - Seismic registration of possible leakage of CO_2 from the field to higher aquifers.

Monitoring strategies are still under development. The effectiveness of monitoring technologies from gas production, applied in CO_2 storage is still unclear. Yet, no rules concerning monitoring, with regard to risk control, are established. However, worldwide there are several pilot project in which CO_2 injection as well as monitoring technologies are tested.

Monitoring data will - as is common in gas production - be used in a reservoir model that will be constantly updated with new information. The model is initially used for optimising the injection operations.

Well types
When injecting in depleted gas fields there are theoretically two options:

- Injection in gas fields that have already been abandoned;
- Injection in gas fields still accessible.

In the first case the original wells have been sealed with cement plugs or plugs consisting of metal and rubber and are no longer accessible for injection. It may be an option to drill a new injection hole in the field. In the second case the wells are still accessible for injection of the CO_2 to be stored. A work over might be needed in this case to ensure that the tubing and casing can resist corrosion by carbonic acid - formed by dissolving CO_2 in water - and acids from H_2S, NO_x and SO_2.

In several gas fields in the Netherlands part of the wells in the fields have already been sealed. However, most fields are still producing natural gas.

Suitability of cap rock and casings for CO_2 storage differ for older and newer abandoned and sealed wells
The sealing of wells that have been abandoned several decades ago - in the first decades of gas production in the Netherlands - was designed for a situation in which there is little gas left at little pressure in the reservoir. The sealing's were not designed for high pressure storage of a substance that can be corrosive in combination with water and may react with cement components. It needs to be examined whether they are satisfactory for conditions in the reservoir after CO_2 injection. In most cases it is very costly to modify an already abandoned well.

On the other hand due to the fact that there is no continuous water phase in most gas reservoirs in the Netherlands[5] the expected steel corrosion and cement degradation rates are significantly lower than when CO_2 is injected in a saline aquifer.

2.2 The reservoir

Main issues in this paragraph:

- **Rock salt is the preferable 'cap rock';**
- **Injected CO_2 will be increasingly fixated in time;**
- **Residual gases in the reservoir may pose additional risks**
- **Residual gases in the reservoir are prove of cap rock integrity**

General specifications

Gas reservoirs in the Netherlands are generally located in porous reservoir rock (compare a sponge) at a depth of 2 to 3 kilometres. At these depths CO_2 will be supercritical because of the temperature and – when the field is filled - the pressure within the gasfield. Gas movements are prevented by overlying gas- and fluid tight layers (cap rock) and lateral barriers, primarily gastight faults.

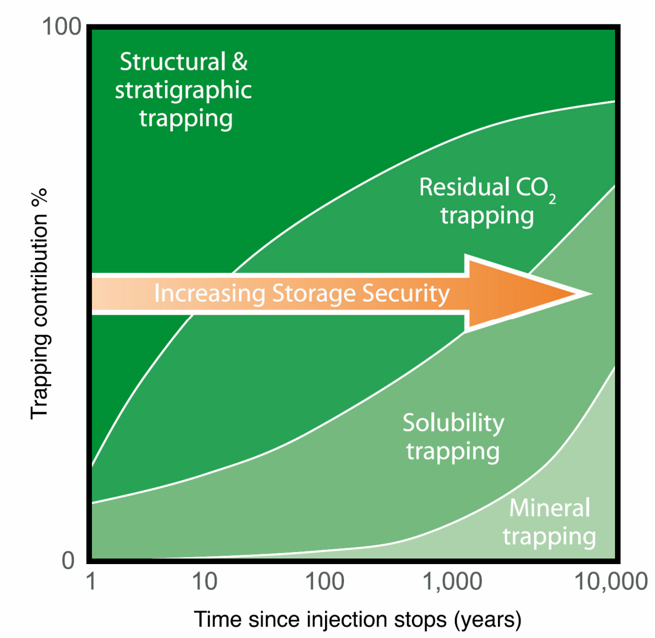
Cap rock consists often of rock salt, clay stone or anhydrite. Of these, rock salt provides the best entrapment. It is often present in layers of hundreds of metres thick and its plasticity provides a continuous unfractionable layer with very low gas and fluid permeability. Claystone has a very low permeability as well. However, it is more sensitive to fracturing under high pressure. Anhydrite is less preferable as a cap rock.
is less preferable as a cap rock.

Increasing entrapment in time

Injected supercritical CO_2 will at first be present mainly as free fluid in the larger pores and is mainly trapped by the cap rock. In time however, it will be trapped and fixated increasingly (see Figure 2). This is partly due to migration into smaller pores (residual trapping), from which it can less readily migrate again due to capillary forces. Next to this, in case formation water is present in the reservoir, part of the injected CO_2 will dissolve in the formation water (solubility trapping) and may eventually chemically bind to the reservoir rock (mineral trapping). Mineral trapping is the most permanent storage mechanism for CO_2.

[5] Fields filled with water are also less attractive for CO_2 injection, since the required pressure for CO_2 injection is higher than for empty fields.

Figure 2. Dominance of trapping mechanisms as a function of time (IPCC, 2005)



Residual gases in the reservoir
Since the recovery rates for natural gas production are always less than 100%, every gas reservoir will contain residues of the natural gas originally present in the field. This natural gas contains additional to methane, a potent greenhouse gas, sometimes also CO_2 (mostly less than 10 vol%), and substances such as radioactive radon, H_2S, mercury and aromatic compounds.

Escape of methane together with CO_2 due to leakage of the reservoir will result in further emissions of greenhouse gases. Escape of the other substances may also give toxicological risks. The presence of CO_2 in the residual gas on the other hand proves that the cap rock and the reservoir rock aren't negatively influenced by the presence of CO_2.

In summary
As is shown above there is great variation in the specifications and quality of gasfields, for example in the kind of cap rock and in the amount and composition of residual gases. It seems logical to determine the suitability of gasfields on the basis of these characteristics. An official determination methodology is not (yet) established in formal legislation.

2.3 Abandonment

Main issues in this paragraph:

- **Up to now for CO_2 storage there is no:**
  - **Criteria for proving a stable situation in the filled up and for proving a stable situation in the abandoned reservoir;**
  - **Protocol for well closure**
  - **Protocol for monitoring after termination of injection and after abandonment.**

Injection wells for monitoring purposes
After sealing an injection well, the situation in a reservoir cannot be monitored directly anymore. Therefore it has to be made sure beforehand that no undesired incidents can appear. In accordance with the Mining act and with common practice in the gas production industry, an injection well can be sealed when a reservoir has proved to be stable for a while and when no leakage of gas is detected. Until a reservoir has shown to be stable it cannot be excluded that it may be necessary to use the wells to retrieve the injected CO_2 in a controlled way to prevent uncontrolled leakage to the atmosphere. To our knowledge, criteria for stability aren't defined yet.

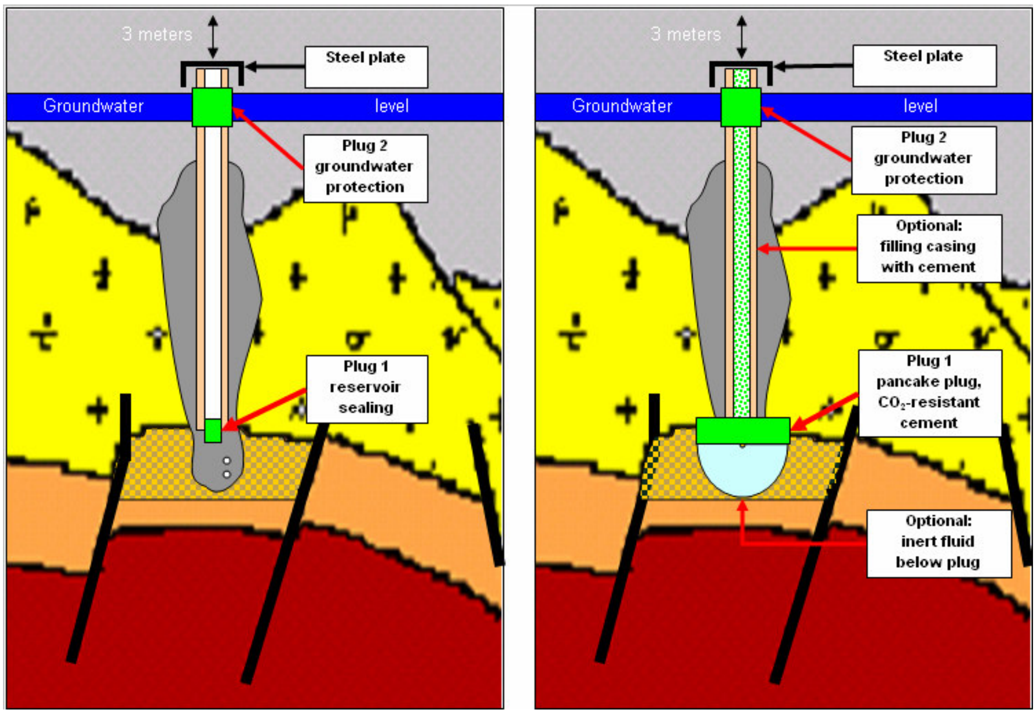
Dismantling and closing the injection wells needs particular attention
The Dutch mining regulation prescribes how a well must be abandoned by the following measures:

- Removal of production tubing.
- Dismantling the shallow part of the casing.
- Installation of minimal two cement plugs with a length of 50 meters (default) or 100 meters (in the case of corrosive gases or high pressure).

Normally an iron plate is welded to the outside of the casing to close up the well. Several hydraulic and mechanical tests on the quality of the cement plug will be performed.

The adequacy of the abandoning measured mentioned above for CO_2 storage is still unknown. Examples of additional measures are the installation of a so called pancake plug (see Figure 3), filling up the complete casing with cement or injection of an inert liquid layer below the lowest plug.

Figure 3. Abandonment constructions, left current strategy, right potential strategy for CO_2-storage, minimizing risks for leakage through well



After closure initially monitoring continues
After a well is sealed, developments within the field can indirectly be monitored by the technologies mentioned in Section 2.1.

There are no comparable obliged measures for monitoring a depleted gas field after termination of gas production and abandoning. When after abandoning the legal criteria for prevention of gas leakage are met, monitoring is suspended and the location can get a new purpose. Currently, gas production sites are restored to a ´green field´ situation and are thereby available for any desired construction activity.

For CO_2 storage the predominant criteria have not been defined yet and it is also unclear whether the site can return to a 'green field' situation or if must remain accessible.

3. ENVIRONMENTAL IMPACT

A large part of the study has focussed on 'what if' questions: what if the stored CO_2 would get out of the reservoir, where would it go, and what impact could it have? As indicated in the paragraphs below this questions are at the moment very difficult, probably impossible, to answer. A systematic analysis of the chance on and the consequences of CO_2 leakage is currently lacking. Besides, the complexity and variability of the subsurface requires a location specific approach. Furthermore, prediction of exposure levels is difficult and there are a lot of uncertainties concerning the effects of chronicle exposure

The AMESCO study therefore resulted in an indication of the relevance of the different paths for leakage, of the time interval between leakage and arrival of leaked CO_2 at the surface and of the relative amounts that may leak from the reservoir per path. Additionally, the relation between CO_2 exposure and its consequences has been analyzed.

With all the uncertainties about paths, time intervals, amounts, effects from exposure etc it seems wise to focus on mitigation of leakage by reservoir selection, operational practice and applied design of well and plugs. In this way, a 'no regret' design may be developed for which the chance of leakage of a measurable amount of CO_2 within the coming hundreds or thousands of years is minimal. In view of this an overview of measures for prevention and reduction of CO_2 leakage is presented.

3.1 General overview of environmental impacts and risks

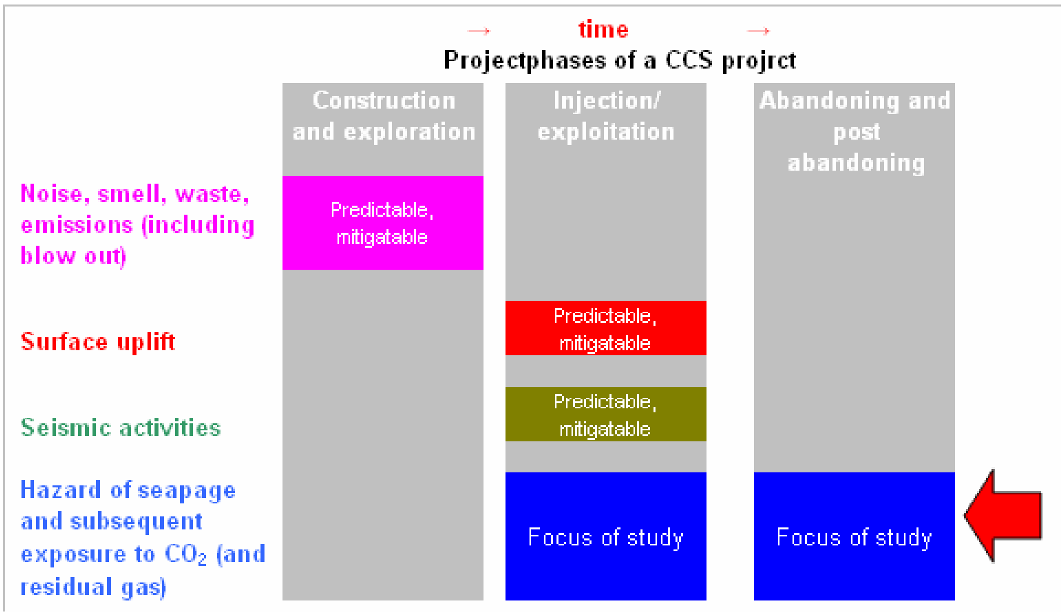
Main issues in this paragraph:

- **Most environmental impacts are predictable and comparable with impacts related to gas production;**
- **Handling of CO2 during exploitation does not give enhanced health and environmental risks;**

Most impacts are predictable and comparable to risks associated with gas production

Figure 4 presents an overview of environmental impacts and risks per project phase of CO_2 storage.

Figure 4. Overview of relevant environmental impacts and focus of the study



As the activities in the first two phases – e.g. drilling, well construction, injection - are comparable to those in e.g. natural gas production and storage, the different types of impacts and risks are too. This also applies to the scale of the impacts and risks. Since the activities are common industrial processes, size of impacts and risks can be predicted fairly to very accurate. Mitigation measures are standard practice in many industries.

Handling of CO_2 does not give enhanced health and environmental risks
Handling of CO_2 during exploitation (transport, compression, injection) does not lead to enhanced health and environmental risks compared to natural gas handling. Although CO_2 is a toxic at exposure to high concentrations (see Section 3.3), it is no more toxic than natural gas. Both substances will at release disperse in the atmosphere. Since CO_2 isn't flammable nor explosive, the risk contours will be smaller than for gas production.

But CO_2 must remain stored
In order to make CO_2-storage an effective measure in reducing greenhouse gas leakage of CO_2 must not exceed a level of 1% of the stored amount per 100 years. This percentage must be significantly lower if residual natural gas could also escape.

Next to this seepage of CO_2 from the reservoir may ultimately result in emission to the biosphere[6] and will in that case result in exposure of living organisms to increased levels of CO_2, compared to natural levels.

3.2 Leakage paths

Main issues in this paragraph:

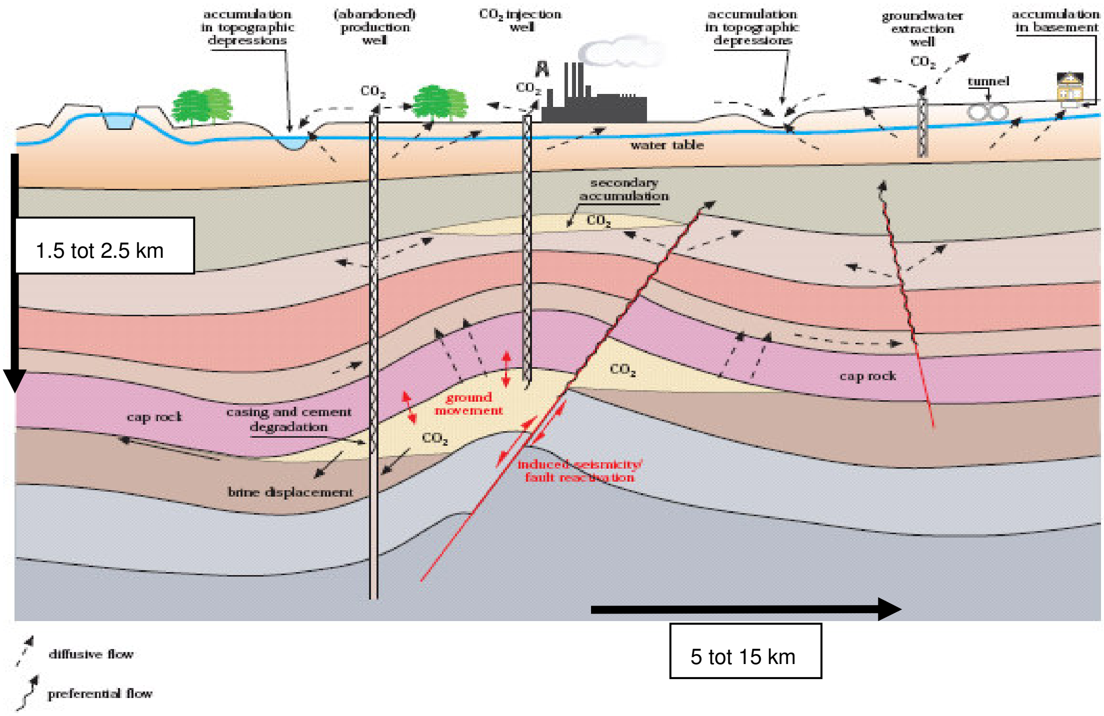
- **Most relevant path for leakage of CO_2 from reservoir to biosphere is the injection well.**
- **It is impossible to present a representative estimation of the amounts of leaked CO_2 is leakage does appear.**

There are in theory four potential leak paths for stored CO_2
These are (see Figure 5):

- Leakage through the cap rock, e.g. after fracturing or chemical reaction of the cap rock with CO_2, impurities or derived chemical products (e.g. carbonic acid).
- Leakage from the reservoir spill-point – pressing the CO_2 past the side way cap rock – due to high reservoir pressure.
- Leakage through or along geological faults from reservoir to surface, running through cap rock.
- Leakage through or along wells after failure of casing, cementation or plugs as a result of CO_2 induced corrosion or chemical reactions with cement.

[6] 'Biosphere' is the umbrella term for the different earth 'compartments' containing and directly supporting live on earth. These include the atmosphere, fresh and marine surface water, earth surface, soil and groundwater.

Figure 5. Main leakage paths for CO_2 to move towards the surface



Large and relatively fast leakages to the biosphere are only possible via high permeable paths in the shape of wells or faults that extent from reservoir to the biosphere. Only via these pathways leaking CO_2 could reach the biosphere within several hundreds of years. Faults that extent from reservoir to biosphere hardly ever exists in the Netherlands. Faults that are present have proven to be gas tight. In the other situations (leakage via cap rock and spill point) migration of CO_2 to the biosphere takes several thousands of years.

Mitigation seems possible

Risks for CO_2 leakage from a gas field can be minimized by:

- Selection of a gasfield with optimal conditions for CO_2 storage;
- Technical measures to minimize the risk of leakage via wells.

Methodologies for field selection on the basis of gas field characteristics are under development in e.g. California and Australia[7]. Possible criteria for risk reduction through field selection are presented in Table 2. It is obvious that risk reduction on the basis of field selection is more promising when more information about the specific gasfield is available.

[7] For example Oldenburg, 2006 en Bowden, 2004

Table 2. Overview of possible mitigation measures

	Leakage through the sealing cap rock	Leakage from the reservoir spill-point	Leakage through or along geological faults	Leakage through or along wells
Acquired injection pressure	X	X		
Presence of aggressive contaminants in CO_2 to be stored	X			X
Reservoir selection				
Thickness of the cap rock	X		X	
Characteristics of the cap rock (plasticity)	X		X	
Resistance of cap rock against chemical reaction with CO_2[8]	X			
Faults in or just above the cap rock			X	
Number of abandoned wells				X
Depth of the reservoir	X	X	X	
Presence of overlaying layers and/or aquifers	X	X	X	
Hazardous substances within the residual gas				

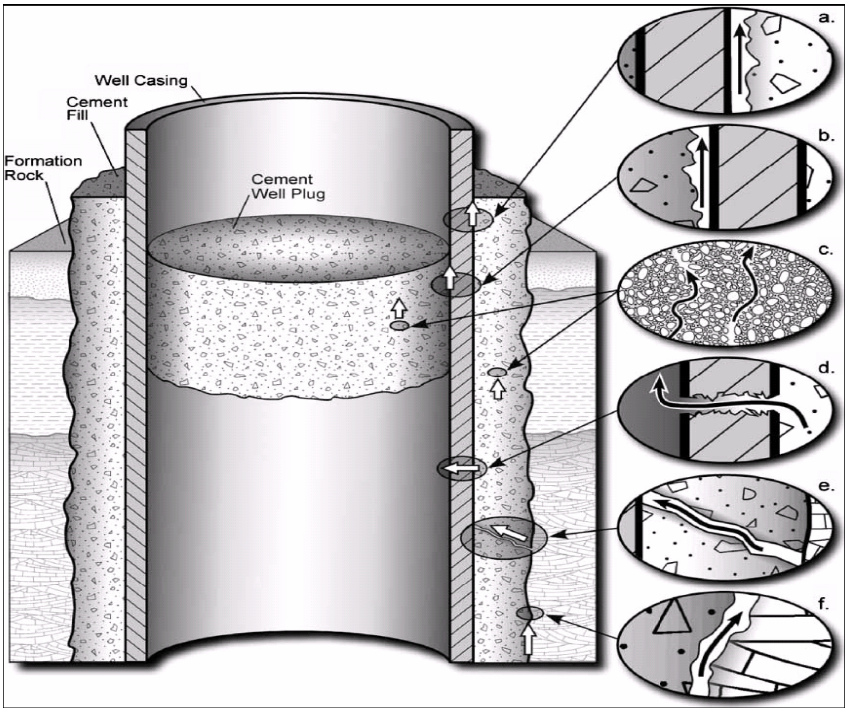
Examples of technical measures to reduce the risk on leakage via abandoned wells en sealed injection points (pancake plugs, inert liquids, filling up the casing) are presented in Section 2.3 and in Figure 3.

A set of ‘best practice’ measures for CO_2 storage in saline aquifers (as applied in the Sleipner project) has been developed with funding from the EU and the gas and oil industry. These measures include location screening and selection and technical measures concerning wells. It is recommended to develop a comparable set of measures for CO_2 storage in depleted gas fields.

Gas fields have proven their ability as gas ‘container’ over millions of years. From this it can be concluded that the geological characteristics of most Dutch fields won’t lead to significant risks for CO_2 leakage. The risk for leakage via cap rock, spill point and faults are minimal - on condition of a secure field selection and good practice during operation. It is essential that the critical pressure within the reservoir isn´t exceeded during design and realization of the project. The most critical points are the injection points and/or abandoned wells. Potential routes via these points are illustrated in Figure 6.

8 Rocksalt hardly reacts with CO_2, gaseous or dissolved in water. The reactivity of claystone to dissolved CO_2 depends on its mineral composition. This composition can have positive as well as negative effects, a mineral analysis is required to prove the suitability of the claystone as a cap rock.

Figure 6. Possible leakage pathways through an abandoned well: (a) between casing and cement; (b) between cement plug and casing; (c) through the cement pore space as a result of cement degradation; (d) through casing as a result of corrosion; (e) through fractures in cement; and (f) between cement and rock. From Gasda et al. (2004).



No representative estimation for the emissions at possible leakage

It turned out to be impossible to present a reliable indication of emissions, time scale and exposure levels representative for CO_2 storage in Dutch gasfields.

Emissions from CO_2 storage in Dutch fields are to a certain degree unpredictable with regard to:

- the amount of CO_2;
- the period between leakage and reaching the surface;
- the effects of exposure at the surface.

Reason for this unpredictability is that evaluation of emissions requires a location specific approach.

Estimation of amounts and time periods

No simulations are performed for Dutch gas fields, therefore, no indication of the risks on leakage and the volume of this leakage can be given. Furthermore, there is no experience with CO_2 storage, so no insight in the frequency and rate of undesired effects, such as failure of the casing as a result of corrosion, is acquired yet.

In practice it is possible to formulate scenarios for specific wells. Already existing (abandoned) wells will be most critical and these wells may differ between fields. For future wells it may be possible to develop a more generic leakage scenario and to obtain the related risks.

Examples from abroad
To get some insight in the subject, some actual figures from authoritative sources are given:

- The in 2005 completed IPCC report on CO_2 capture and storage concluded that it is likely (60% - 90%) that after 1000 years 99% of the stored CO_2 is still present in the reservoir on condition of good field selection, good practice at injection and proper monitoring.
  For reservoirs with a capacity of 10-100 Mton CO_2 such as the Dutch fields, this amounts to an average emission of 100 to 1000 tonnes a year.
- In Australia a loss of a maximum of 1% of the injected CO_2 over a period of 1000 year is accepted. It is required that the chance on such a loss is less than 20%. It is however still unclear how this has to be demonstrated.

Emissions of 100 to 1000 tons per year are small compared to emissions from natural systems such as geothermic (volcanic) systems (Mammoth Mountain, USA and , Albani hills and Poggio dell'Ulivo in Italy) or natural CO_2 fields (e.g. Mátraderecske, Hungary). Natural emissions often amount upto ten thousands tons of CO_2 a year.

3.3 Effects of exposure

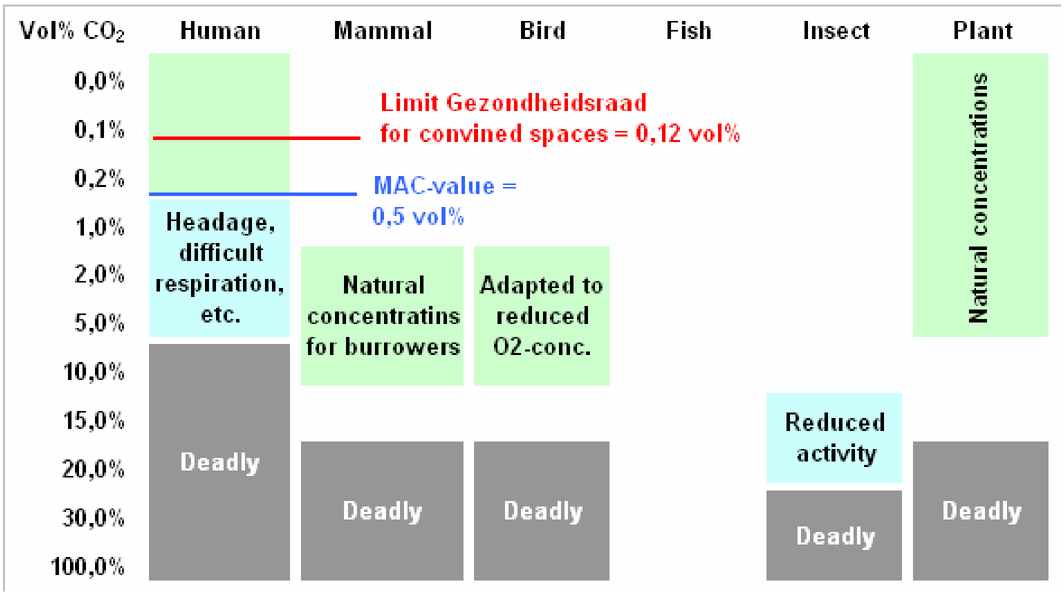
Main issues in this paragraph:
- **An indicative overview of dose effect relations illustrates the relative sensitivity of humans.**
- **Concentrations seldom reach harmful levels**
- **Emissions of up to several thousands of g/m^2/day:**
  - **Will very likely result in damage to vegetation, insects and burrowers.**
  - **Will give a low possibility for harmful concentrations in the atmosphere and will only give dangerous accumulations in rooms with limited ventilation and on windless days**
  - **Will give a moderate to significant probability of harmful levels in surface water.**

Indicative dose effect relations illustrate sensitivity of humans
Exposure to CO_2 can potentially result in adverse health effects to all life forms in the biosphere (vegetation, mammals, birds, fish, insects) and can also result in damage to materials (see also Figure 7):

- Animals and especially humans are sensitive to even short periods of elevated atmospheric levels of CO_2. For humans negative health impacts occur at concentrations above 3 vol% and death occurs at concentrations above approximately 10 vol%. The maximum allowable value for working environments is 5.000 ppmv (0,5 vol%). Other organisms are less sensitive to elevated concentrations in the atmosphere.
- Plants can tolerate short periods of high concentration levels but die when exposed over periods of several days. Adverse effects in this case are not so much related to air concentrations as to elevated concentrations of CO_2 in the soil. The threshold for adverse effects lies around 5 vol%, the lethal concentration is about 20 vol%.
- For fish the concentration of dissolved CO_2 should not exceed 200 to 250 mg/l.

- Materials such as cement, concrete and steel can be damaged by corrosion or chemical reaction with by carbonic acid, produced by dissolving of CO_2 in groundwater.
- Formation of carbonic acid by dissolved CO_2 can result in hardening of water (increased Ca^{2+} and Mg^{2+} concentrations) and may result in deterioration of the drinking water quality Acidification of ground water will also result in reduced availability of nutrients for vegetation.
- Heavy metals within the soil such as zinc and cadmium may be mobilized. Concentrations aren´t expected to exceed current standards.

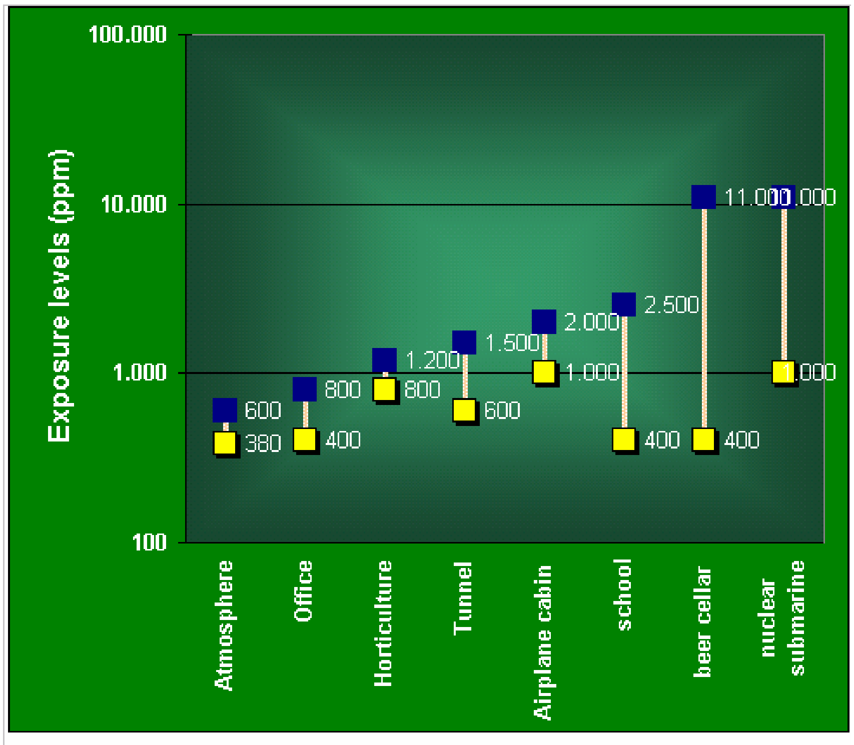
Figure 7. Indicative dose-effect relations



Concentrations seldom reach harmful levels in current situation

In the current situation in the Netherlands situations with hazardous concentrations of CO_2 seldom occur. Atmospheric CO_2 concentrations vary in natural circumstances from 380 ppm up to approximately 600 ppmv (0.038-0,060 vol%; see Figure 8). This concentration may reach values of 880 ppmv to 11.000 ppmv (0,088-1,100 vol%) due to anthropogenic activities in confined spaces.

Figure 8. Examples of natural concentrations and concentrations from anthropogenic activities



Concentrations in soil amount to several volume percentages and concentrations of dissolved CO_2 and derived carbonic acid in groundwater and surface water may amount to several hundreds of mg/l for specific biotopes with peat soil.

Leakage from CO_2 storage reservoirs might result in exposure to harmful concentration levels

Leakages from CO_2-storage reservoirs may result in elevated CO_2 concentrations in soil, water and atmosphere, that are harmful to the living organisms and materials present in them. Leakage leading to hazardous concentration can be precluded by secure field selection, an elaborate operation and monitoring system and technical measures to preserve well integrity. In the considerations below a maximal acceptable leakage scenario of 1% in 1000 years (100 tons/year) is assumed.

- The possibility for harmful concentrations in the atmosphere is estimated as being low. Emissions to well ventilated spaces and open air will often be diluted to harmless levels by wind and ventilation air.
- Experience with diffuse emissions at the surface of natural CO_2 fields or geothermic systems in Hungary, the US and Italy show however, that emissions of thousands or even hundreds of g/m^2/day to confined and unventilated spaces or to depressions within the scenery could lead to harmful or even lethal concentrations.
- For plants, insects and burrowers concentration levels in soil air will very likely reach harmful levels because of the limited mixing of soil air and limited exchange of soil air with open air. The limited mixing and exchange means that upward fluxes of CO_2 are not diluted.
- Soil concentrations will probably reach harmful levels for plants, insects, soil organisms and burrowers. On the basis of the emissions from natural systems, it

must be concluded that even at emissions of only tens to hundreds of grams/m^2/day, hazardous concentrations (> 10 vol%) are reached in the air within the soil.

Without further analyses and model simulations and without location specific information, it is difficult to estimate the probability of CO_2/HCO_3^- and CO_3^{2-} concentrations in surface water and groundwater reaching harmful levels.

4. LEGISLATION

Current situation, prevailing legislation concerning CO_2 storage

Compared to neighbouring countries a lot of the required legislation is already (partially) in place. The Mining act presents a general regulative framework. Next to this the Environmental Management Act and the Spatial Planning Act are of special interest for CO_2 storage. A limited overview of these acts and their relevance for CO_2 storage is given below:

- Mining Act
  The minister of financial affairs is the competent official concerning the Mining Act. The act mainly concerns oil and gas activities in the Netherlands.
  The Mining Act in a way already provides the legal framework for CO_2 storage activities because it contains the most appropriate instruments for all deep subsurface mining activities, for example with regard to attendance systems during exploitation and risk management. The Mining Act includes a large number of legislative liabilities with regard to this. Several of these are mentioned in Chapter 2. Under the Mining Act a storage permit and storage plan are required for CO_2 storage projects.

- Environmental Management Act
  The Environmental Management Act, together with the national waste plan (LAP) and the EIA[9]-Decision focus primarily on the control of environmental impacts that might occur due to hazardous events and the measures required in case of impacts.
  Within the Environmental Management Act, there are three regulations that are related to the underground storage of CO_2.
  - The first concerns waste treatment, which is regulated in the National Waste Plan (LAP).
  - Second is the obligation to perform an Environmental Impact Assessments for certain activities, which is regulated in the EIA-Decision.
  - The third relates to the Regulation External Safety.

- Spatial Planning Act
  The Spatial Planning Act, which applies to the above ground installations and activities, provides the legal framework for the spatial plan at regional (province) level and the spatial plan at a municipality level.

[9] EIA = Environmental Impact Assessments

Current situation, uncertainties and gaps in legislation and regulation

Although there already is a general regulative framework for CO_2 storage, there are a few important issues that will need to be addressed or fine tuned before CO_2 storage projects can be implemented:

- *Leading authority: agreement between all involved authorities on who will take the lead and how others will be involved/consulted*
  There is currently debate in relation to the Mining Act about whether the provinces should remain the responsible authority for deep subsurface storage or whether such issues could be better accommodated within the Ministry of Economic Affairs.
- *Ownership of CO2, and associated short- and long-term responsibilities*
  According to the Mining Act the short term liability for the stored CO_2 bears with the company that actually stores the CO_2 (the so called 'operator'). This liability term amounts to a maximum of 30 years (in conformity with legislative liability). It seems preferable that the long term liability, after this 30 year period, is passed on to a governmental organization. There are however no regulations on this transfer, the conditions on which it can take place and the moment at which it has to take place. A financial pre-arrangement for the eternal aftercare, such as available for landfills, is also lacking. It is expected that potential operators will wait till these kind of issues are officially regulated.
- *Current legislative classification of CO_2 and its consequences*
  CO_2 stored in the deep surface is in the current Dutch classification system assigned as non hazardous waste, this is because of a provision in the (adapted) LAP[10]. As a consequence an EIA has to be performed for large scale CO_2 storage. It is unclear if stored CO_2 will be seen as waste in future Dutch (and European) legislation concerning CO_2 storage (see below). Possible impurities in the stored CO_2, such as H_2S, SO_2 and NO_x - which possibly are hazardous compounds - should also be taken into account in future legislation. Questions like what concentrations of these substances are aloud and what if these concentrations are exceeded need to be answered.

New developments

Currently, a new Act, called the WABO is being reviewed by various governmental bodies (Ministry of Environmental Affairs, Ministry VROM, municipalities). It is expected that the new Act will become into force in 2008. This new act will combine several permits related to building and the environment into one permit called 'Omgevingsvergunning'.

International developments

In the international arena it is also recognized that an EU CCS policy and regulatory framework should be developed as soon as possible (at least before 2012). Currently, there are no national or international standards for the performance of geological CO_2 storage sites for example, and many countries are currently developing relevant regulations to address the risks of leakage.

[10] It needs to be addressed that the first pilot projects are outside the scope of the LAP.

5. CONTINUATION

Completion of this study provides background documentation for a project specific or a plan EIA.

It is intended that this document is checked by the EIA commission. The provinces will initiate this.

On the short term, several parties (also parties involved in this project) intend to initiate pilot projects. For them the AMESCO report will serve as a starting point.

The initiators of this study hope that governmental institutions will, on the short tem, get busy with the issues identified in this report.

1 INTRODUCTION, SCOPE AND LIMITATIONS

1.1 Background to this project

At the moment climate change is a ‘hot topic’ in the social-political debate in several industrialized countries. General consensus has been reached among scientists and politicians about the fact that mankind is very likely changing the global climate. Fossil fuel consumption, agriculture, chemical processes and waste disposal are all contributing to the emission of the greenhouse gas carbon dioxide (CO_2). One of the possibilities for reducing the amount of CO_2 discharged to the atmosphere is to capture and store the CO_2 underground.

Several Dutch companies and governmental organizations (national and regional) have expressed the wish to initiate schemes for Carbon dioxide Capture and Storage (CCS) in the near future in the Netherlands. This has led to a discussion on how to judge the potential effects of such activities on the environment. This is a relatively new field of research. No dedicated legislation, specific policy and examples or precedents of Environmental Impact Assessment have been formulated on this topic so far to give guidance to initiators, permitting authorities and stakeholders who have interests in Carbon Storage projects. For this reason a broad group of parties (private, governmental and institutional) initiated this study on the general environmental impacts of underground, onshore CO_2 storage called AMESCO (Algemene Milieu Effecten Studie CO_2 Opslag). The focus of this study is the storage of CO_2, which is only a part of CCS.

There is already a considerable amount of knowledge about storing CO_2 underground but this is dispersed. Many parties are already researching or planning projects to store CO_2 and a number of research groups are working together on different aspects of carbon dioxide capture and storage. CATO, a research program in the Netherlands (CO_2 afvang, transport en opslag), and GESTCO, a European initiative (Geological Storage of CO_2), are examples of these multidisciplinary project and research groups. Technical knowledge and knowledge on policies and legal aspects of CCS is available but it is scattered among many institutes, companies, governmental organisations and research teams. This knowledge needs to be combined to give a reliable insight into the possibilities for CCS in the Netherlands in the near future. These possibilities depend especially on the potential environmental impacts of CO_2 storage and the results of the Environmental Impact Assessments (EIA) to be performed for such projects.

Only little practical experience in CO_2 storage is available and the amount of work done on EIA’s for these operations is limited. A comparison with other long-term underground storage projects can be made (like waste water injection into oil reservoirs, nuclear underground repositories, acid-gas injection, etc.). It is also relevant to look at underground interim gas storage, where the natural gas replaces the (already used) natural gas in the reservoir. The storage time in that case is only tens of years at a maximum. Considering the demands for CO_2 storage connected with climate change, the time spans involved and the potential volumes to be stored are substantially different.

It is foreseen that many CO_2 storage projects will be needed. Underground CO_2 storage can be seen as an intermediate solution to the challenges of climate change, with the aim of having a fully sustainable energy supply by the end of this century. To achieve underground CO_2 storage, the dispersed knowledge needs to be combined with practical experience to formulate clear guidelines and policy. These will balance, on the one hand, potential greenhouse gas risks and impacts with, on the other hand, the potential risks and impacts associated with CO_2 storage.

1.2 Objectives

The background and problem statement as formulated above lead to the following objectives:

Main objective
The main objective of this research is to give insight into the environmental effects and boundary conditions involved with the storage of CO_2 in onshore underground reservoirs in the Netherlands in order to provide a background document for Environmental Impact Assessment (EIA).

Sub-objectives
The following sub-objectives have been identified. These are required to facilitate the implementation of CO_2 storage projects in the Netherlands:

- To identify common issues, concerns, data gaps, etc. in connection with the storage of CO_2 in underground reservoirs by gathering expert knowledge on the subject.
- To assist stakeholders by providing in an efficient way a common source of information on CO_2 storage for use in the environmental assessment of specific projects.
- To give insight into the priorities of legal and other issues which need to be addressed before actual project-specific EIA's can be carried out.
- To inform all stakeholders involved in the EIA process in order to reduce the risks of significant delays during EIA procedures in the future.
- To provide useful information for other Dutch environmental policy measures, such as:
  - Strategische Milieu Beoordeling (SMB).
  - Governmental plans like POP's (Provinciaal OmgevingsPlan) and LAP (Landelijk Afvalbeheer Plan) etc.
  - EIA's of projects where CO_2 storage may need to be addressed as, for example, the most environmentally friendly alternative.
- To give insight into the need for (and scope of) specific regulations concerning CO_2 storage projects.

1.3 Scope limitations

This study is limited in its scope, with a fixed budget and a limited time to produce the report. The Steering Committee has made explicit choices, in order to give maximum attention to the possible impact resulting from long-term CO_2 storage. The following five scope limitations have been defined to guide this research and report:

1. Focus on impact and risks resulting from the storage of the CO_2
   This study is focused on the possible environmental effects of CO_2 storage underground. Environmental effects that may result from capture or transport of CO_2 (likely to be important aspects of a CCS scheme) are not included within the scope. Nor are the effects of surface equipment for CO_2 storage, such as pumps and other

installations. Only the effects and risks of the presence of CO_2 in wells, of the injection process and of the long-term containment will be dealt with. This restricted scope results from the objective of this research, which is to fill the knowledge gaps associated with an Environmental Impact Assessment. The environmental effects of the capture and transport of CO_2 can be assessed based on existing knowledge and experience and therefore do not fall within the scope of this research.

2. CO_2 storage in gas reservoirs only
   The second limitation is that the research is limited to depleted gas fields, from which the economically recoverable resources have already been taken. CO_2 injection into aquifers or other reservoirs will not be considered in this study. Oil and gas reservoirs have demonstrated their suitability by holding hydrocarbon compounds for millions of years. Since oil fields often still contain a large quantity of oil, and in many cases water, the gas fields look more suitable in the short-term. The number of gas fields in the Netherlands is also much larger than the number of oil fields. Gas fields in general have a low pressure (although still about 30-40 bar on average) at the end of their lifetime and a high recovery rate, which makes them suitable for CO_2 storage.

3. Onshore projects only
   This research only considers the use of Dutch onshore fields. The first storage projects are likely to be onshore. The offshore legal and environmental issues are very different. The experience gathered with CO_2 injection and storage in offshore fields may nevertheless be relevant to onshore projects. Therefore information from offshore projects is used in this study.

4. Permanent storage only
   This study assumes that the CO_2 is stored permanently. This means that it must be contained for a long period of time, with no intention to remove or reuse the CO_2. In particular, there is uncertainty about the issue of the long-term behaviour and containment. Also, the responsibility for the stored CO_2 in the long-term has to be established.

   Short-term storage is possible, e.g. for use of CO_2 in greenhouses, but this is a less critical case. The injection of CO_2 with the aim of extracting more oil or gas from a reservoir is also outside the scope of this research. This technique is called Enhanced Oil (Gas) Recovery (EOR or EGR). However the findings of this study will be used to mention the consequences for EGR and EOR (see chapter 12).

5. Alternative options for CO_2 storage in gas reservoirs; but not other forms of CO_2 emission reduction
   In an Environmental Impact Assessment (EIA) alternatives to the proposed scheme are considered. In this study only the alternative options for CO_2 storage in depleted gas fields will be compared. Other alternatives for CO_2 emissions reduction, for example energy conservation and renewables, are not taken into account. This study is not aimed at finding the best alternative for reducing the emission of CO_2 to the atmosphere and a comparison with broad alternatives is therefore not relevant in this context.

1.4 Stakeholders

As stated in the introduction to this chapter there is still considerable uncertainty about the possible risks involved with the underground storage of CO_2. There is little guidance for stakeholders on how to deal with these risks. In addition to the initiators and the authorities a number of other organizations are involved in the discussion about the desirability of CO_2 storage. In consultation with the Steering Committee the following additional external stakeholders have been identified:

- Political: deputies of the involved Dutch provinces.
- The energy experts of political parties.
- NGO's (Environmental organizations).
- EIA-committee.
- Involved municipalities.
- The umbrella organization of Dutch municipalities, VNG.
- Nature and Environment Foundation.
- Ministry of Economic Affairs / state supervision of mines.
- International stakeholders.
- European Commission.

From this list a few stakeholders have been selected to give their constructive critical opinion on the scope of this project. These are:

- EIA-committee (commissie van de m.e.r.).
- Friends of the Earth Netherlands (Milieufederatie en Natuur & Milieu).
- Ministry of Economic Affairs / state supervision of mines (Ministerie EZ en SodM).
- University of Utrecht.

1.5 Structure of the report

This report contains all the chapters that are usually part of an EIA. In each chapter background information is given, which would be needed for a project-specific EIA. Each chapter also contains a recommendation concerning the issues which should be addressed in a project-specific EIA.

In chapter 2 the background of CO_2 storage in relation to climate change is described. Chapter 3 deals with the technical aspects of CO_2 injection and the characteristics of reservoirs. Legislation and policies concerning CO_2 storage are the subject of chapter 4. The standard structure of an EIA is followed in chapter 5, making clear what the specific issues are for a CO_2 storage project. In chapter 6 the relevant vulnerability of the environment, both physical and in the biosphere, is described. The risk of leakage and impact of possible leakage is the focus of chapter 7. Chapter 8 describes the possible alternatives to choose from in a specific project. The monitoring program is described in chapter 9 with the possible contingency plan in the case of unwanted effects in chapter 10. There are gaps in knowledge, as described in chapter 11, leading to necessary follow-up activities as discussed in chapter 12.

1.6 Issues for a project-specific EIA

At the end of each chapter a description is given of what might be expected in a project-specific EIA. This includes the regular information as presented in any EIA. Extra attention is given to the findings within the chapter concerning CO_2 storage. The conclusions of these findings and how to deal with them in a project specific EIA will be described.

When for a specific CO_2 storage project an EIA has to be written, the findings of this report can be taken as guidelines.

General issues for an EIA in Chapter 1
Chapter 1 generally describes the setting and the reason for carrying out the project. The role of the initiator, the history etc. are also covered.

Specific attention to CO_2 storage in Chapter 1

- Storage of CO_2 will be connected to capture and transport activities. It is important to describe the relation between these aspects. So there should be a description of the storage project within the total chain of the larger CCS-project, including relevant information on capture and transport.
- Possibly more organizations are active, including the activities of CO_2 capture and transport. Therefore it is important to describe the role of each party.
- The purpose of the project has to be made clear. It is of course meant to reduce the amount of CO_2 emission. When the storage project is a pilot scheme, the objectives should explicitly be given like the intention of learning and testing storage mechanisms or investigating a low cost CO_2 reduction activity.

2 BACKGROUND TO CO_2 STORAGE

2.1 Introduction

In February 2007 the Intergovernmental Panel on Climate Change of the United Nations (IPCC) released the latest report (the 4th Assessment Report). This report states clearly that climate change is taking place at a very rapid tempo. The temperature is changing worldwide at a rate much faster then anything recorded in the past thousands of years.

As an important cause for the increase in temperature the emission of CO_2 and other greenhouse gases is mentioned. It is very probable, according to IPCC, that the increase of emissions is caused by mankind. These emissions result from fossil fuel consumption, agriculture, chemical processes and waste disposal (IPCC, 2001), (TK, 2004).

If the greenhouse gas concentrations built up in the atmosphere are not contained and stabilized within this century the climate changes will have severe and probably irreversible negative impacts. Awareness of this problem has been growing since the sixties/seventies of the twentieth century and ever since then politicians and scientists have been thinking about ways to control and reduce the emission of greenhouse gases into the atmosphere.

Capture and sequestration of CO_2 (CCS) produced by power plants (and other process installations) is one of the possible measures for mitigating greenhouse gas emissions. In this chapter the background against which the technology for CCS has been developed is described. Attention will be paid to the technical aspects of climate change (Sections 2.2 and 2.3) as well as to the policies that have been agreed upon to address the problem (Section 2.4). The technical and political issues have led to the development of solutions (Section 2.5). The possibilities and the justification for CCS in the Netherlands as one of the options for combating climate change will be discussed in Section 2.6. After this section we discuss the content of this chapter in a specific EIA (Section 2.7).

2.2 Climate change

2.2.1 Evidence of climate change

Evidence from monitoring of worldwide climate-related phenomena over a period of hundreds of years has yielded a strong suggestion of rapid change in climate in the last decades. According to the IPCC, an increasing body of observations gives a collective picture of a warming world and of other changes in the climate system.

From monitoring data the climate change can be measured by:

- global increase in average air and surface temperature (increase over the 20th century by 0.6 +/- 0.2^{o}C);
- global increase in average sea level (between 0.1 and 0.2 meters during the 20th century);
- acidification of the oceans;
- decrease of snow cover of about 10% since the late 1960's;
- retreat of mountain glaciers in non-polar regions.

Effects can already be seen in changes in precipitation patterns. Also the weather is becoming more extreme. In this paragraph we refer to the figures published by the IPCC.

Figure 2.1 shows global temperature for a period of 1,000 years and for the past 140 years. The figure for 1,000 years shows a rapid increase of about 0.4^{o}C since 1900. During the last 140 years there was a period between 1940 and 1980 when the temperature did not increase. However from 1980 onwards the increase is almost another 0.4^{o}C.

Figure 2.2 shows examples of sea level rise at different locations around the world.

2.2.2 Impact of global warming

Although there are still uncertainties, global warming, if it takes place, could have severe consequences. Some are mentioned below.

Threatening of coastal zones
Effects of increased global warming will result in large costs. An example is melting of ice caps and glaciers, together with warming of the water, which result in an expected rise of sea levels of 0.1 - 0.9 meters, the level depending on the future increase in atmospheric greenhouse gas concentrations. Strengthening coastal defences to prevent flooding from these rises could require € 9 billion in the period up to 2090 for the Netherlands alone.

Reversing ocean currents
A further unrestricted increase in temperature in the coming decades might ultimately result in more extreme and eventually perhaps irreversible effects, such as the shut-down of the North Atlantic warm current or an increase in temperature caused by e.g. methane released from previously permanently frozen soils[11].

Impact on plant and animal life
An impact of global warming is expected on the ecological system. If the weather conditions are changing quickly, plants and animals may not be able to adjust. Also new diseases can arise.

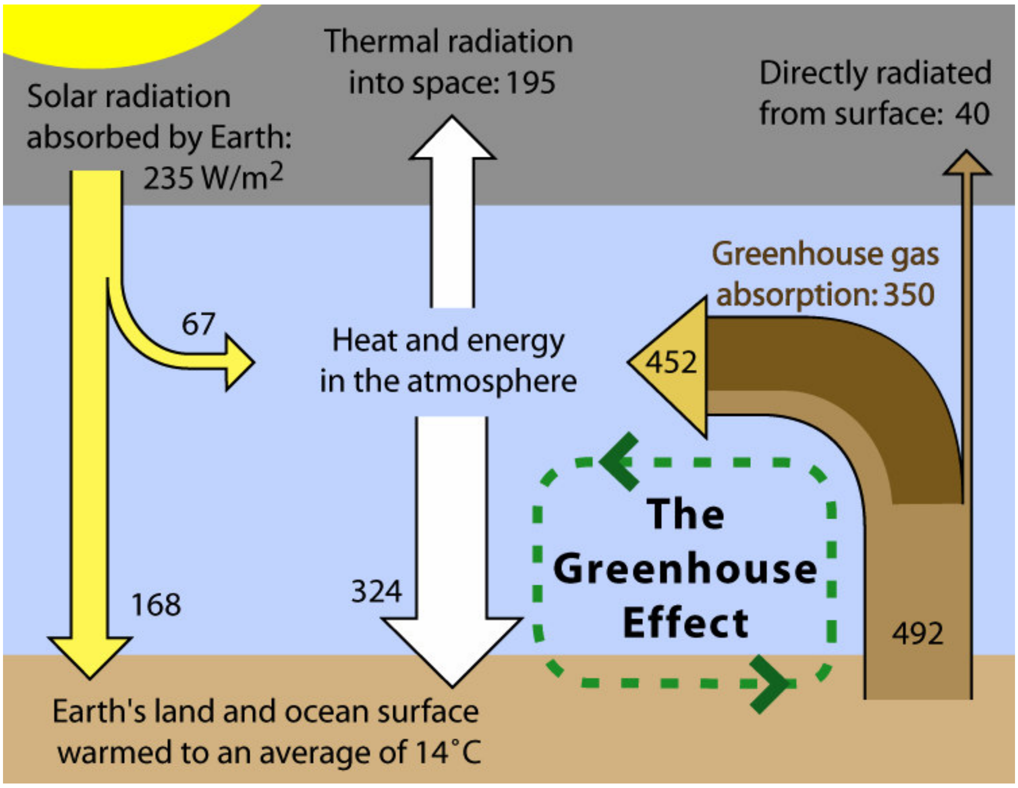
2.3 Causes of climate change

2.3.1 Impact of greenhouse gases

The previous paragraphs might give the idea that greenhouse gases are solely the product of human activities. This is not true. The greenhouse gases CO_2 and CH_4 (methane) are part of the natural system and are emitted by, for example, plants, soils, organisms in seas and oceans and by volcanoes. Another important greenhouse gas is water vapor.

[11] See e.g. Climate 'time bomb' forecast, methane bubbles out of permafrost at increased rate.
By Seth Borenstein, Associated Press | September 7, 2006. © Copyright 2006 Globe Newspaper Company.

The greenhouse gases in the atmosphere make up an insulating layer that absorbs some infrared radiation from the earth's surface. The infrared radiation is the result of the heating of the surface due to solar radiation. The radiation absorbed by the atmosphere is partly emitted back to earth's surface, thereby increasing the temperature further.



(http://en.wikipedia.org/wiki/Image:Greenhouse_Effect.png; all figures in W/m^2)

Figure 2.3 Energy flows in earth's atmosphere

As illustrated by Figure 2.3 a global average of 235 W/m^2 is absorbed by earth and its atmosphere, of which 168 W/m^2 is absorbed by the surface and 67 W/m^2 by the atmosphere.

When the system earth is in thermodynamic equilibrium the incoming radiative energy must be offset by an equal outgoing energy flow. However, only 40 W/m^2 of the radiation absorbed by earth's surface is radiated directly back into space. The other 122 W/m^2 is absorbed again by earth's atmosphere, heating it up, and is partly radiated back to earth. The part that is radiated back to earth is of course radiated back into the atmosphere, is again largely absorbed by that atmosphere and partly emitted back to the earth's surface, etc, etc. This mechanism results in a loop in which the atmosphere is heated up to a temperature at which 324 W/m^2 on average is trapped inside this loop and the balancing amount of 195 W/m^2 is radiated into space.

The figure gives an indication of energy flows in the earth's atmosphere. The yellow shows the radiation from the sun. The white indicates the radiation into space and to the earth from the atmosphere and the brown the energy flows from the earth's surface, indicating the impact of greenhouse gases. The presented amounts of energy can be different from place and time.

In fact, without greenhouse gases, the average surface temperature on earth would be approximately 40℃ lower and life on earth would be much harder if not impossible in many regions.

Over periods of millions of years as a result of a range of terrestrial and extraterrestrial factors the climate has varied naturally; including extremes such as glacial periods. The current observed change in climate - discussed in Section 2.2 - could therefore be another natural change.

The main reason for concern is the coincidence of the climate change with an increase in greenhouse gases in the atmosphere. In Figure 2.4 it can be seen that the amount of CO_2, methane and nitrous oxide in the atmosphere have increased rapidly since the industrial revolution of the nineteenth century. An increase in the amounts of greenhouse gases reduces the direct radiation to space from the earth's surface and as an unwanted result the temperature of the atmosphere increases to compensate for this and rebalance the energy flows.

This indicates, with a large probability, that the increase of temperature is caused by emissions of greenhouse gases, and is not solely a natural change in conditions. This conclusion can be made although the anthropogenic contribution to the total carbon balance is still limited compared to the natural carbon fluxes.

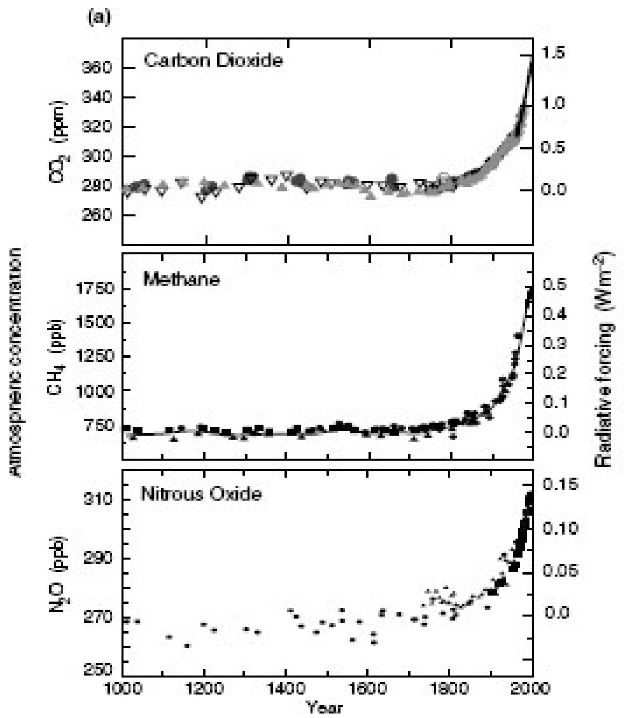
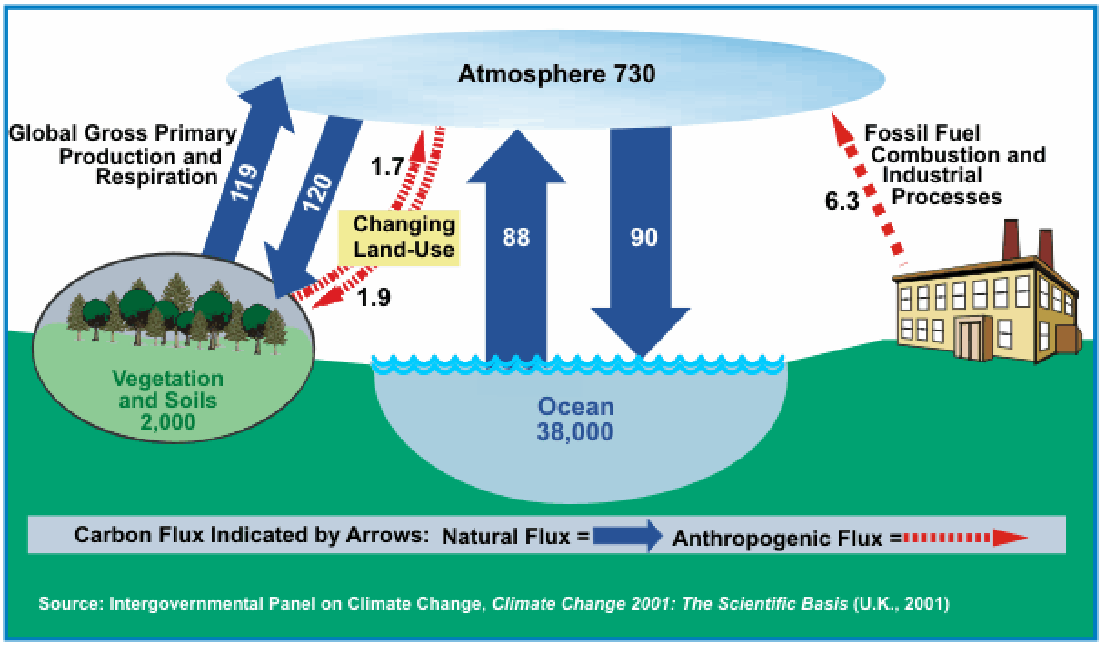


Figure 2.4 Increase in atmospheric greenhouse gas concentrations (Rooijers, 2004)



http://www.eia.doe.gov/oiaf/1605/ggccebro/chapter1.html

Figure 2.5 Earth's carbon cycle (figures in Gton C/year)

As illustrated by Figure 2.5 there is a very large exchange between the atmosphere and the soil, oceans and the earth's surface. This exchange is partly biological, related to the growth and death of living organisms. The other part concerns chemical equilibrium between carbon present as CO_2 in the atmosphere and carbon present as carbonate/bicarbonate or as dissolved CO_2 in the oceans. Anthropologic activities create an extra flux of CO_2 into the atmosphere, thereby influencing the carbon cycle and the thermodynamic equilibrium in the atmosphere.

The most important anthropogenic factors are:

- fossil fuel consumption;
- agriculture and deforestation;
- chemical processes;
- waste disposal.

There is still debate on a number of issues. One of them is the mass balance of CO_2. The amount produced by mankind can be calculated more or less, but other source and sink mechanisms are not yet fully understood. The extra input into the system by human activities is partly compensated by an observed extra ocean uptake, but other sinks that also partly compensate the anthropogenic emissions are not yet fully understood (see, for example, http://www.whrc.org/carbon/missingc.htm).

2.3.2 Scenarios for reduction of global warming through greenhouse gases

According to IPCC (IPCC, 2001) limiting the severity of potential impacts of climate change requires stabilization of atmospheric greenhouse gas concentrations at a level resulting in a maximum average global temperature increase of 2°C compared to pre-industrial values. The probability of stabilization at a maximum temperature increase of 2°C is more than 70% for a concentration level of 450 ppm CO_2-equivalent and 30% at a level of 550 ppm. Figure 2.6 shows the required emission levels for five different stabilized atmospheric CO_2 concentrations. Worldwide the emissions have to be reduced by 60-80% in 2100.

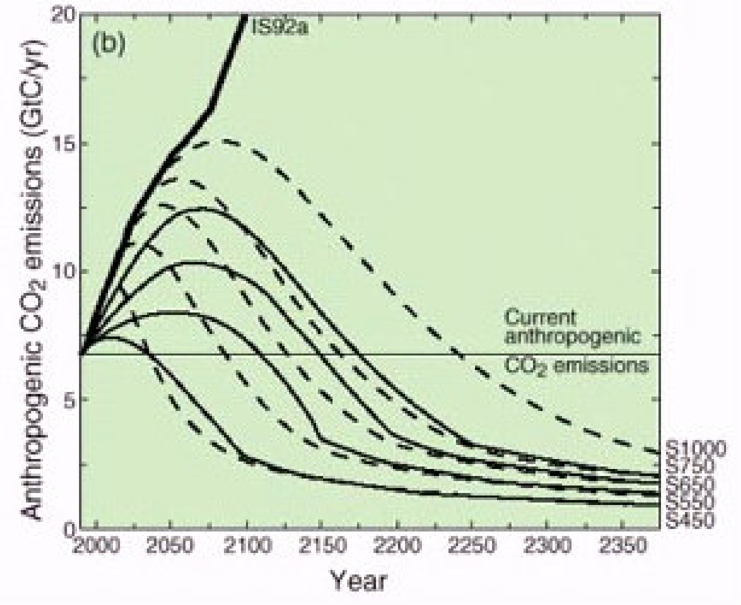


Figure 2.6 Example of scenarios for greenhouse gas emission reductions as a function of desired stabilized atmospheric CO_2 concentration (IPCC, 1995)

Due to the inertia and delays in the climate system even with stabilized concentrations the world will be subject to some significant climate changes for centuries to come.

2.4 Climate policy - Kyoto

2.4.1 Global climate policy

The risks related to climate change have been recognized and this resulted in the 1992 Rio de Janeiro climate treaty. The aim of the Treaty is stabilization of atmospheric greenhouse gas concentrations at such a level that a dangerous human impact on the climate is avoided. In 1997 the treaty was extended with an extra protocol, the Kyoto-protocol. The protocol is an agreement by the industrialized countries for a first step of a 5.2% reduction of greenhouse gases compared to the emissions in 1990. It entered into force on 16 February 2005. Reduction targets vary with the strength of the economy of the individual industrialized countries. An overview of targets for individual regions and countries is given in Table 2.1 and Table 2.2.

Table 2.1 Targets from the Kyoto-protocol, given changes in greenhouse gas emission compared to 1990 (Wikipedia)

	Target (1990-2008/2012)
EU-15, Bulgaria, Czech Republic, Estonia, Latvia, Liechtenstein, Lithuania, Monaco, Romania, Slovakia, Slovenia, Switzerland	-8%
US	-7%
Canada, Hungary, Japan, Poland	-6%
Croatia	-5%
New Zealand, Russian Federation, Ukraine	0
Norway	+1%
Australia	+8%
Iceland	+10%

Table 2.2 Targets for individual EU member states, given changes in greenhouse gas emission compared to 1990

	Target	Emissions in 2003	2008-2012 with existing policies & measures (PAMs[12])	2008-2012 with additional PAMs and/or Kyoto mechanisms
EU-15	-8.0%	-1.7%	-1.6%	-9.3%
EU-25	-	-8.0%	-5.0%	-11.3%
Austria	-13.0%	16.6%	8.7%	-18.1%
Belgium	-7.5%	0.6%	3.1%	-7.9%
Czech Republic	-8.0%	-24.3%	-25.3%	-26.5%
Denmark	-21.0%	6.3%	4.2%	na
Estonia	-8.0%	-50.8%	-56.6%	-60.0%
Finland	0.0%	21.5%	13.2%	0.0%
France	0.0%	-1.9%	9.0%	-1.7%
Germany	-21.0%	-18.5%	-19.8%	-21.0%
Greece	25.0%	23.2%	34.7%	24.9%
Hungary	-6.0%	-31.9%	-6.0%	-
Ireland	13.0%	25.2%	33.4%	na
Italy	-6.5%	11.6%	13.9%	-3.7%
Latvia	-8.0%	-58.5%	-46.1%	-48.6%
Lithuania	-8.0%	-66.2%	-50.6%	-
Luxembourg	-28.0%	-11.5%	-22.4%	na
Netherlands	**-6.0%**	**0.8%**	**3.5%**	**-8.5%**
Poland	-6.0%	-32.1%	-12.1%	-
Portugal	27.0%	36.7%	52.1%	42.2%
Slovakia	-8.0%	-28.2%	-19.7%	-21.3%
Slovenia	-8.0%	-1.9%	4.9%	0.3%
Spain	15.0%	40.6%	48.3%	21.0%
Sweden	4.0%	-2.4%	-1.0%	-
United Kingdom	-12.5%	-13.3%	-20.3%	-

As of December 2006, a total of 169 countries and other governmental entities have ratified the agreement, representing over 61.6% of emissions from industrialized

[12] PAM refers to Policies And Measures

countries (Annex I from the Kyoto protocol). The USA and Australia have not ratified the protocol.

The individual signatories can realize their targets on one hand by taking measures such as:

- energy conservation;
- reduction of emissions of methane and other non-CO_2 greenhouse gases, e.g. reducing methane emissions from landfills or sewage treatment plants or reducing industrial N_2O emissions;
- switching to low-carbon fuels (natural gas, biomass);
- development and implementation of the subject of this study, CCS.

Another option for the signatories is supporting similar initiatives in developing and transitional countries within the Joined Implementation and Clean Development Mechanism frameworks. These frameworks allow industrialized countries to support similar initiatives and projects as mentioned above in developing countries and transitional countries, and (partly) assign the environmental credits to their own national account.

However, the Kyoto protocol is only the first step in achieving a reduction of 60% - 80% in anthropogenic greenhouse gas emissions. Realizing this, the European Union and Dutch Government have defined additional and more ambitious reduction targets. The strategies and policies envisaged for reaching these targets and the role of CCS in these strategies are discussed briefly in the next two subparagraphs.

2.4.2 European climate policy[13]

The 2007 Spring European Council demonstrated that the EU is taking the lead in the fight against global warming. EU heads of state and government adopted an energy policy for Europe which doesn't simply aim to boost competitiveness and secure energy supply, but also aspires to save energy and promote climate-friendly energy sources.

CCS is mentioned in the strategy report 'energy and climate control' of the European Union as a way to reduce the CO_2 emission from energy plants. By the year 2020 every coal-fired power plant needs to have a CCS system.

The proposed EU energy policy targets the following objectives:

- Reducing greenhouse gas emissions from developed countries by 30% by 2020; the EU has already committed to cutting its own emissions by at least 20% and would increase this reduction under a satisfactory global agreement.
- Improving energy efficiency by 20% by 2020.
- Raising the share of renewable energy to 20% by 2020.
- Increasing the level of biofuels in transport fuel to 10% by 2020.

[13] (bron: COUNCIL OF THE EUROPEAN UNION, Brussels, 9 March 2007, 7224/07 en An Energy Policy for Europe - the need for action, European Commission, Directorate-General for Energy and Transport, Brussels, 10 January 2007 en Communication from the Commission to the Council and the European Parliament - Sustainable power generation from fossil fuels: aiming for near-zero emissions from coal after 2020, 10 January 2007).

For carbon capture and storage, which it sees as one of the key technologies in combating climate change, the European Commission has a multiple strategy:

1. The EU will design a mechanism to ensure that by 2015 twelve sustainable fossil fuel power plants are in operation It also proposes that all new coal-fired plants built after 2020 should include carbon capture and storage.
2. Initiatives and more fundamental research in CCS is sponsored and promoted through several platforms and forums, e.g.:
   - The Technology Platform on Zero Emission Fossil Fuel Power Plants (ETP ZEP) in which all key stakeholders in this field, such as the European Commission and European energy industry, research community and non-governmental organizations are involved. Its aim is to enable EU fossil fuel plants with zero emission of carbon dioxide by 2020. The platform consists of 25 members (http://www.zero-emissionplatform.eu). In September 2006, the Zero Emission Technology Platform presented its Strategic Research Agenda and a Deployment Strategy.
   - The EU Commission is also a member of the Carbon Sequestration Leadership Forum, an international framework for co-operation in research and development of CCS. The purpose of the CSLF is to make these technologies broadly available internationally; and to identify and address wider issues relating to carbon capture and storage. This could include promoting the appropriate technical, political, and regulatory environments for the development of the technology. The CSLF is currently comprised of 22 members, including 21 countries and the European Commission[14].
   - The EU Commission is funding research into clean coal technologies and carbon capture and storage under the EU's seventh research framework programme (FP7). The aim is to bring down the cost of CCS technology to less than € 20 per ton, with capture rates above 90%[15].
3. Within the framework of 'Capturing and storing CO_2 underground - Should we be concerned?', the European Commission is preparing a legislative proposal which aims at establishing the regulatory framework for the capture of carbon dioxide and its geological storage, often referred to as 'carbon capture and storage' (CCS). A consultation was open until 16 April 2007. At present, few countries have specifically developed legal and regulatory frameworks for onshore CO_2 storage. Specifically, long-term liability issues, such as global issues associated with the leakage of CO_2 to the atmosphere, as well as local concerns about environmental impact, have not yet been addressed (IPCC Special Report on Carbon dioxide Capture and Storage). (http://ec.europa.eu/environment/climat/ccs/consult_en.htm).

2.4.3 The Netherlands - climate policy

Current and future Dutch greenhouse gas emission reduction strategies are based on a mix of reduction measures within the Netherlands and reduction measures within Joint Implementation and Clean Development Mechanism Frameworks.

14 (www.cslforum.org).
15 (http://cordis.europa.eu/fp7/cooperation/energy_en.html).

In the Dutch coalition agreement (2007-2011) of 7 February 2007, one of the pillars is Sustainable Environment. Within this pillar the energy policy targets for the Netherlands are defined as follows:

- 20% share of renewable energy by 2020, consisting of a mix of green electricity, green gas and biofuels;
- 2% higher energy efficiency per year;
- no new nuclear power plants;
- CO_2 storage as one of the important measures for realizing the desired reduction goal.

Together these measures are projected to result in a 97 Mton reduction in greenhouse gas emissions in 2020, compared to 1990:

- Energy efficiency improvement = 27 Mton
- Renewable energy = 29 Mton
- **Carbon Capture & Storage = 4 Mton**
- Clean Development Mechanism = 30 Mton
- Miscellaneous greenhouse gas policy = 7 Mton

The Dutch government is promoting technological development and initiatives for reaching the targets through a number of platforms and forums:

- The Dutch government is working together with market actors (industry, knowledge institutes etc.) and public actors for the Dutch energy transition. The goal is to reach within 50 years a sustainable energy system in the Netherlands. This means an affordable, reliable and clean energy system. Six platforms have been defined through which energy transition will be implemented. One of these platforms is the New Gas platform with a working group CO_2 storage/clean fossil. That working group (www.senternovem.nl/energietransitie) is stimulating options such as CO_2 storage onshore.
- The CATO platform represents a strong knowledge network in the field of CO_2 Capture and Storage in the Netherlands, assessing and developing new knowledge, technologies and approaches in this field. The aim of CATO is to identify whether and how CO_2 Capture and Storage can contribute to a sustainable energy system in the Netherlands, from an economical, technical, social and ecological point of view and under which conditions this option could be implemented in the energy system.
- A subsidy of M€ 80 will be granted through a tender procedure for two different projects, M€ 60 for a project that should result in the actual sequestration of 0.4 Mton of CO_2 annually and M€ 20 for a test facility for CO_2 capture at a coal-fired power plant.

Local Dutch permitting authorities and energy companies also aware of the potential negative impacts of climate change and are preparing themselves by including initiatives in their plans and policies. Most power companies operating in the Dutch market and considering new coal-fired production capacity indicate that they will voluntarily make their design ‘capture ready’ and suited for co-combustion of large percentages of biomass. The Ministry of environment and the Rotterdam and Rijnmond authority have drawn up criteria for new coal-fired power plants that require such a power plant to be ‘capture ready’. A good definition of ‘capture ready’ is not yet available, therefore there is still some debate about what is expected from new coal-fired power plants. The

International Energy Agency (IEA) made a first attempt in drafting a report on capture readiness.

2.4.4 The Netherlands - current level of annual CO_2 emissions

The current total annual greenhouse gas emissions, including CH_4, N_2O, SF_6 and HFC's and PFC's (expressed in CO_2 equivalent) amount to:

- Approximately 220 Mton for the Netherlands[16] see: http://www.broeikasgassen.nl/, of which approximately 65 Mton is emitted annually by large industrial sources (nearly 30%).
- Approximately 20 Gton for industrialized countries.
- Approximately 49 Gton world wide.

For completeness, current and 1990 emission rates of greenhouse gases for the Netherlands are given in Table 2.3. From this table it is clear that CO_2 forms the main greenhouse gas emission in the Netherlands and also the main reason for the increase since 1990. In the Netherlands therefore, the focus is on measures to reduce CO_2 emissions.

Table 2.3 Overview of different greenhouse gas emissions in the Netherlands, expressed in Mton.

GREENHOUSE GAS EMISSIONS	**Base year (1990)**	**2004**
	CO_2 equivalent (Mton)	CO_2 equivalent (Mton)
CO_2 emissions	162	183
CH_4	25	17
N_2O	21	18
HFCs	4.4	1.5
PFCs	2.3	0.28
SF_6	0.22	0.33
Total	215	220

(including net CO_2 from LULUCF)[(3)]

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	**2004**
	CO_2 equivalent (Mton)
1. Energy (power stations, refineries, space heating in residences and service industries, transport)	176
2. Industrial Processes (N2O from HNO3 production, NH3 and H2 production, etc)	16.4
3. Solvent and Other Product Use	0.23
4. Agriculture (N2O, CH4 from manure management, CO_2 from landuse changes)	18.2
5. Land Use, Land-Use Change and Forestry[(7)]	2.36
6. Waste (CO_2 from waste combustion, CH4 from landfills)	7.26
7. Other	NA
Total (including LULUCF)	**220.45**

16 CH4, N2O, HFC's, PFC's, SF6

A reduction of greenhouse gas emissions in accordance with the Kyoto protocol would require:

- A reduction of Dutch greenhouse gas emissions from currently 220 Mton per year to approximately 200 Mton annually, 6% lower than the level of 1990 of 215 Mton annually. Reports of the NMP describe the possible domestic versus the foreign measures for reduction.
- A total reduction of greenhouse gas emissions from industrialized (Annex I) countries to approximately 17.3 Gton, 5.2% below the 1990 emission level of 18.4 Gton/year.

The Kyoto protocol has not yet resulted in a trend change from the continuous increase in global greenhouse gas emissions towards the agreed reduction. Instead, emissions of greenhouse gases are projected to continue to increase in the next decades, both globally and for the Netherlands. Population growth and increasing economic activity result, and will continue to result, in increasing consumption of energy, industrial production, waste production and agricultural expansion. In other words, the trend is a growing gap between the reduction goal and the expected increase in greenhouse gas emission levels (see Figures 2.7 and 2.8).

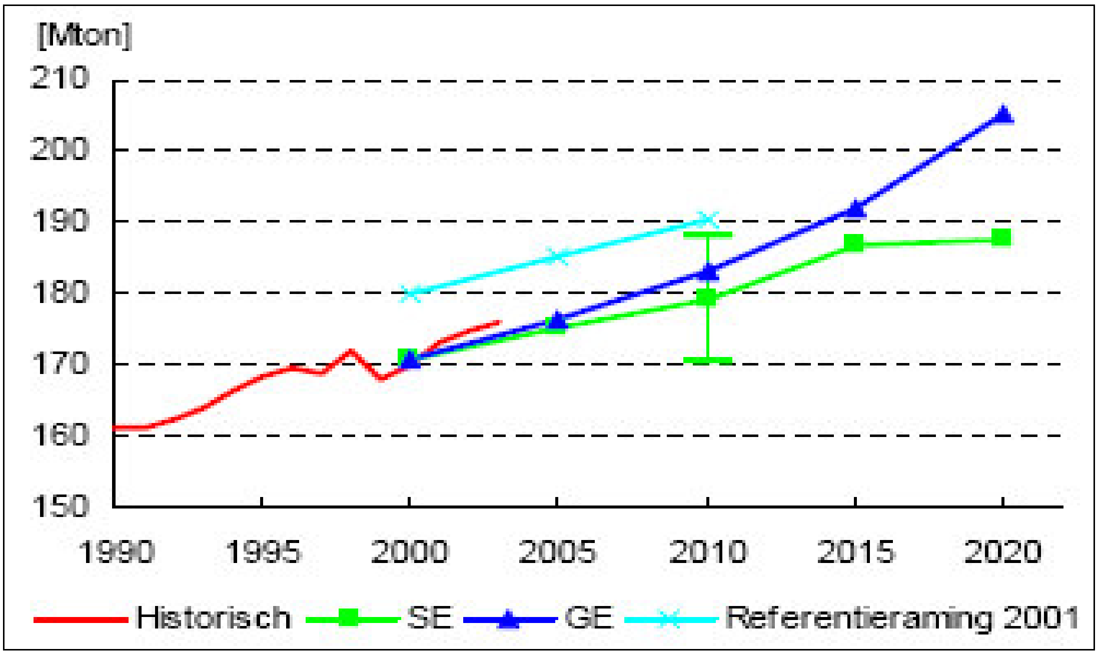


Figure 2.7 Projection of total Dutch annual CO2 emissions (ECN, 2006)
SE is a scenario for a Strong European Economy, GE a scenario for a Global Economy

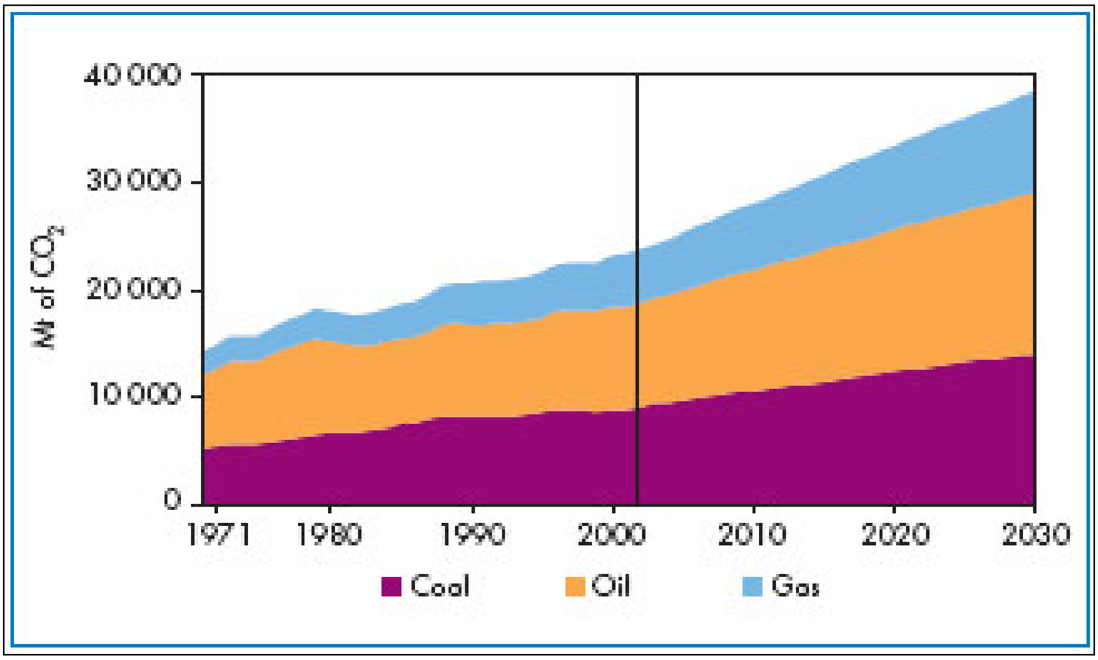


Figure 2.8 **Projection of total global annual CO2 emission from fossil fuel consumption (EIA, 2004)**

Figure 2.7 should be considered as a demonstration that in spite of ratification of the Kyoto protocol by the Netherlands the actual emission of CO_2 is still increasing, as a result of economic growth and of the limited measures for greenhouse gas emission reduction. This implies that additional measures are required to reaching the Kyoto protocol target and any additional reductions beyond this. Figure 2.8 has a similar purpose at a global level.

Figure 2.7 shows emissions in the Netherlands presents a somewhat distorted image as a percentage of the reduction target will be reached by investment in 'Joint Implementation and Clean Development Mechanism' measures and buying emission rights abroad.

2.5 Possibilities for reducing greenhouse gas emissions

In order to achieve the required trend change, and stabilize atmospheric greenhouse gas concentrations at a level at which effects of global warming will remain limited and manageable, every possible means of emission mitigation will probably have to be applied as a *combined* effort. Measures at our disposal are:

- Energy conservation.
- Application of renewable energy.
- Switch to low carbon fuels.
- Nuclear power.
- The subject of this study - CCS.

IPCC illustrates this necessity in its recent CCS technical report with two scenario analyses. This conclusion that all measures must be applied - including CCS - applies to the Netherlands as well. This is because of the limited reduction potentials of the other options.

Energy conservation in the Netherlands
Estimates of maximum greenhouse gas reduction potential by energy conservation within the next fifteen years amount to approximately 35 Mton/year, a reduction of approximately 15% compared to greenhouse gas emissions levels in 1990 (ECN, 2006). Greenpeace claims a maximum greenhouse gas reduction of 50% with energy conservation is technically achievable by 2050 (Greenpeace, 2006). But according to ECN and MNP realizing maximum reduction potential will probably require a fair number of measures with specific CO_2-reduction costs of € 100/ton - € 200/ton, this being much higher than current probable specific reduction costs using CCS (maximum € 55/ton CO_2).

Renewable energy
The maximum potential for greenhouse gas emission reduction by renewable energy in the Netherlands is limited to approximately 40-50 Mton/year or 20%-25% of the emission level of greenhouse gases in 1990 (ECN, 2002). Renewable energy technologies applied in the Netherlands will remain expensive within the next decades, and this applies even to offshore wind. According to (ECN, 2006) this is the cheapest source of renewable energy in the Netherlands.

The potential for renewable energy may be limited further by restriction of import of biomass for electricity generation and automotive fuels production. There are concerns about sustainability and potential negative environmental impacts from crop cultivation for this purpose. Cultivation also generates greenhouse gas emissions (N_2O, CH_4) and biomass cultivation for substituting fossil fuels does not necessarily result in a net reduction of greenhouse gas emissions.

Less carbon-intensive fossil fuels
The reduction potential for switching to less carbon-intensive fossil fuels (e.g. from coal to gas in power generation) is limited in the Netherlands given the already dominant role of natural gas in energy supply.

Nuclear energy
There is still public opposition to use of nuclear energy in the Netherlands because of concerns about safety, weapons proliferation and nuclear waste. Currently opposition is declining and a minority in Parliament is now actively backing construction of a second nuclear power plant. However, proven global uranium reserves (4.2 Mton) allow for nuclear electricity generation at the current level for only approximately 60 years - the technical life of a modern nuclear power plant. Increased generation capacity will require additional reserves. From this perspective the situation for nuclear energy is comparable with that of natural gas and oil, i.e. nuclear energy is a finite energy source.

Current mining production capacity doesn't even cover current uranium demand. OECD and IAE conclude in their latest 'Red Book' overview of reserves and current and near future mining production (Red Book, 2006) mine production capacity will probably restrict growth of nuclear power production in the next decades.

Concluding
Taking together energy conservation, renewable energy and nuclear energy Dutch greenhouse gas emissions can probably be reduced by a maximum of 40%-50%. This however is a long term perspective.

This underlines the need for CCS in the Netherlands if significant reductions in greenhouse gas emissions are to be realized within this century. CCS is only a temporary solution and therefore a time span, in which is stated what the period of transition is, needs to be defined.

2.6 Reduction of CO_2 emissions through CCS in the Netherlands

2.6.1 CCS as a medium-term solution

The use of CCS is not considered as a final solution to preventing adverse effects on the global climate. It is anticipated that it can contribute to a reduction for a period of time during which long-term measures can and must be taken.

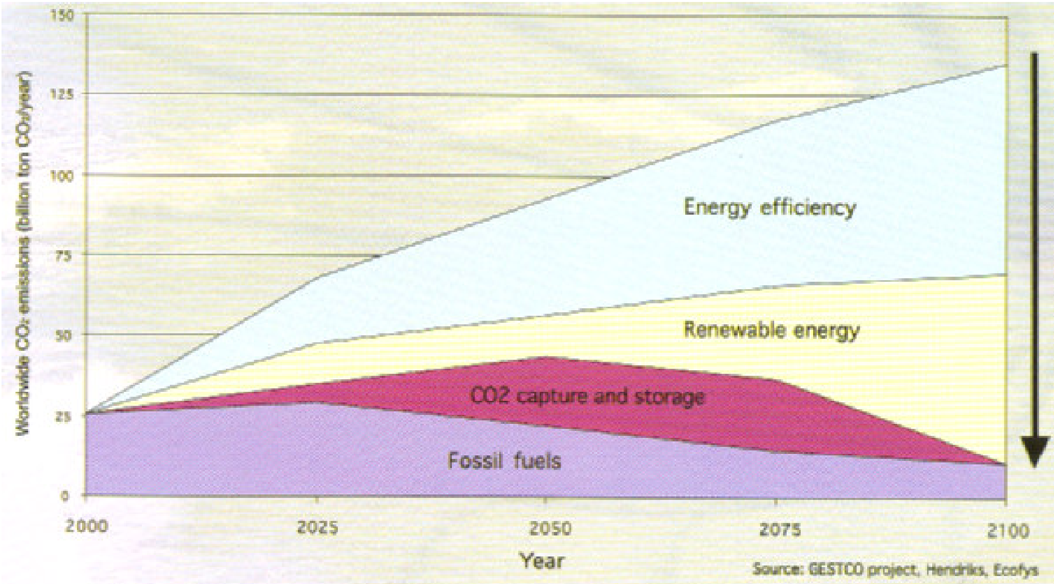


Figure 2.9 The potential role of CCS in a strategy for reducing CO_2 emissions – Source: Ecofys 2004

2.6.2 Is CCS an option in the Netherlands?

CCS is a logical greenhouse gas emission mitigation option for the Netherlands. Natural gas production and oil production in the past forty years have yielded a good knowledge of the Dutch subsurface. The declining reserves of natural gas leave, or will leave, a storage capacity of - roughly estimated - 1,600 Mton (not considering the Groningen field Slochteren, see also Section 3.4). Deep aquifers provide another potential capacity for roughly 1,500 Mton CO_2.

As mentioned before, a reduction of CO_2 emission is required. Reduction of CO_2 emission through capture and storage of CO_2 can best be achieved from large industrial point sources (power plants, furnaces in refineries, etc.). These rich and diluted off-gases (>4 vol% CO_2) amount currently to approximately 65 Mton/year. Typical yearly amounts and CO_2 concentrations for different industrial sources are given in Table 2.4. The table also gives the average specific costs per ton of avoided CO_2, applying current state of the art technology.

Table 2.4 Overview of industrial CO_2 sources, concentrations and capture costs[17] in the Netherlands

	CO_2 - concentration (vol% dry gas)	Yearly amount per unit or location (Mton)	Dutch production (Mton/year)	CO_2 capture costs (/ton avoided)	
Power stations					
• coal fired base load power station, 600 Mwe	12% - 15%	3.3	23.0	35 ± 8	for a new unit
• IGCC, in syngas after watergas shift	40% - 45%			18 ± 8	for a new unit
• gas fired partial load power station	3% - 5%	large variation	22.7	42 ± 9	for a new unit
H2-production tail gas, H2 separation by PSA	> 90%	0.6	1.2	10 ± 8	
NH3, MDEA CO_2-capture	100%	1.8	3.5	5?	already separated as pure CO_2, needs drying
Blast furnace gas, after gas utilization	25% - 30%	5.7	5.7	15	costs for oxy fuel combustion
Refinery furnaces, gas fired	7% - 10%	large variation	11.8	45	
PER+ gasifiers and H2-production	100%		1		
Total			68.9		

As illustrated by the table, CCS does not necessarily have to wait for further development of post-combustion capture technology for coal-fired power stations as is the focus in current Dutch long-term CCS policy. Already large amounts (up to 11.4 Mton/year) of directly available or easily isolatable CO_2 could be captured and stored. This 11.4 Mton is made up of:

- The currently available pure or highly concentrated flows from ammonia production (3.5 Mton/year), hydrogen production (1.2 Mton/year) and Shell Pernis gasifier (1 Mton/year). A total of 5.7 Mton/year.
- The 5.7 Mton produced by Corus Ijmuiden that can be made available relatively easily by applying oxyfuel combustion in the Velsen 24 and Velsen 25 power units with oxygen produced by the to be replaced four Linde Hoekloos air separation units[18]

Producing additional gas from reservoirs

CCS could also boost the supply of fossil fuels. Injection of CO_2 in depleted gas fields can improve the recovery of the residual gas, increasing the gas field´s exploitable life time by several years. There is however a risk of CO_2 mixing with the gas. According to model calculations conducted by NAM CO_2-sequestration in depleted gas fields in North

[17] Information sources:
Amounts of CO2 per year from (ECN, 2005), (TNO, 1998), (DCMR website) and (IPCC, 2005);
Concentrations from (IPCC, 2005)
Costs from (IPCC, 2005) and (CRUST, 2003)

[18] Linde Hoekloos currently operates four cryogenic oxygen production plants at the Corus Ijmuiden location that will be replaced by a new 75 M€ plant in 2009, see: http://www.doppelklicker.de/Linde_baut_On-site-Anlage_fuer_niederlaendisches_Stahlwerk.10955.0.html, http://financialreports.linde.com/2006/ar/lindeannual/markets/on-sitesystems/projects2006.html

Netherlands may result in a total extra natural gas production 35 billion Nm^3, approximately 3.5 times current domestic consumption (SEQ, 2006).

Costs and benefits of CCS

Given the global potential for CCS and the role IPCC envisages for CCS in global energy supply, the implementation, demonstration and further technical development of CCS in the Netherlands should result in innovations and expertise that could be exported.

CCS is already a commercially applied technology with some major projects around the world (see also Chapter 3.5), like:

- Sleipner project in the Norwegian part of the North Sea.
- the In Salah project in Algeria.
- the Weyburn project in Canada.

There is still a lot of room for costs reduction and process optimization. Desk top studies performed by e.g. Alstom, FLUOR, Bechtel Nexant and Chevron suggest that cuts in specific reduction costs of € 20/ton to € 30/ton are possible even for gas-fired power plants (compare table 2.4). A recent study performed by KEMA, Ecofys, Spinconsult, TNO and ECN also gives indicative specific costs per ton avoided CO_2 of approximately € 30/ton. This price can vary depending on the used capture technology, the transport distance and the storage location.

For comparison, ETS market prices vary up to € 30/ton, depending on availability of rights in the market. However, scenario analysis performed for EEA[19] and UNFCCC estimate CO_2 market and permit price levels of € 60/ton CO_2 for 2030, resulting from ever tighter emission ceilings for greenhouse gases. This means that technologically improved CCS technology and strategy could very well prove economic in the future.

Summarizing, CCS is a relatively cheap measure for greenhouse gas emission mitigation with a large potential in the Netherlands. For at least several decades it can be an addition to other mitigation measures, energy conservation and renewable energy in particular.

Conclusions

- In reservoirs onshore there is a volume of about 1,600 Mton available for storage of CO_2.
- According to the Kyoto protocol the Netherlands needs to achieve a reduction from the current 220 Mton per year to 200 Mton per year in 2012 (6% reduction).
- Over the long term measures can be taken to realize a reduction of 60% or 80% by 2050.
- For the medium term CCS can provide an option (starting from perhaps 2015).
- CCS can be used to reduce the 65 Mton per year of emissions from large industrial point sources.
- The costs are still a problem, calculated to be € 50 to € 60 per ton CO_2. This is likely be reduced to € 20 to € 30 per ton CO_2.

[19] The European Environment – State and Outlook 2005, report written for EEA., see http://reports.eea.europa.eu/eea_report_2005_4/en

- As far as availability of CO_2 is concerned CCS could be implemented directly, based on pure and highly concentrated off-gas streams from ammonia production, hydrogen production, Shell Pernis gasifier and blast furnace gas.

2.7 Issues to be mentioned in Chapter 2 of an EIA

General issues for an EIA in Chapter 2
In this chapter the purpose of the proposed activity is explicitly described. There is a description of what is intended and the objectives from perspective of the initiators, the authorities and society.

Specific attention to CO_2 storage in Chapter 2
In case of a CO_2 storage project, it is important to make clear what kind of contribution to CO_2 emission reduction is expected. The chapter will describe the need to store CO_2 in gas reservoirs in general terms (referring to this document), to underline why CO_2 storage is a good option, compared to other available options.

This chapter can provide a description of the different possible gas reservoirs that are available and why this reservoir has been chosen (see also the conclusions from Chapter 8). As part of the overall description the expectation about the volume of CO_2 storage can be described, how many wells are to be used, and during how many years CO_2 injection will take place.

The chapter will also focus on the results from the project in:

- Amount of CO_2 emission reduction per year.
- Learning targets of the project.

3 SUBSURFACE CO_2 STORAGE SYSTEMS

3.1 Introduction

Decades of extracting gas and oil in the Netherlands have led to an extensive body of knowledge and experience with this type of industry. Many of the techniques developed in the oil and gas industry can be applied directly for the storage of CO_2 in the subsurface. Particularly relevant is the experience with CO_2 injection for enhanced oil recovery (EOR). This has been carried out in many reservoirs since it was first adopted on a large scale in the 1970's. The objective of EOR is primarily to increase the oil or gas production of a field while the objective of storing CO_2 in depleted gas fields is to reduce the emission of CO_2 into the atmosphere.

Storage in gas fields versus storage in aquifers
The literature on CO_2 storage refers quite often to storage in aquifers and very little to storage in depleted gas fields. Storage in gas fields is different from aquifer storage in several respects:

- *Information level*: Storage in depleted gas fields can make use of a long track record of site characterization with the main focus on the static and dynamic properties of the reservoir. It has been shown that the behaviour of the reservoir during CO_2 injection can be well predicted from the gas production history (CO_2 injection pilot in the offshore K12-B gas reservoir; Van der Meer). These data and information are mostly missing for aquifers.
- *Proof of containment*: The very presence of gas trapped in reservoirs for geological time periods indicates that these structures can contain CO_2 as well, provided that the sealing properties of the caprock and bounding faults have not changed due to gas production, the cap rock entry pressure for CO_2 is not exceeded, and the sealing properties are not affected by chemical reactions with CO_2-loaded fluids. Most reservoirs in the Netherlands are capped by rock salt, which is very gas tight and largely inert to CO_2. Furthermore rock salt is plastic and has self-healing properties; faults below the caprock are disconnected from faults in the overburden. The containment of CO_2 in aquifers would have to be proven with the help of additional field and laboratory measurements.
- *Reservoir conditions*: Most reservoirs in the Netherlands are at a depth of more than 1200 m, whereas aquifers can be found also at shallower depths. The pressure in most gas fields in the Netherlands has dropped to very low levels, 30 to 50 bar, which is 100 to 300 bars below the initial reservoir pressure. This pressure window can be used for injecting CO_2 until the initial reservoir pressure is reached, preventing any negative effect on the seal, e.g. fracturing will be prevented. Injection in aquifers starts at the initial (hydrostatic) pressure and builds up pressure well above it, with potential adverse consequences for the seals..
- *Reservoir properties*: In general the porosity and permeability of gas reservoirs is higher than those of the water-saturated alternatives. This will result in a larger capacity and better injectivity for CO_2 storage than in aquifers. In gas reservoirs there is less free water than in aquifers, which will limit the corrosion of well casing and degradation of the well cement. On the other hand the high water saturation of aquifers promotes the dissolution of CO_2 in water, making the CO_2 less mobile.
- *Penetrations:* As a consequence of the gas production the cap rock and reservoir will be penetrated by wells. The exact locations and deviations of both active and abandoned wells are known. In general the number of wells in aquifers is much

lower. In the Netherlands well construction and abandonment are subject to strict regulations that ensure the restoration of the sealing capacity of cap rock with respect to hydrocarbons. However, these high standards may not be sufficient to withstand for thousands of years the chemical degradation effects of wet CO_2 on cement and casing steel. Especially the older abandoned wells require caution, since abandonment standards have improved over the years and CO_2 storage was not considered at the time of abandonment. Nowadays wells can be plugged and abandoned with state-of-the-art techniques and, more importantly, with the objective of preventing leakage of CO_2.

- *Infrastructure*: An advantage of gas fields is that existing wells and pipeline infrastructure can be re-used for the purpose of CO_2 storage. The majority of the fields haven't been abandoned yet. This will give the opportunity to make measures for improved abandonment in CO_2 storage fields.

As mentioned in the first chapter this study is focused on the storage activity only. The main normal activities are therefore the construction of the storage system, its operation and then its closure. This chapter is focused on all processes that occur in the underground related to the system that is created to store CO_2. On the one hand the natural system consisting of the reservoir, cap rock and trapping mechanisms already exist. By carrying out the development activities and storing CO_2 a human system is added. These two systems are combined in a new system in which all elements interact and contribute to its overall performance.

The various subsurface physical components of this system for the long-term storage of CO_2 in an onshore gas reservoir in the Netherlands will be discussed in the remainder of this chapter. In Section 3.2 the storage system will be discussed; the injection wells, the storage reservoir, the trapping mechanisms and cap rock and the features of the injected CO_2. In Section 3.3 the activities in the various phases of the storage lifecycle will be described. In Section 3.4 the storage capacity available in the Netherlands will be examined and the consequences of upscaling CO_2 storage will be evaluated. Finally, in Section 3.5 experience with other relevant projects and the lessons learned will be discussed.

In this chapter different options are listed, as part of the generic character of this report. In Chapter 8 there is a discussion of how different options are appraised, as part of the alternatives and mitigating measures.

3.2 CO_2 storage system

Generally CO_2 may arrive in supercritical condition at the storage facility via a transport pipeline. On site, depending on the required injection pressure at the wellhead, additional compression might be needed before CO_2 is injected via the well and injection tubing into the subsurface geological reservoir.

Surface facilities
In this study the focus is on the subsurface activities. However to provide a complete picture and an understanding of the potential impact at the surface level, a description of the site area is also given.

The surface components for a CO_2 storage facility are:

- A fenced area which can be accessed by cars and trucks.
- Optional compressor including transformer, liquid discharger and air cooling system.
- Measurement and control unit.
- Wellhead including a system of safety valves.
- Local transport pipeline from compressor to well head.

There is some debate about the necessity for a compressor in the storage site area. Compression prior to transport by pipeline will take place at the source site, where CO_2 is captured. If this pressure is sufficient for the injection the site will only contain the pipelines, a well and measuring equipment.

As an illustration of possible operations after separation and prior to injection the activities for the Gorgon project (see Section 3.5) are planned to consist of the following:

- The wet CO_2 is compressed to 45 barg, dehydrated by TEG, further compressed to approximately 135 barg, cooled, then compressed supercritically to 300 barg and exported to the reinjection wells.
- This unit comprises of 2 x 50% compression /dehydration trains and a single 100% accumulator/supercritical liquid pump set. Each 37 MW compressor operates on a single shaft, has four stages and a fixed speed electric motor driver.
- The interstage pressures, export pressure and pipeline size are to be optimised.
- The CO_2 will be reinjected down several wells in the reservoir.
- The wells are to be located in the north of Barrow Island, approximately 15 km from the LNG Plant.

Sub-surface system
The sub-surface system considered in this study is the one that is created by the activity of storing CO_2. The system is formed by the interaction of the following elements: the injection wells, the storage reservoir, the trapping mechanisms and cap rock and the stored CO_2. There will be surface equipment for such purposes as controlling flows and for conditioning the delivered CO_2, but this equipment and its possible impacts are not discussed further here.

The main underground components of a CO_2 storage facility, which will be discussed in this chapter, are:

- CO_2 to be stored.
- Wells (both injection and abandoned).
- The storage reservoir (including cap rock, faults, adjacent rocks).
- Trapping mechanisms.
- Overburden and faults.
- Optional monitoring system (like observation well, seismic array, CO_2 sensor etc.).

Key alternatives for a storage facility are also discussed.

3.2.1 CO_2 characteristics

The quality of the CO_2 that will be injected

It is evident that the captured CO_2 from power plants contains several impurities (Table 3.1). Post-combustion capture leads to the lowest levels of impurities with a CO_2 purity of 99.99 percent. Application of oxyfuel leads to a CO_2 purity of about 96%. The main impurities are N_2, Ar and O_2 with traces of SO_2 and NO. The same type of impurities can be found for pre-combustion capture but with other proportions. The CO_2 purity for pre-combustion capture is between 95 and 98% and the main impurities are H_2, CH_4 (only for gas-fired plants), H_2S (mainly for coal-fired plants), CO and N_2, Ar and O_2. It is possible to remove these impurities but this will lead to higher costs (Xu et al. 2004).

Table 3.1 Concentrations of impurities in dry CO2, % by volume (IPCC, 2005)

	SO_2	NO	H_2S	H_2	CO	CH_4	$N_2/Ar/O_2$	Total
COAL FIRED PLANTS								
Post-combustion capture	<0.01	<0.01	0	0	0	0	0.01	0.01
Pre-combustion capture (IGCC)	0	0	0.01-0.6	0.8-2.0	0.03-0.4	0.01	0.03-0.6	2.1-2.7
Oxy-fuel	0.5	0.01	0	0	0	0	3.7	4.2
GAS FIRED PLANTS								
Post-combustion capture	<0.01	<0.01	0	0	0	0	0.01	0.01
Pre-combustion capture	0	0	<0.01	1.0	0.04	2.0	1.3	4.4
Oxy-fuel	<0.01	<0.01	0	0	0	0	4.1	4.1

Temperature and pressure of CO_2

The objective is to store CO_2 in its supercritical state (see Figure 3.1). To keep CO_2 in its supercritical state certain temperature and pressure conditions must be met (pressure > 74 bar and temperature > 34°C). Considering a normal geothermal and hydrostatic gradient this basically means a minimum depth for the top of the CO_2 reservoir of 800 m. In the long term part of the CO_2 may dissolve in the ambient porewater or may mineralize by reaction with reactive mineral components in the reservoir.

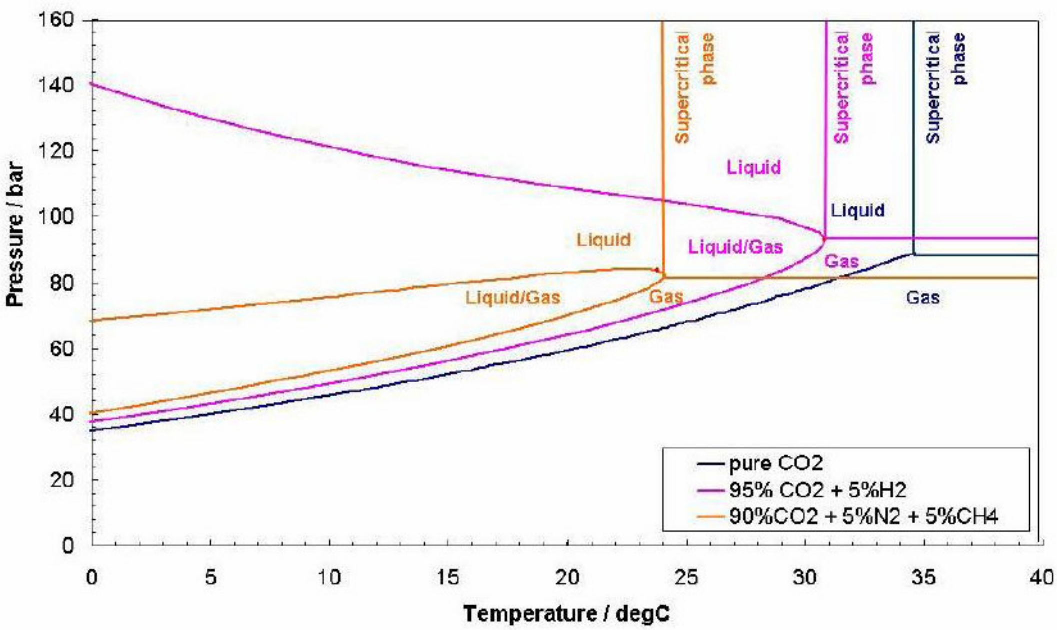


Figure 3.1 Different phases of CO_2 and mixtures

3.2.2 Wells

Operational injection wells

In depleted gas fields wells will be present that were once used for the production of hydrocarbons. These cannot be reused after they have been plugged when the field was abandoned, as abandoned wells are physically disconnected from the wellhead (the tubing is removed and the casing is cut off). The possibility exists however that wells can be reused if storage is started before abandonment. A workover might be needed in this case to ensure that acid fluids will not corrode the steel.

The number and type of wells depend on factors such as the desired injection rate, the permeability and thickness of the formation, maximum allowable injection pressures and availability of land-surface area for the injection wells (IPCC 2005). Permeability multiplied by the thickness (transmissivity) together with reservoir pressure are needed to make an estimate of the possible injection rate.

A vertical well is probably the best choice accounting for costs and injection rate in thick, homogeneous and highly permeable layers. Such layers can be found in the Slochteren Formation. On the other hand, the relative thin Vlieland Sandstone layers (on average around 20 m thick, versus more then 50 meters for the thick layers) will possibly need a horizontal completion to obtain a large enough inflow area to guarantee an adequate injection rate without exceeding the allowable pressure.

The materials used in the wells and their closures, primarily metals in the well casing and cementitious materials used in sealing around the casing and in constructing a closure plug within it, have to be resistant to long-term degradation. CO_2 in water is slightly acidic and CO_2 itself reacts with alkaline components of Portland cement to produce carbonate compounds. In specific cases consideration will also be given to the potential effects of other components of the injected gas.

Abandoned wells

For the long-term situation the details of the abandonment of wells can be extremely important. It may be necessary to distinguish between:

- The well used for CO_2 injection.
- Older wells used or drilled for the purpose of gas production.

The injection well will be abandoned and sealed only once the conditions in the storage zone have been shown to be stable. Until that point it cannot be excluded that it may be necessary to use the well to retrieve the injected CO_2.

For older wells the quality of the abandonment depends in part on when the abandonment was performed. In the 1950's most wells were abandoned in compliance with the regulations and legislation of that time. Now there are stricter guidelines for abandonment. It is also important to realize that the older wells have been abandoned with the idea that there is hardly any gas left and little pressure. It needs to be checked whether they are satisfactory for conditions in the reservoir after CO_2 injection. In most cases it is very costly to modify an already abandoned well.

An abandoned well has two essential components - the materials acting to seal it (the plug) and the casing installed during construction and for operation.

Plug
Cement is the material commonly used to seal-off wells. The main objective of a primary cement sheath (between casing and formation rock) is to provide zoned isolation and to prevent fluid flow from one geological zone to another. Cement plugs inside the casing prevent fluid flow through the well itself. Abandonment plugs are placed inside a well in order to prevent fluids flowing through the well. Basically two types of plugs can be distinguished:

- mechanical bridge plugs, mainly consisting of metal and rubber;
- cement plugs.

Both should be composed of material which resists the corrosive effects of CO_2-loaded fluids.

In specific cases there may be other penetrations into the storage zone which could be used for monitoring. It is necessary to consider the condition of these penetrations, and of any decommissioned ones, in order to ensure they will not form a leakage pathway.

Injection rate
In the pilot CCS projects involving empty gas fields a maximum injection rate between 0.2 and 1 Mton CO_2 per year is applied. The injection rate of 0.2 Mton per year is comparable with the CO_2 reduction achieved by an average offshore wind park. Most wells will have an injection rate of 0.5 to 1.0 Mton per year.

The abovementioned injection rates of 0.2 Mton per year, 0.5 Mton per year and 1.0 Mton per year correspond with 550 ton per day, 1,350 ton per day and 2,700 ton per day.

The mentioned rates are consistent with the injection rates per well mentioned in literature:

- Studies for CO_2 sequestration in De Lier and figures for water injection give an indication of the potential injection rate per well, ranging from approximately 650 ton/day for CO_2 sequestration in De Lier to approximately 1,000 ton/day in case of injection rates as applied for water injection at Borgsweer.
- An early study concerning CCS in the Netherlands and performed by Shell gives an injection rate of 2,500 ton/day per well.

For a large coal-fired power plant emission rates are in the range of 2 or 3 Mton per year. Clearly one well is not enough to inject the captured CO_2 from such a plant. Injection rates can be increased by increasing the number of injection wells per field. Applying horizontal wells can also increase injection rate, due to larger total contact area with the reservoir.

In the Netherlands clusters of gas fields are located close to each other and large flows of greenhouse gases of several Mton per year could be stored by simultaneous storage in several different gas fields.

3.2.3 The storage reservoir

A storage reservoir as considered in this study is a depleted gas field. There is the cap rock and beneath this the porous reservoir rock. In the Netherlands this predominantly consists of sandstone. The spaces between the mineral grains making up the rock are known as the pores and this volume may contain liquids or gases or both, depending on the original characteristics of the field and the extent of its depletion. During production (depletion) the pressure in the well is lowered from the initial reservoir condition and the gas flows towards it, and then to the surface. In the depleted condition in a gas reservoir the pore volume will be filled with the residual natural gas at a pressure very much lower than the original pressure. In most Dutch gas fields the low pressure is hardly increasing because the reservoirs are well isolated from the surrounding rocks and consequently fluids cannot enter the reservoirs or only flow at very low rates.

All Dutch onshore fields have a depth greater than 800 m, which implies that the stored CO_2 would be supercritical in the final phase of injection. Although this is no longer a gas its density is always lower than that of formation water.

In hydrocarbon reservoirs with little water encroachment the injected CO_2 will occupy the pore volume previously occupied by natural gas. In other cases injecting CO_2 will result in some displacement of water from within the reservoir rocks.

Residues of natural gas in reservoir
Since the recovery rates for natural gas production are always less than 100%, every gas reservoir will contain residues of the natural gas originally present in the field. This natural gas consists of methane, but it may also contain hazardous substances such as radon, H_2S, mercury and aromatic compounds usually referred to as BTEX[20]. BTEX, especially benzene, is present in Dutch natural gas.

Methane is a potent greenhouse gas, with a contribution to warming per unit of weight 23 times stronger than that of CO_2. It could therefore be counterproductive if residual methane is released due to reservoir leakage induced by storage of CO_2. That the emission of the other compounds mentioned above is undesirable is obvious given their potential for harm.

3.2.4 Trapping mechanisms and cap rocks in depleted oil and gas reservoirs

The main trapping mechanism in the Netherlands is structural trapping: the deformation of sedimentary rocks caused the development of fault blocks and folds in which the hydrocarbons were trapped. Hydrocarbons have a low density and are buoyant relative to the formation water. A cap rock above is then needed to trap the hydrocarbons in the reservoir. This material is marked by very low permeability and high entry pressure for CO_2. Dutch gas reservoirs are capped by different types of seals:

- Rock salt;
- Claystone;
- Anhydrite;
- Clay.

20 BTEX is an abbreviation for benzene, toluene, ethylbenzene and xylene, four aromatic compounds found in natural gas fields.

Initially, the injected CO_2 may displace the remaining natural gas and after some time it will blend into a CO_2-methane mixture. When CO_2 flows through rock under the influence of pressure differences and buoyancy forces, some of the CO_2 is retained in the pore spaces by capillary forces. This type of trapping is called residual trapping.

Another mechanism that could play a role in the trapping of CO_2 in gas reservoirs in the Netherlands is geochemical trapping. This mechanism may play a role over a geological timeframe and it consists of both solubility trapping and mineral trapping. The amount of free water in the reservoir is important for the extent of both these processes:

- Solubility trapping refers to the dissolution of CO_2 in water. A benefit of solubility trapping is that once CO_2 is dissolved, it no longer exists as a separate phase, thereby eliminating the buoyancy force that drives it upward. The density of the water will increase due to the dissolution of CO_2, and it will migrate downwards. (IPCC, 2005).
- Mineral trapping is the most permanent storage mechanism for CO_2. Free ions in the formation water can interact with the host rock to form carbonate minerals.

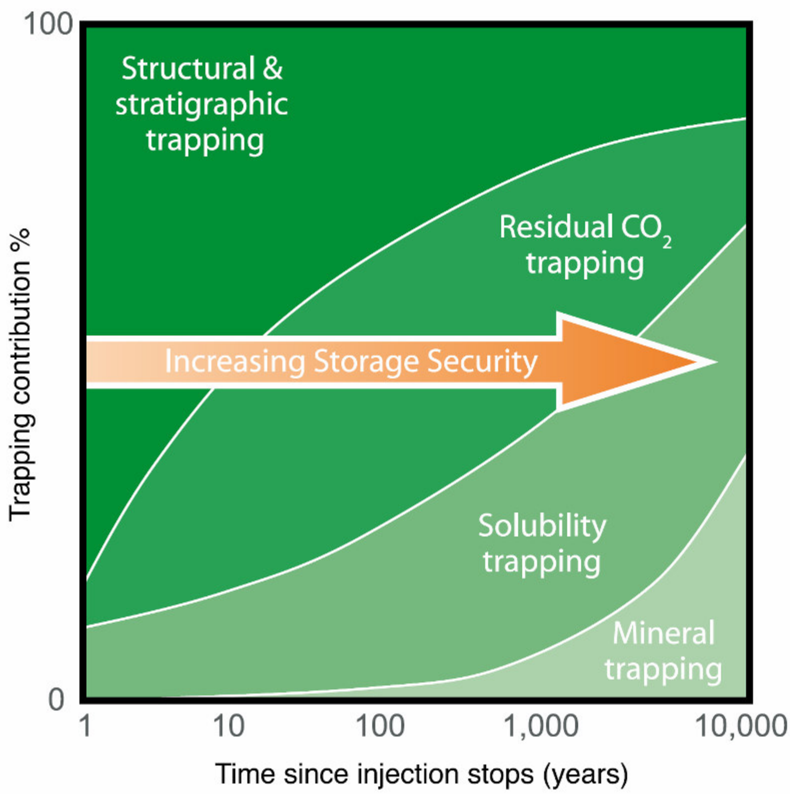


Figure 3.2 Dominance of trapping mechanisms as a function of time (IPCC, 2005)

3.2.5 Overburden and faults

Geologically the Netherlands deep geological structure can be regarded as a tilted plate, declining from east to west. Sedimentary rocks found near the coast at a depth of 1 to 2 kilometres surface near the border with Germany. This regional depth trend is disturbed by differential tectonic movements resulting in a strong subsurface structural relief. As a consequence the depth of individual layers can change by up to a kilometre or more over short distances.

Quite a dense fault pattern can be found at the level of the lowermost gas reservoirs in the Rotliegend. Because the rock salt on top of these gas reservoirs has viscous or ductile properties these faults do not continue into the rock salt itself. In this way the deeper faults are disconnected from the shallower fault system. At shallower levels the number of faults decreases; only a few transect the shallowest Tertiary clay layers and cross the shallow fresh groundwater aquifers.

Gas reservoirs are found at different levels in the subsurface, the lowermost of which is the Carboniferous. These sedimentary rocks contain coal reserves and are found in almost all parts of the Netherlands subsurface. The bulk of the gas fields are found at several levels above the Carboniferous, i.e. Rotliegend, Triassic and Lower Cretaceous. Only a few gas fields are present in the shallow unconsolidated Tertiary rocks.

Depending on the stratigraphical level of the reservoir and its depth a variable sequence of rock salt, anhydrite, claystones, marls, carbonates and sandstones, and unconsolidated clays and sands can be found on top.

The shallowest layers were formed as a result of the interplay of the four main rivers (Rhine, Meuse, Schelde and IJssel) and the influence of the North Sea. Almost all of the western Netherlands is composed of the Rhine-Meuse river estuary, but recent human intervention greatly modified the natural processes at work. Most of the land area in the western Netherlands is below sea level due to the human process of turning standing bodies of water into usable land, a polder.

Although the Netherlands seems to be a tectonically quiet area, some fault activity has been recorded in the past. The latest (1992) strong earthquake (5.4 on Richter scale) had its epicentre close to the Limburg city of Roermond. It should be noted that no strong tectonic earthquakes have been recorded in parts of the Netherlands where the main gas fields are located. The south of the Netherlands is topographically higher and is linked to the geology of the Ardennes and the London-Brabant Massif.

3.2.6 Monitoring of CO_2 storage

Monitoring can be done in the subsurface via deep or shallow wells, from the surface with geophysical methods like seismic, electromagnetic methods and gravimetry, airborne with geophysical methods used from planes and even from space with the help of satellites.

During the CO_2 injection activities
The following main monitoring options are available prior to closure of the storage system:

- Surface level measurements at the start of activities to determine uplift or subsidence.
- Pressure and temperature at the wellhead, in the reservoir and in the well. These are used together with the injection rate for comparison with the projected performance of the reservoir.
- Injection rate.

- Sampling to determine fluid composition.
- Well logging and seismic surveys to assess the extent of the injected CO_2 within the reservoir.
- Pressure in the well annulus.
- Well condition logging.

After abandonment

- With seismic monitoring CO_2 leakage into water saturated zones can be detected.
- Observation wells in deeper aquifers.
- Soil gas sampling.
- Remote sensing for monitoring change sin vegetation due to CO_2 leakage.

A more elaborate discussion of monitoring is given in Chapter 9 Monitoring options.

3.2.7 Key alternatives

Re-use of pipelines on the storage site is only possible if their characteristics in terms of allowable pressure and sensitivity to corrosion are in line with the requirements for CO_2 transport. Instead of doing a workover on the existing pipeline a new pipeline could be constructed.

CO_2 can be transported most economically in a relatively dense phase. The option which is generally referred to is transport of supercritical CO_2. This implies that compression takes place at the point source directly after capturing the CO_2 stream and before transport. Additional pressure build-up for the purpose of CO_2 injection in the late stages of a storage project might also be accounted for by the compression near the point source. Alternatively, an additional compressor might be located at the storage site.

Transport of CO_2 in a liquid phase instead of the supercritical phase would be possible if the pipeline is buried and properly insulated (Zhang et al., 2006). They showed that this might be economical.

Existing wells can be re-used for the purpose of CO_2 injection provided that the cement sheath and casing are in good condition. A workover might be needed to prevent corrosion by CO_2-loaded fluids. The alternative is drilling new wells, which could be vertical or horizontal. Horizontal wells are more expensive than vertical wells but the injectivity of horizontal wells is much larger.

A more elaborate discussion of alternatives is included in Chapter 8.

3.3 Phases and activities deployed in CO_2 storage

The phases and activities which need to be deployed are discussed below.

Phases						
Preparation phase			Storage operation phase	End phase		
Activities						
Site selection & concession and permits	Design and construction of facility	Testing facility	Operation, CO_2 injection	Closing activities (Abandoning)	Transfer liability	Post-closing
Monitoring						

Selection

The information for a depleted gas field is already at a very high level, which implies that little or no additional data acquisition in the field is needed. All regions with known gas fields are covered with high-resolution 3D seismic surveys. It is important that the existing information becomes available to those who are planning to start a project.

A decision might be taken to start the gathering of data to establish a baseline for monitoring (see also Chapter 9). This might include an additional baseline seismic survey for sensitive items of the storage system, and drilling of shallow observation wells for groundwater sampling, soil gas sampling and measurement of emitted natural gas streams in the area. For seismic monitoring equipment will be transported with a truck to the storage site. Acquisition crews would be active in the area for several days.

Construction

If wells and pipelines can be re-used, activities will concentrate on workovers. The workover of a well can take several weeks to months. The wells will have to be modified so that they can withstand the corrosive effects of CO_2 injection. This might need a new injection tubing of high-quality material. A small drill rig might be needed for the workover. Drilling of a new well takes a few months.

A local pipeline connecting the transport pipeline with the wellhead will need to be constructed. The pressure in the pipeline will be about 80 bar or more, while in the reservoir the pressure will be 30 to 50 bar in the initial phase rising up to 150 to 350 bar in the final injection phase.

Testing

Drilling of new wells and testing takes a few mouth. It can take up to one or one and a half years before operations can start. During drilling a drill rig will be visible on the site and will be producing noise. The rig components will be transported with trucks to and from the site. Materials like drilling fluid will also be transported with trucks. Drilling crews will work in shifts for 24 hours per day. Drill mud and cuttings will be processed on site, and the residues will be transported to a dedicated location. Testing of the wells takes several days and can result in limited emissions of the injected gas to the atmosphere.

A venting device might be needed for the release of the injected gas during emergency situations, like overpressure or leakage. Monitoring activities will continue.

Operation and maintenance
Normal injection operations have hardly any noticeable effects on the environment. Noise will be minimised according to the current state of the art. For safety reasons it might, in very extreme cases, be decided to release gas to the atmosphere for a limited period of time. For this purpose a venting mechanism has to be in place.

Applying the proposed approach from the environmental impact assessment for gas storage in Norg, the status of the well will be tested once every two years. If necessary, measures to stimulate injection will be taken once every five to ten years. These activities will be performed by crews using trucks, and will hardly cause any noticeable effect on the environment. During major maintenance of the wells, mobile cranes and pneumatic equipment will be used. Monitoring activities will continue.

Closure
Dismantling and closing the injection wells needs particular attention. The mining regulations prescribe how a well must be abandoned and contain, amongst other requirements:

- Several mechanical and/or cement plugs at prescribed locations in the well.
- Unsealing annuli between casings require cutting and retrieval of casing sections and subsequent cement plugging.
- Dismantling the shallow part of the casings to 3 metres below the ground surface.

Several hydraulic and mechanical tests on the quality of the cement plug must be performed. Furthermore, it is common practice to close off the well with a plate welded to the topside of the casing. Additional regulatory requirements might be defined for a CO_2 well because of the higher reservoir pressure at the end of injection and the chemical reactivity of CO_2-saturated fluids.

Monitoring activities will continue. For the sake of monitoring it might be necessary to postpone dismantling and closing off the well until no leakage is reported for a sufficiently long period of time.

Post-closure
Initially monitoring continues. Once pre-set abandonment criteria on leakage prevention have been met, monitoring can stop and a decision on re-use of the area can be taken.

3.4 Storage capacity for CO_2 in the Netherlands

3.4.1 Generic assessment for the Netherlands

In this section we give an overview of the storage capacity for CO_2 in the depleted onshore gas fields in the Netherlands. Most of the text in this section is a revised version of parts of the report: ‘Options for CO_2 storage in the Netherlands - Time dependent storage capacity, risk aspects, legal and finances’. This report was written for an EnergieNed project sponsored by EnergieNed, ‘het Ministerie van VROM’ and ‘het Ministerie van EZ’. Most of the Dutch onshore and offshore hydrocarbon fields are located at depths of 2000-3000 metres. Gas in these fields usually occurs in permeable sandstones or carbonates closed in at the top by impermeable rocks like rock salt or claystone.

Gas fields (on and offshore)

In total 47 onshore gas fields were identified with a storage volume larger than 5 Mton CO_2 and a depth of more than 800 m. Figure 3.2 gives an overview of all the gas fields (onshore and offshore) in the Netherlands which satisfy these boundary conditions. The CO_2 storage capacity is represented by the symbol size. The geological stratigraphical unit in which the reservoir is located is represented by the colour of the dots. It should be noted that in some fields gas is produced from several stratigraphical units. In these cases the stratigraphy of the field was classified on the basis of the most significant unit. Depleted gas fields have been divided on the basis of geological age.

Some general remarks can be made in relation to costs and safety. For instance, a Rotliegend reservoir is often capped by a thick Zechstein salt layer, which eliminates any possibility of leakage through seals and faults. On the other hand, these reservoirs are generally deeper than the Cretaceous reservoirs, resulting in higher costs for wells. These selection criteria (and many more) will all be addressed in the site selection procedure and the best alternatives would be addressed in a site-specific EIA (see Chapter 8).

For the Dutch onshore gas fields the total CO_2 storage capacity is 8,967 Mt, when the Groningen field is included. Without the Groningen field (the Groningen field will only be released in the second half of this century) the onshore CO_2 storage capacity is 1,616 Mton CO_2.

Table 3.2 Summary of storage capacity in onshore gas fields in the Netherlands (TNO, 2007)

Gas fields by location	By Stratigraphy	Storage capacity (Mt)
	Carboniferous	96
	Rotliegend (excl Groningen)	781
	Zechstein	319
	Triassic	249
	Post Triassic	171
Total onshore (excl Groningen)		1,616
Groningen		7,351

The storage capacities have been calculated without considering the reservoir thickness and are based on surface area only. This introduces an uncertainty but it is known that the thicknesses of reservoirs of Zechstein and Carboniferous age are relatively small compared with the thicknesses of Triassic and Rotliegend reservoirs. It can therefore be assumed that the storage capacity of Zechstein and Carboniferous fields is overestimated.

An overview of the development of cumulative available CO_2 storage capacity in gas fields, resulting from the dates of expected end of production, is shown in Figure 3.3, as taken from the production reports (Groningen field excluded). In this figure the CO_2 storage capacity has been subdivided by reservoir stratigraphy.

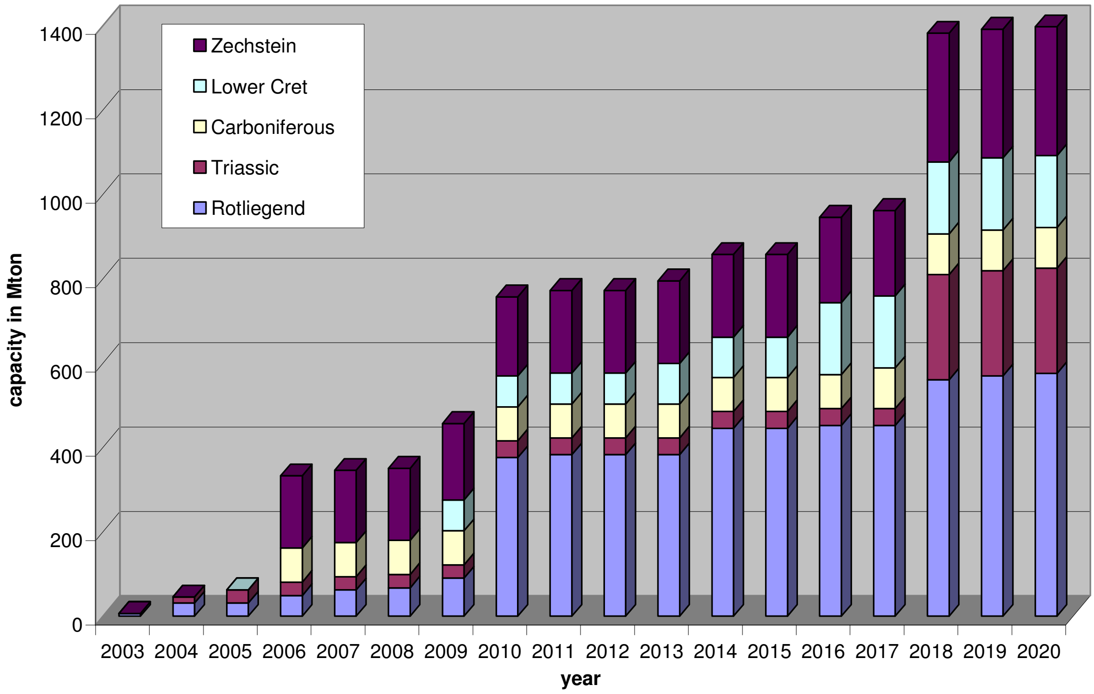


Figure 3.3 Development of storage capacity in depleted gas fields in the Netherlands (Groningen excluded) (TNO, 2007)

It is known that the presumed end of production of most of the gas fields has already been postponed, due to adjusted production strategies resulting from changed economics and changed policies for small field development and effective exploitation. Unfortunately, this update has not been published and cannot be used in this study. It can be assumed that the dates as shown in Figure 3.3 are too early. The figure shows the storage capacity for the producing fields and the fields from which production has ended. About 200 Mton of capacity will become available in the undeveloped fields and the fields currently used for natural gas storage.

Upscaling of storage

If the full potential of the available gas reservoirs were to be used for storage of CO_2, the impact on land use would not be bigger than that of current gas and oil exploitation. The size of the areas needed for CO_2 storage will in general be smaller than those for gas production because fewer facilities for gas treatment are needed for CO_2 storage. When a gas field is abandoned, the area becomes available for another industrial or a residential use, and this may hamper the use of the field for CO_2 storage. In the densely populated western part of the Netherlands this is especially likely to be the case. Upscaling of CO_2 storage will involve competition with other subsurface applications, like ongoing hydrocarbon exploitation, gas storage or geothermal energy production.

3.5 Other relevant CO_2 storage projects

CO_2 has been injected on a large scale and in many projects since the 1970s with the objective of increasing the output of oil or gas from hydrocarbon reservoirs (Enhanced Oil Recovery - EOR). These are projects outside the Netherlands. While this experience is relevant in relation to some technical aspects of injection it is generally less so in relation to the objectives and the timescales of CO_2 sequestration. EOR activities are subject to very dynamic injection schemes, which need to be actively managed. This is unlike a repository for CO_2, which, after completion of injection, must contain the CO_2 for a very long period and without any further intervention. In this respect there is a similarity between repositories for CO_2 and those for radioactive waste.

3.5.1 CO_2 storage projects - onshore

There are some pilot projects in which small quantities of CO_2 have been injected (of the order of 1000s of tons) but there are only three onshore locations in which significant quantities are being injected at present. However, these activities are not examples of storage in depleted gas fields.

The Weyburn Field in Canada is technically an EOR project, but it is also considered as a demonstration of CO_2 sequestration and is being monitored and evaluated with this objective. CO_2 (alternating with water) has been injected at a rate of about 0.18 Mton per year into a partially depleted oil field at a depth of about 1500 m. It is anticipated that 30 Mton of CO_2 will be stored there over a period of 30 years. This will be about two thirds of the total quantity injected, with the remainder removed in the produced oil. The project started in 2000 and is generally considered to be successful. A report on the work in 2004 concluded that geological conditions in the Weyburn oil field are favourable for long-term storage of CO_2 and that this could be monitored with appropriate tools and technologies as will be developed and assessed during the course of the project.

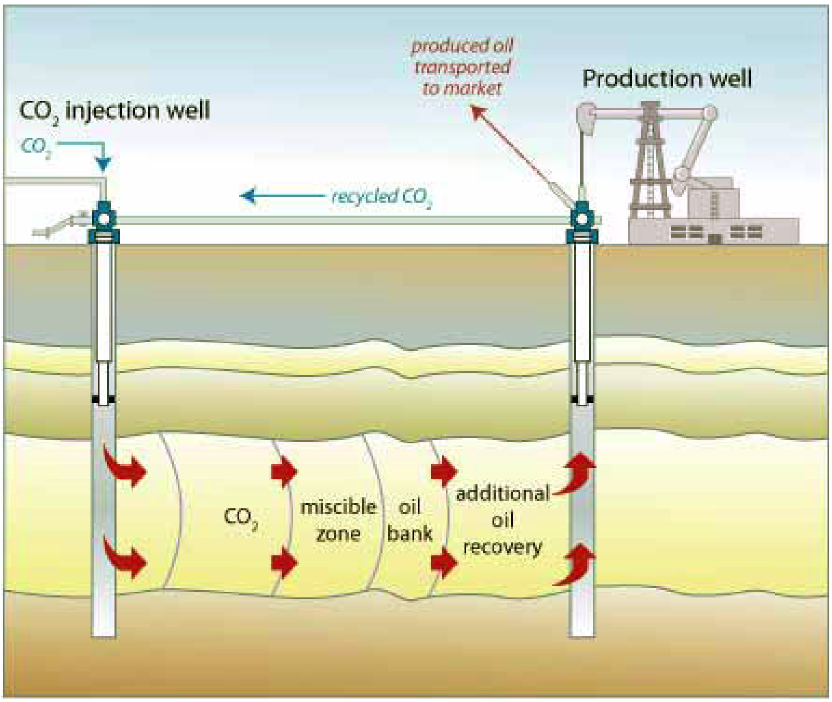


Figure 3.4 Principle of Enhanced Oil Recovery (EOR) as used in the Weyburn field

At the In Salah gas project in Algeria CO_2 separated from the gas is being reinjected in the vicinity of one of the gas fields, into the down-dip, water-filled part of the formation from which the gas is being produced. It is reported that injection was commenced before the monitoring strategy was finalized. The planned injection rate was over 0.9 Mton per year.

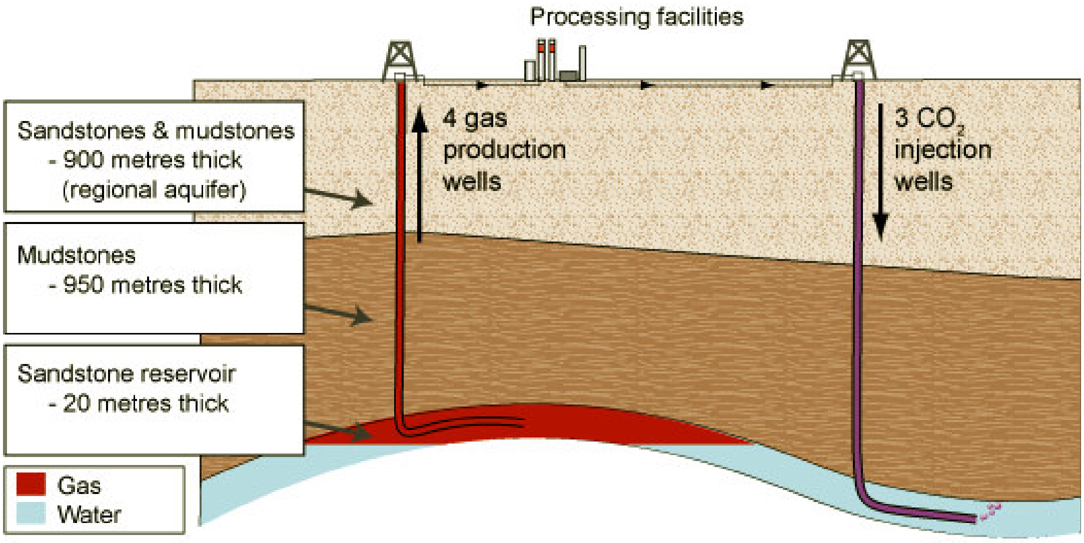


Figure 3.5 CO_2 injection at In Salah, Algeria

Teapot Dome in the USA is a research project for CO_2 injection in connection with EOR. The field has production records extending over 80 years. It was planned to start injection in 2006 at a rate of about 0.18 Mton/year. The project is considered as preparation for a large-scale EOR project nearby, which would result in about 55 Mton of the injected CO_2 becoming stored.

In addition there are projects in Australia. These projects are still in the preparation phase.

The Gorgon Gas Development project in Australia is considered to be relevant, even though no gas has yet been injected, as an EIA has been prepared and this has been published. In this scheme CO_2, separated from the natural-gas produced in offshore fields, will be injected into the Dupuy aquifer at a depth of about 2.700 - 3.000 m beneath Barrow Island, which is about 130 km from the Australian mainland. Production is not anticipated to start before 2008.

The Zerogen project in Australia could develop into one of the first large commercial CO_2 capture and storage projects in combination with coal-based gasification for 100 MW baseload electricity. Storage is planned in saline aquifers in the deep subsurface of Queensland. Two wells have been drilled for the purpose of CO_2 storage. Once the test of the wells is positive a decision on the further development of the project will be taken.

3.5.2 CO_2 storage projects - offshore

In the Norwegian zone of the North Sea beneath the Sleipner production platform CO_2 separated from the produced natural-gas is being injected into a thick sandstone aquifer - the Utsira Formation - at a depth of about 800 m. The injection at a rate of about 1 Mton/year has been in progress since 1996. It has been shown that the development of the zone affected by the CO_2 injection can be followed using successive seismic surveys.

An experimental injection of CO_2 separated from produced natural-gas has been carried out since 2004 at the K12-B field, which is about 100 km offshore in the Netherlands zone of the North Sea. The reservoir, which was used for production and now for the injection, is about 3800 m below seabed. This is in the Upper Slochteren Member. The tests are reported to have shown that 0.02 Mton/year can be injected without any problems. Monitoring during testing involved comparing downhole pressures and temperatures with those predicted from modelling. The objective is to increase the rate of injection up to 0.48 Mton of CO_2 per year.

3.5.3 Existing natural CO_2 pockets

CO_2 is a natural constituent in most gas reservoirs in the Netherlands (see Figure 3.6). The database from TNO DINO*Shop* shows that concentrations of CO_2 in natural gas accumulations onshore and offshore in the Netherlands vary between 0 and 77%. Most gas accumulations contain concentrations of CO_2 less than 10%. As a result CO_2 storage already occurs in natural circumstances in the Netherlands.

Occasionally a well is drilled into such a reservoir, expecting to find gas. If the field consists mainly of CO_2 it will be abandoned immediately. In the Netherlands there are a number of such wells. Very CO_2-rich gas accumulations are encountered in Jurassic and Triassic units in the Roer Valley rift system. For example, at well WED-01 in the Werkendam gas field, a very large content of CO_2 (77Mol%) was reported to occur in gas accumulations in the Werkendam Formation of the Altena Group at depths of approximately 2000m (Verweij, 2006) and in WED-03 at a depth of approximately 2800 m in Triassic sandstone (72%; Neele, 1994). These experiences can be used as an analogue for CO_2 storage in gas fields in the Netherlands.

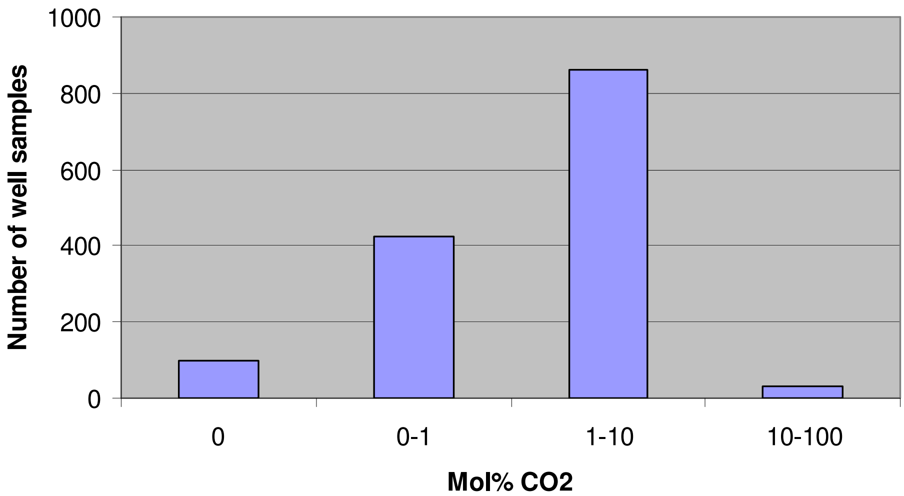


Figure 3.6 CO_2 concentration in Mol% measured in 1416 well samples from the on- and offshore (see dinoloket.tno.nl).

3.6 Issues in Chapter 3 of a project specific project EIA

General issues for an EIA in Chapter 3

In an EIA a Chapter 3 will be used to describe the functional and technical aspects of the project. Therefore the different components of the project will be described, together with the connections to parts outside the project (electricity or water, transport of goods). Each of the components is then described in more detail (either in this chapter or in a separate volume if there is a complex process), including the boundary conditions. The purpose of the descriptions is to give a background to the possible environmental impacts and to explain what kind of alternatives and variants are possible, or impossible. The descriptions will be based on the project plans and on the results of investigations and modelling carried out in order to develop them.

Specific attention to CO_2 storage in Chapter 3

In case of a CO_2 injection project, the functional and technical information should contain:

Surface facilities

- Description in a functional way of the CO_2 source and capture mechanism, the transport pipeline and the local CO_2 compressor if there is one. This description should include an organisation diagram and a listing of volumes and production periods.
- Description of the CO_2 flow, during normal operations, maintenance and in case of an accident.
- Description of the plant area, including the pipelines and possibly the CO_2 compression unit.
- Description of the wellhead (including modifications of the well head).
- Facility location, describing the adjustments needed to transform the site from gas production to CO_2 injection.
- Description of the plant area after abandonment.

Injection system

- Characteristics of the gas;
- Injection rate and duration;
- Wells, number of wells, existing and abandoned;
- Injection process;
- Contingency measures;
- Monitoring.

Storage reservoir

- Geological description of the subsurface, based on seismic data.
- Type of reservoir, information on cap rock (rock material, cap rock material, water or aquifer characteristics).
- Operational history.
- Current conditions within the reservoir - remaining gas, oil or water in reservoir.
- Prediction of the results of injection.
- Possible leakage paths.
- Leakage monitoring measures.

4 POLICIES AND PERMITS FOR CO_2 INJECTION

4.1 Introduction

It is recognized that CO_2 storage in underground reservoirs can play a potential important role in reducing the amount of CO_2 in the atmosphere. However, the current legal and administrative position in relation to CO_2 Capture and Storage (CCS) in the Netherlands is at some points unclear and some existing laws and regulation may need to be adjusted for the wide application of CO_2 storage projects.

In this chapter relevant deficiencies in present laws and regulation in the Netherlands are discussed and suggestions are made to facilitate the realization of CO_2 storage projects. The Mining Act (MA)[21], the Environmental Management Act (EMA)[22], the Spatial Planning Act (SPA)[23], the Environmental Impact Assessment (EIA)[24] and Strategic Environmental Assessment (SEA)[25] are all addressed. The current state and developments in international and European legislation with respect to CO_2 storage is also discussed.

Several questions have to be addressed that relate to legal aspects of CO_2 storage, in order to facilitate the application of CO_2 storage projects:

- Should CO_2 be regarded as 'waste' or differently? And what are the legal consequences of this classification?
- Is an Environmental Impact Assessment (EIA) required for CO_2 storage and if yes, how should this be embedded in national and regional legislation?
- Which is the responsible authority for deep underground storage of CO_2 during the various phases of the storage lifecycle of a project?
- Who is responsible for the costs of long term monitoring?
- Should CO_2 be recoverable? And if so, what needs to be considered?

In order to consider these questions, this chapter starts with a description and overview of the present legal framework of laws, regulations and permits relevant for CO_2 storage in the Netherlands (Section 4.2). In Section 4.3, several key-questions are discussed, such as those indicated in the list above. Section 4.4 provides suggestions to the questions posed in the previous section and provides recommendations on how to deal with the gaps in legislation. In the following Section 4.5, international developments are discussed, which might influence legislation in the Netherlands. Then, in section 4.6 some examples are presented of existing international projects and the accompanying legislation. The chapter is finalized with conclusions on the relevant EIA related legislation of CO_2 storage and the gaps in legislation that have been detected during this study. Interim-conclusions from subsections are presented in the grey boxes and texts of relevant Dutch regulations are shown in the appendix Chapter 16.

[21] Mijnbouwwet (Mw)
[22] Wet Milieubeheer (WM)
[23] Wet voor de Ruimtelijke Ordening (WRO)
[24] Milieueffectrapportage (MER)
[25] Strategisch milieubeoordeling (SMB)

4.2 Overview national legal framework relevant to CO_2 storage

4.2.1 Overview

The Mining Act (hereafter called MA), the Environmental Management Act (hereafter called EMA) and the Spatial Planning Act (hereafter called SPA) provide the main legal framework for the application of CO_2 storage. The MA describes among others the legal aspects associated with the underground storage activities undertaken at a depth of over 100 meter[26]. The Ministry of Economic Affairs (hereafter called Min. EA) is the responsible authority for the MA. The EMA describes the environmental aspects of (industrial) installations and activities, including emissions and measures or efforts to reduce these. Although the EMA and the MA do refer to one another, they are separate Acts. The SPA provides the legal framework for the planning of above ground activities and installations.

The MA mainly focuses on the requirements and conditions to *prevent* hazardous events, such as the uncontrolled leakage of CO_2 from the storage reservoir. Preventive measures can include technical, organisational, procedural and supervisory aspects. Chapter 8 elaborates on these measures in more depth. The EMA, together with the national waste plan (LAP)[27] and the EIA-Decree[28], focus primarily on the control of environmental impacts and the measures required in case of impacts. However, there are exceptions to this rough subdivision, as the MA also focuses on mitigating of undesired events, e.g. for ground movement due to CO_2 storage.

In the MA it is stated that it is prohibited to store substances underground without permission from the Min. EA[29]. This means that for the underground storage of substances, a permit is required in the context of the MA. In addition, a permit is required within the EMA.

Former mining legislation also covered environmental aspects of mining activities. Since December 2002 the EMA is predominant when it concerns environmental aspects of mining activities, with Min. EA as the leading authority. However, provinces are the competent authority for granting an environmental permit for the subsurface part when waste is stored that originates *from outside the mining work*[30].

In table 4.1 an overview is presented of all legal documents that are directly, or indirectly associated with CO_2 storage, including the accompanying permits and responsible authorities.

[26] Mining Act article 1i
[27] Landelijke Afvalbeheerplan
[28] Besluit MER, 1994
[29] Mining Act article 25
[30] Mijnbouwwerk of Inrichting

Table 4.1 Overview of all relevant legal documents, permits and responsible authorities for CO_2 storage (source: Province of Drenthe)

Permit	Legal framework	Responsible authority
Storage permit	Mining Act	Min. EA
Environmental permit surface installation	Environmental Management Act	Min. EA
Environmental permit subsurface[31]	Environmental Management Act	Provincial Executive[32]
(Change in) spatial plan	Spatial Planning Act	Municipalities
Building permit	Building Act	Municipalities
Construction permit	Spatial Planning Act	Municipalities
'Ontgrondingsvergunning'	'Ontgrondingenwet'	Provincial Executive
'Onttrekkingsvergunning/melding'	Groundwater Act	Provincial Executive
Discharge permit	Contamination surface water Act	Water Board
Nature Protection permit	Nature Protection Act	Provincial Executive
Archaeological Research	Monument Act	Provincial Executive
Exemption	Vegetation and animal life Act	Min. Agric. Nature, Fishery
Exemption Provinciale Omgevingsverordening	Provincial environmental regulation	Provincial Executive

In the following sections, the permits and responsible authorities will be discussed for the main relevant legal documents related to the subsurface activities of CO_2 storage. Only the first four legal documents and permits (marked in grey) will be dealt with in this chapter. The reason for only dealing with these acts and permits is because they are the main legal framework for subsurface storage (MA) and associated environmental issues (EMA), or because there are some developments that are relevant for the future legislation for CO_2 storage.

As indicated in the table, there is currently a discussion about the responsible authority for the environmental permits. It will become clear in this chapter that for CO_2 storage, the legal situation is rather complex, because the activity is related to mining, waste disposal, environmental and spatial aspects.

4.2.2 Mining Act

On 1 January 2003 the (new) mining legislation consisting of the Mining Act, the Mining Decree[33] and the Mining Regulation[34] became effective. The MA provides the general legal framework for mining activities, including activities such as CO_2 storage[35]. The Mining Decree contains a more detailed elaboration on the aspects stated in the MA and the Mining Regulation is in turn an even more detailed legal document that verifies how to fulfil the requirements as stated in the Decree. Min. EA is the legal authority for both the MA, the Decree and the Regulation. The Dutch State Supervision of Mines continues to be the supervisory (inspection) body for mining activities (also) under the new MA regime. They are responsible for the inspection and supervision of activities related to the storage of substances below 100 meter[36].

31 The future responsible authority for the environmental permits is currently under debate
32 The Ministry of Economic Affairs is responsible for waste originating from mining activities
33 Mijnbouwbesluit (6 december 2002) houdende regels ter uitvoering van de Mijnbouwwet
34 Mijnbouwregeling
35 Articles 25, 26, 27, 28, 29, 33, 34, 35, 36, 41 and 127 are the main relevant articles for CO2 storage in the Mining Act
36 Mining Act article 127

Article 37 of the Mining Decree requires from the operating mining company that their Health & Safety Management System AND the underlying Health & Safety Documents (safety cases) as meant in the Arbeidsomstandighedenwet (Working Conditions Act) also addresses the external safety. This type of safety concerns the safety of persons and the protection of goods, insofar as no rules have been prescribed in this area by or by virtue of the Arbeidsomstandighedenwet.

The MA is important in the legal framework for CO_2 storage activities because it contains the most appropriate (managing) tools and instruments for the deep subsurface, risk management and liability issues. Important articles, which refer to the evaluation, prevention, control and minimization of risk related to CO_2 storage, are article 33 of the MA and article 26, of the Mining Decree (see appendix chapter 16 for the text of these articles). The main relevant aspects for CO_2 storage projects, e.g. concerning safety, monitoring and liability, are actually already included in the MA, as CO_2 storage has been considered specifically during its drafting. In principle, the storing of CO_2 should comply with the same level of safety-precautions as other mining activities such as oil and gas production. Nevertheless, as will be shown later in this chapter, there are still gaps that need to be filled in to legally facilitate the realisation of CO_2 storage (pilot) projects.

Storage permit

Under the MA a storage permit is required for CO_2 storage projects, which can be obtained after approval from Min. EA. Subsequently, a storage plan has to be submitted and approved of as well. Prior to requesting a storage permit, a closure plan has to be approved of by the Minister for possible activities that were undertaken in the reservoir prior to the CO_2 storage activity, such as extracting natural gas. It is stated in article 71 of the Mining Decree that a well can only be used for the storage of substances, when the abandonment of the original mining activity is properly and safely carried out after decommissioning. The requirements for the closing plan will not be described further in this chapter. Also, there is exclusivity, meaning that it is not possible to obtain a storage license if a mining or storage license for the same area is already in the hands of another licensee[37]. This ensures that the overall management of the reservoir remains in the hands of a single licensee.

The storage licensee is obliged by law[38] to take all measures that can reasonably be asked for the prevention of any negative consequences to the environment, any damage due to movement of the subsurface or any reduction of safety due of the activity undertaken. In case the licensee wants to change the storage activity, Min. EA has the authority to intervene and take action. Renewed permission has to be obtained by the operator in that case.

The storage plan[39] must contain:

a. description of the quantity and composition of the stored substances;
b. description of the structure and location of the storage reservoir including its geological, geophysical and geochemical characteristics and uncertainties;
c. the storage method and the activities and substances associated with it;

37 Mining Act article 26 subsections 1 and 2
38 Mining Act article 33
39 Mining Decree article 26

d. an inventory of risks if the stored substances leak; the possible occurrence of chemical processes in the subsurface and the possible harm to minerals present in subsurface reservoirs or of any changes in their composition;
e. an inventory of measures that will be applied to avoid the risks mentioned in the previous bullet;
f. a description of the way the storage location will be abandoned after storage has been terminated;
g. risk analysis related to ground movement and (micro-)seismicity due to storage.

The chemical processes mentioned in the fourth bullet refer to the fact that some substances, such as CO_2, are known to react with the liquids present in the reservoir and with the reservoir rock itself. These reactions might harm the containment properties of the reservoir. The risk assessment in the storage plan should show whether or not there are such containment risks.

In the context of the duty of care it is also stated that (the occurrence of) for example possible movement of soil as a result of the storage and (possible) measures to prevent loss or damage must be described in the storage plan. In article 30 and 31 of the Mining Decree for example it is stated that for ground movement a monitoring plan must be drawn up, carefully followed and communicated. These articles are also applicable for the storage of CO_2[40].

The grounds for refusing to grant a storage license are referred to in article 26 of the MA. A limited summary of reasons for refuse are provided in article 27 of the MA. These include such matters as the technical and financial abilities of the applicant and issues in the interests of safety, national defence and systematic management. The latter refers to possible competition with other uses of the subsurface such as geothermal energy or temporary storage of natural gas. The license states the listed aspects above, including for which substances, for how long the storage will be carried out, for which area and whether it relates to permanent or temporary storage[41].

4.2.3 Environmental Management Act

Within the EMA, there are three regulations that are related to the underground storage of CO_2. The first concerns waste treatment, which is regulated in the National Waste Plan[42] (LAP). Second is the obligation to perform an Environmental Impact Assessment for certain activities, which is regulated in the EIA-Decree[43] and chapter 7 of the EMA. The third relates to the Decision External Safety[44].

LAP

Even though the LAP is not an Act, it is officially legally binding for the State, Provinces and Municipalities. Furthermore, executing parties undertaking activities covered by the LAP have to take account of the plan. Min VROM is obliged to set up a revised plan at least every 6 years. Formerly every 4 years a renewed plan had to be made. Some amendments were proposed to be included in the LAP. The revised LAP has been

[40] Mining Act article 32
[41] Mining Act article 28
[42] Landelijk afvalbeheerplan (LAP)
[43] Besluit milieu-effectrapportage 1994
[44] Besluit Externe Veiligheid (Bevi)

accepted by the Min. VROM at the end of March 2007 and has been extended until 2009[45]. It will become applicable on May 3rd 2007.

For the storage of waste in the subsurface an environmental permit[46] is required under both the EMA and the Installation and Permitting Decision[47]. In the future, the Installation and Permitting Decision will be replaced by the Decision for General Regulation for the Environmental Law[48].
CO_2 can either originate from within or from outside a mining work. In case CO_2 originates from outside a mining work the Provinces have to decide whether storage is the most proper and efficient way to dispose of CO_2 (LAP). The Provinces are then responsible for the coordination and granting of the environmental permit. When the CO_2 originates from within a mining work, as is the case in some existing pilot projects, then Min. EA is the responsible authority[49].

The LAP and the issue of the definition of waste will be elaborated in more detail in section 4.3.2.

EIA and SEA
The EIA-Decree (1994) is based on the EMA and on the European Directive 97/11/EG on EIAs, which is a follow up of the EU Directive 85/337/EG. Member states of the EU are obliged to incorporate the Directive into their legislation. It defines the cases for which an EIA has to be performed and the cases for which it has to be assessed whether or not an EIA is required. In appendix chapter 16 some background is provided on the European Directive 97/11/EG.

During initial formulation or changes of the regional and local spatial plan and the LAP, there might be decisions taken at a strategic level that affect the environment. Such decisions might require a Strategic Environmental Assessment[50] (SEA), which is a generic EIA, conducted at a strategic level. A SEA intends to identify the -possibly cumulative- environmental effects of decisions and plans in an early stage. Depending on the level of detail and stage of the plans, the available information, knowledge and evaluation methods, an SEA generally includes (www.eu-milieubeleid.nl):

- Goals of the plan/programme.
- Relation with other relevant plans and programmes.
- Existing situation and autonomous developments.
- Environmental aspects of the locations for which the impacts can be significant.
- Environmental issues addressed.
- Reference to relevant national and international environmental protection guidelines and indication of the way they are taken into account.
- Protection objectives of the locations.
- Environmental effects of the plan, especially for those locations that are most sensitive.
- Measures for avoiding and minimising the effects.
- Possible alternatives.
- Plan and measures for monitoring.

[45] Exact date: 3-3-2009, Decision taken at 23 March 2007, Staatscourant 4 april 2007, nr. 67
[46] Inrichtingsvergunning
[47] Inrichtingen- en Vergunningenbesluit milieubeheer (IVb)
[48] Besluit Algemene Bepalingen Omgevingsrecht (BOR)
[49] Environmental Management Act, article 8.2, section 3
[50] Strategische Milieubeoordeling, SMB in Dutch

Furthermore, the organisations that might become involved in possible environmental effects caused by the plans; NGO's and the general public should get the opportunity to respond to the plans before they are approved of. This means that sustainability and environmental aspects of strategic decisions, e.g. related to locations and techniques, are discussed before actual project EIAs are requested; hence, a project EIA will be more rapid (www.eu-milieubeleid.nl).

In appendix chapter 16 some background is provided on the SEA in an international context.

The European Directives 2001/42/EG and 2003/35/EG have been implemented in Dutch legislation (in chapter 7 of the EMA and in the MER-Decree) in September 2006 (www.infomil.nl). In case an EIA becomes obligatory for CO_2 storage projects, an SEA will also have to be conducted at a strategic level (for national and provincial plans), with reference to the aspects listed above. The issue of EIA obligation in the existing legislation will be elaborated in more detail in section 4.3.3.

Regulation External safety
The third regulation that is of importance to CO_2 storage is the Decision External Safety. In the 'Staatscourant' of April 3rd (2007), a change in the regulation was announced. In 2007 the Regulation will be complemented with activities and companies concerning mining installations among others. The elaboration of the conditions for those mining installations will be included in the Regulation External Safety[51]. It is not clear whether the planned amendment will include regulation related to CO_2 storage.

4.2.4 Spatial Planning Act

The SPA, which applies to the above ground installations and activities, provides the legal framework for the spatial plan at regional (province) level[52] and the spatial plan at a municipality level[53]. Environmental aspects form part of the spatial plans. The use of the subsurface should become an increasingly important aspect of the planning programmes of Provinces and municipalities[54]. As can be seen in table 4.1, municipalities are responsible for a.o. granting a construction permit for the installations required for a CO_2 storage project.

In the following section recent developments in relation to the SPA are addressed.

4.2.5 Developments

Currently, a new Act, called the WABO[55], is being drawn up by various governmental bodies (Min. EA, Min. VROM, provinces and municipalities). It was expected that the new Act would become effective on the 1st of January 2008, but this date will most likely be postponed. This new act will combine several permits related to building and the environment into one permit called 'Omgevingsvergunning', hereafter called OV (www.infomil.nl). For CO_2 storage only the storage permit (and associated closure and storage plan) will remain under the MA. The other permits would be combined

51 Regeling Externe Veiligheid (Revi)
52 The Spatial plan at regional level is also called the POP: Provinciaal Omgevingsplan. The Spatial plan at municipality level is based on the POP
53 Bestemmingsplan
54 Source: VROM document 'Beleidsverkenning duurzaam gebruik ondergrond'
55 Wet Algemene Bepalingen Omgevingsrecht

in the OV. In the act the main rule is that municipalities decide about the request for an OV. Only in case of projects of provincial or national interest, this might become differently arranged than the general rule (www.vrom.nl). Then either the Provincial Executive or Min. EA will be the responsible authority and will be responsible for all permissions regarding the project (www.infomil.nl).

Also, presently a new Coordination Regulation[56] for the State, Provinces and Municipalities is being drafted under the SPA. The regulation aims at making the decision making process for (changes in) spatial plans and associated permitting procedures more efficient and faster. The targeted efficiency improvement also means that one governmental organization should preferably become the responsible authority in the decision process. Also for this regulation it is not yet clear who will become the responsible authority for activities covered by it. CO_2 storage projects are expected to become subject to the regulation as it concerns large energy projects of national interest that need to be incorporated in spatial plans. It is therefore uncertain which governmental body will become the primary responsible authority for CO_2 storage projects in the future. It is expected that at the end of 2007 the new spatial planning act, which is presently being drafted will become applicable (www.vrom.nl).

In conclusion
from the overview of the legalisation and the adjacent section on permits can be concluded that the basic aspects of CO_2 storage are already covered in the MA and the EMA. Furthermore it is clear what permits are required for CO_2 storage and reasonably clear on what basis a permit will be granted.

4.3 Discussion of key regulatory issues

4.3.1 Regulatory issues for CO_2 storage

Several key questions concerning the regulatory aspects of CO_2 storage are introduced and discussed in this section. In the subsequent sections, suggestions will be made on how they could be resolved. The key questions are listed below:

1. Is CO_2 defined as waste or other product? And, if it is defined as waste, is it classified as hazardous or non-hazardous? What are the legal consequences of the definition?
2. Is an EIA required for CO_2 storage (the injection of CO_2 in the subsurface)?
3. Who is responsible for the CO_2 and the storage reservoir in the short and the long term? And, if a transfer of liability is necessary, when and on the basis of which criteria should this take place?
4. Which is the competent authority for deciding whether or not CO_2 will be stored at a certain location (province/state), considering spatial planning and the Strategic Environmental Impact Assessment?

It is possible to draw parallels to the legislative framework for the underground storage of natural gas and storage of CO_2 (Lemstra, 2006). The same legislative framework can be used for both activities.

[56] Rijkscoördinatieregeling

The main difference between underground storage of natural gas and storage of CO_2 are first of all that CO_2 might be regarded a waste product, as opposed to natural gas (see also discussion in section 4.3.2). Secondly, CO_2 storage for the purpose of the prevention of climate change has to be stored permanently or at least for a long time, whereas natural gas is stored temporarily. This implies a difference in responsibilities on the long term. Furthermore, we have to take into account the differences in the characteristics of these substances in terms of juridical consequences when finalizing legislation for CO_2 storage. Some of these differences are elaborated further in the sections hereafter.

4.3.2 Is CO_2 a waste product of not?

The classification of a material is important for determining which legislation and regulations are applicable. First of all it needs to be determined whether CO_2 is regarded as waste within current Dutch legislation. If it is defined as waste, it is also relevant to determine whether CO_2 and any associated contaminants in the CO_2 stream should be regarded as hazardous or non-hazardous.

For the European Union the most important direction is given in the Waste Framework Directive[57]. This defines waste as being: 'any substance or object belonging to the categories referred to in Annex 1 that the custodian disposes of, intends to dispose of or has to dispose of'[58]. In the Annex 1 of the Waste Framework Directive, sixteen categories of waste are formulated. Definition of Category 16 is formulated in a way that virtually all substances, materials or products can be classified as wastes. A few exceptions to this are given in Annex 2, including gaseous effluents emitted to the atmosphere. This exception may not be applicable in the case of CO_2 capture and storage, where the point of the storage operation is to refrain from emitting the gaseous effluent (CO_2) into the atmosphere.

The CRUST Legal Task Force concluded in 2003 that 'CO_2 can be classified as waste in the context of underground storage' (CRUST legal aspects, 2003). This corresponds with the recent text in the 'Wijziging LAP' (2006), which states: *'Als CO_2 wordt opgeslagen in de diepe ondergrond en dan dus niet meer in de atmosfeer wordt geloosd, is sprake van het opbergen van afvalstoffen'*. (If CO_2 is stored in the ground and as a result not will be released into the atmosphere, this will be seen as storage of waste). In November 2006 this amendment to the LAP was submitted by Min. EA to the European Commission. In the 'Staatscourant' of 4 April 2007 it was stated that the amendment was accepted by the Commission. The new LAP with the amendment has become valid in May 2007.

In the amendment it is clearly stated that CO_2 is classified as waste when it is stored underground instead of being released into the atmosphere. Therefore the LAP should in general be applicable to the storage of CO_2. However, the underground storage of CO_2 is not specifically mentioned in the LAP, as this activity was not taken into account when policy makers were preparing it. Some regulations, such as the recoverability requirement are based on the storage of radioactive and highly toxic waste and should therefore not necessarily apply to CO_2 storage. The regulations are therefore not particularly suitable for CO_2 storage the way they are written now.

57 75/442/EEC16 as amended by virtue of 91/156/EEC17 and 91/692/EC18
58 Waste Framework Directive, article 1 paragraph a

Min. EA and Min VROM have recognized the gap in this regulation concerning CO_2 storage; therefore, an exception is made for this activity. The prerequisites for CO_2 storage have to be analyzed before the LAP can be made applicable to CO_2 storage. The required conditions for CO_2 storage in the LAP will, amongst others, be based on future pilot projects and experiments. This means that the LAP will not be applicable for these first pilot projects. It is expected that this process takes a few years, which depends on the course of the development of CCS pilot projects. There is no international commission that takes care of the set up of uniform conditions for CO_2 storage. The amendments are communicated to other member states for information only.

Hazardous or non hazardous waste

There is no indication that pure CO_2 will be classified as hazardous waste under EU regulations, as the Hazardous Waste Directive (91/689/EEC) does not include CO_2 in the list of hazardous substances. This decree designates certain processes whereby hazardous wastes are released and substances that are characterized as a hazardous waste at a particular concentration. Also in the EMA there is no special classification for CO_2. However, it is likely that there will be other substances present in the CO_2 stream which might be classified as hazardous. Therefore, all possible contaminants should be taken into account when determining whether or not the CO_2 stream should be classified as hazardous, in order to determine which regulations are applicable.

In conclusion

In the current Dutch legislation, CO_2 is defined as waste. The consequences of this definition are the following; **first** of all it means that according to the current legislation, provinces are the responsible authorities, when the CO_2 originates from outside the mining work (otherwise the responsible authority is Min. EA). **Secondly**, the definition further implies that the EIA-Decree refers to CO_2 storage, as the EIA obligation is linked to the waste definition. **Furthermore**, it means that the LAP is applicable. However, the conditions for CO_2 storage specifically are not yet defined in the LAP. Conditions for CO_2 storage will be developed based on experiences with the first CO_2 storage pilot projects in the Netherlands. These pilot projects are expected to start in 2007. The LAP will not be applicable for these first pilot projects.

It is unclear whether CO_2 and possible contaminants in the CO_2 stream will be regarded as hazardous or non-hazardous waste in legislation, but it seems likely that CO_2 is a non-hazardous waste and that it will be treated as such in future regulations. In addition, conditions have to be developed for the contaminants in the CO_2 stream, in such a way that the whole stream can be treated as non-hazardous in legislation.

4.3.3 Is an EIA required for CO_2 storage?

At the moment the EIA-Decree does not refer to CO_2 storage directly. However, it does refer directly to the storage of waste. It says that an EIA has to be conducted for the storage of waste, both hazardous[59] and non-hazardous[60]. From that perspective, the definition of CO_2 as waste or not, is in part decisive for determining whether or not an EIA has to be conducted. If there is not any storage of waste it is possible that an EIA is nevertheless necessary for other reasons.

59 EIA-Decision, Appendix, Part C, Table number 18.2
60 EIA-Decision, Appendix, Part C, Table number 18.5

The decision whether CO_2 is hazardous or non-hazardous waste is not decisive for the EIA obligation. Only when it concerns non-hazardous waste in small amounts, an EIA is not obligatory.

There is an obligation to perform an EIA for activities and decisions that are listed as C-category of the EIA-Decree. C-category activities include the storage of hazardous and non-hazardous waste in the deep subsurface. In the international regulation an EIA has to be conducted for hazardous waste, but not for non-hazardous waste. When the activity is not listed as a C-category activity, there might still be the obligation to conduct an EIA whenever the responsible provincial[61] authority decides so. The EIA-Decree is based on the EU directive 97/11/EG about environmental impact assessments and the EMA. Chapter 7 of the EMA (which relates to the EIA) is also applicable in this context.

Where a 'critical value' is defined, an EIA has to be performed when the scale of the activity is larger than the critical value. A critical value for the storage of waste is the design capacity of the installation 'intended for the placement of non-hazardous waste in the deep subsurface, not being dredging spoil[62]' (Besluit MER, 1994). When this exceeds 500,000 m^3 an EIA is obligatory for the activity.

Activities within the D-category have to be *assessed* for EIA obligation[63]. The responsible authority decides whether an EIA has to be conducted based on specifications, location, correlation with other activities and specific environmental issues associated with the activity. D-category activities that could relate to the storage of CO_2 are the drilling of wells[64] (with the exception of wells for the purpose of research on ground stability, archaeological research or the exploration and exploitation of oil, natural gas or salt) and the storage of natural gas underground[65] if the created storage capacity exceeds 1 million m^3. There is an obligation to *assess* the requirement for an EIA for executing, changing or extending a deep drilling (in this case creating an underground storage facility by making use of an existing mining installation). Furthermore, there is an environmental impact *assessment* obligation for a change in or expansion of an installation for the storage of hazardous and non-hazardous waste[66]. Finally, for any mining activity, which will take place in one of the Ecological zones[67] in the Netherlands, an EIA has to be conducted.

If a project has environmental consequences for a neighbouring country, special attention should be paid in the EIA to cross-border effects. International agreements have been made within the Espoo-treaty. (Convention on EIA in a Transboundary Context) of the Unece (see section 4.5.2). The obligations from this treaty have been incorporated in article 7 of the EU directive 97/11.

61 In the provinciale milieuverordeningen, article 7.6 of the EMA
62 Baggerspecie
63 MER Beoordelingsplicht
64 EIA-Decision, Appendix, Part D, Table number 17.2
65 EIA-Decision, Appendix, Part D, Table number 25.3
66 EIA-Decision, Appendix, Part D, Table number 18.3
67 Ecologische hoofdstructuur

In conclusion
There is no *specific* reference to the underground storage of CO_2 in the EIA-Decree. But since CO_2 is currently defined as waste, CO_2 storage is EIA obligatory according to the definition in the EIA-Decree. For non-hazardous waste the obligation is applicable when the capacity exceeds 500.000m^3. It is also considered wise that an EIA should be conducted for (at least the first) CO_2 storage projects, as it concerns a relatively new activity. In addition, an EIA might be a suitable instrument for Provinces to determine the environmental impact of storing CO_2 in underground reservoirs. This view also takes into account the discussion concerning CO_2 storage and the need to ensure adequate communication.

4.3.4 Long term liability

In order to discuss who is responsible for the stored CO_2 in the long term it is necessary to consider the various phases that are associated with CO_2 storage and the relevant time scales that need to be taken into account. The phases and activities that can be distinguished for CO_2 storage are indicated in the scheme below. The preparation phase takes only a few years and the operation/storage phase may take a few tens of years or more, whereas the end phase is expected to last for many centuries or longer.

Phases						
Preparation phase			Storage operation phase	End phase		
Activities						
Site selection & concession and permits	Design and construction of facility	Testing facility	Operation, CO_2 injection	Closure activities (Abandoning)	Transfer liability	Post closure
Monitoring						

Ownership versus liability
In the MA[68] it is stated that the State is the owner of the minerals present in the deep subsurface. For the necessary mining activities the operator gets a temporary permit to subtract the minerals. From the moment the resources are extracted from the earth, the licensee is owner of the mined substances. For the temporary storage of natural gas, it means that the State is the (temporary) owner of the stored gas, but that this ownership is again returned to the operator when they recover the stored gas.

There are several views on who is owner of the subsurface. Some legal experts think that the 'res nullius' concept is applicable, which means that the subsurface (apart from the mining minerals) belongs to nobody. When CO_2 would be classified as a mining mineral, the ownership is the State, as it would then concern a mining mineral that is stored in the subsurface. Nevertheless, CO_2 is not a mining mineral. It is stated in an explanation to the MA[69] that it is not the intention to classify stored substances as minerals.

[68] Mining Act article 3
[69] Tweede Kamer vergaderjaar 1998-1999, chapter 12

Depending on the interpretation, either the State or nobody is the owner of the stored CO_2. However, it is also the question whether ownership issues need to be answered to determine who is responsible for the activities undertaken in the subsurface. Currently it is stated in the Mining Act, Decree and Regulation that operators are responsible for applying measures to prevent hazardous events from occurring before and during the operational lifetime of the reservoir and also some time after abandonment of the reservoir.

As the ownership for CO_2 storage sites is unclear, it is also unclear who will be responsible for hazardous events after abandonment. For this study, the discussion on liability is regarded as more important than the discussion on ownership issues.

There seemed to be a general consensus among the participants of the expert workshop held on 12 March 2007[70], that it is reasonable and preferable, that at some stage after the closure of the storage site, the responsibility of the operator should be taken over by a governmental body. An operator cannot be held responsible for possible hazardous events infinitely.

So the Dutch legislation does not cover long term liability and the possible necessity for a transfer of responsibility in the case of CO_2 storage. Clarity is required on this issue before companies will take the initiative in setting up pilot projects. This point is also highlighted by the IEA-CSLF[71], who state that '*there is a need to ensure that existing regulatory frameworks, arrangements and government policy cover all aspects of liabilities that might arise from any unique aspect of CCS projects, both while the project is in operation and in the post-closure period*' (IEA-CSLF, 2006).

In order to facilitate CO_2 storage projects, it needs to be decided who will be the responsible authority after transfer. Secondly, criteria will need to be set up for determining when such a transfer should take place. These could be based on the presence of a stable situation as demonstrated by certain indicators and measurements, or perhaps – but less likely - on a predetermined period following abandonment. Financial arrangements will have to be made to cover the expenses to counteract for possible hazardous events and monitoring activities.

Parallels with well-known processes
There is a clear parallel with the decommissioning of petroleum and mine site operations, long-term management of hazardous waste disposal sites, high level radioactive waste sites, and contaminated site remediation as they are all intended to store a substance for an unlimited time period. They can provide models to assist in dealing with post-closure liability issues as they are based on the same principles (IEA-CSLF, 2006). Often a fund is established for 'aftercare activities' such as monitoring. In case of CO_2 storage this still has to be arranged in legislation.

It should be mentioned that the transfer of responsibility actually concerns a minimal residual risk. The MA aims at reducing the possibility of hazardous events both during and far beyond the operational lifetime of a reservoir, by demanding that at the beginning of a project, appropriate precautionary design and measures are established.

[70] Appendix chapter 15 lists the participants of the expert workshop
[71] International Energy Agency, Carbon Sequestration Leadership Forum

Nevertheless there is always a certain residual risk, because the chance that a hazardous event occurs can in principle never be fully omitted.

In conclusion
It is not clear from the Dutch legislation who would own the CO_2 when it is stored underground. Furthermore, it is not stated explicitly in Dutch legislation which would be the responsible authority after transfer of liability some time after the abandonment of a storage site. Furthermore, it is uncertain if and when liability would be transferred from an operator to the government and on the basis of which criteria. Finally, no financial arrangements for aftercare activities are defined in the legislation. It is expected that operators need more certainty on these issues before projects will actually be initiated.

4.3.5 Authorities and spatial planning

The subsurface may be suitable for various functions, such as the temporary storage of natural gas and water, the use of geothermal energy and (permanent) CO_2 storage. Currently a number of organisations have responsibility for certain activities in the subsurface, but no clear direction is provided by any singe governmental body[72]. To assess several options of using the subsurface it is necessary to be aware of effects that these activities might have on the environment. Furthermore, clarity is required on which (governmental) body is giving direction to the spatial plans and lastly clarity is required on which (governmental) body has the final decision in the future in determining whether or not CO_2 will be stored at a certain location.

As described earlier, at the moment there is a discussion in the Netherlands in the context of the new WABO, about who will be the responsible authority for the OV. Also for the Coordination Regulation, which concerns projects of national interest that need to be incorporated in spatial plans, a similar discussion is going on.

It is likely to be more efficient and simple if one governmental body is the competent authority; however, it is the question whether steering from the state governmental body is most preferable. As CO_2 storage is of national (actually global) interest, one could argue that this can best be regulated from the national policy.

Provinces, on the other hand, prefer to remain the competent authority for the storage of waste that has originated from outside the mining work as they have to deal with the possible ‘burden’ of associated decisions. Regional considerations play an important role in deciding about suitable locations for CO_2 storage. One could argue that it is logical that the responsibility would remain at the Provinces.

For companies, it is important that clarity is provided. They might have closer relations with the local governmental authorities that are more involved in and committed to local initiatives than the national government. There should also be a stable and clear policy plan as to how a CCS project will be facilitated legally, so that continuity in policy is guaranteed. Such a plan should in any case be developed on a national level, but also at a provincial level when the responsible authority for CO_2 storage remains at the provinces.

[72] source: VROM ‘Beleidsverkenning duurzaam gebruik ondergrond’

4.4 Possible scenarios

This section provides possible scenarios for solving the regulatory issues that were introduced in the preceding section. They are meant to give some direction to the discussion that is associated with the process towards a clear and complete legislation for CO_2 storage projects and the required actions that need to be undertaken to get there. It should be noted that the scenarios consist of suggestions and can not be seen as ready-made solutions.

4.4.1 Definition of CO_2 in relation to EIA-obligation

As mentioned earlier, the definition of CO_2 either as waste or non-waste dominates the discussion about which legal framework is applicable and thus whether or not an EIA is obligatory for CO_2 storage under the current legislation. Even though the definition as waste is clear in the Netherlands, it is not clear yet which position the international (European) policy makers will take. Both possibilities are depicted in the diagram at the end of this section.

Discussion on whether or not CO_2 should be regarded as waste has been going on for quite some time in the Netherlands. In the Netherlands, the majority of the attendants of the expert workshop held at March 12 (2007) have indicated that it would be best not to repeat this discussion, but to build upon the existing definition and associated legislation. As mentioned earlier, this means that the LAP has to be adjusted to incorporate requirements for CO_2 storage.

The international policy makers might choose to set up specific legislation for the full chain of CCS, including capture, transportation and storage of CO_2. There might then be a new Directive on CCS which obliges Member States to implement uniform CCS legislation. In fact, according to Brockett (pers.-comm., 2007), defining CO_2 as waste means that the regulation of CO_2 storage is very fragmented over many directives. The proposal of the European Commission will therefore most likely be to take CO_2 out of the waste definition so long as a separate freestanding directive can be made. From this perspective, it is a risk to choose for the direction of our current national legislation and its definition of waste. Nevertheless, this study does take that direction for now for the sake of continuity and clarity. Moreover, it will take time to wait for applicable EU regulation, which might delay the implementation of projects.

The implication of choosing the current Dutch direction is that adjustments have to be made to the existing LAP, in order to make it applicable for CO_2 storage. One of the adjustments relates to the issue of recoverability of the stored CO_2. One could argue that for precautionary reasons it should be demanded that the CO_2 that is not yet chemically bound to the reservoir rocks or dissolved in water should be recoverable in case this is required i.e. for safety reasons. The recoverability should be regarded as a final safety measure. On the other hand, it is generally accepted that CO_2 storage for the purpose of mitigating climate change is meant to be indefinite. From this perspective it makes no sense to demand its recoverability. Furthermore, for this discussion it should be taken into account that it is technically possible to recover the unbound and non-mineralized CO_2, even after closure of the injection wells by drilling a new well. For these reasons, it is recommended that recoverability should not be demanded in the LAP for CO_2 storage.

CO_2 can be lethal at high concentrations as it might cause asphyxiation. Furthermore, contaminants in the CO_2 stream might be hazardous. In dedicated legislation it is necessary to define the requirements for the quality of the CO_2 stream. These requirements and applicable criteria should be drawn up in terms of effect on human and the biosphere in general as well as on the underground containment and the confining layers. One can think of:

- defining maximum percentages of certain contaminants that are allowed to be present in the CO_2 stream;
- defining minimum percentage of CO_2 (amongst others to ensure efficient use of storage reservoirs).

The above mentioned definition of acceptably safe compositions can be based on:

- the origin of CO_2 (the type of capture and plant that causes the CO_2 emissions); for example derived from best available technology;
- a site-specific basis, taking the local geology and geochemistry into account.

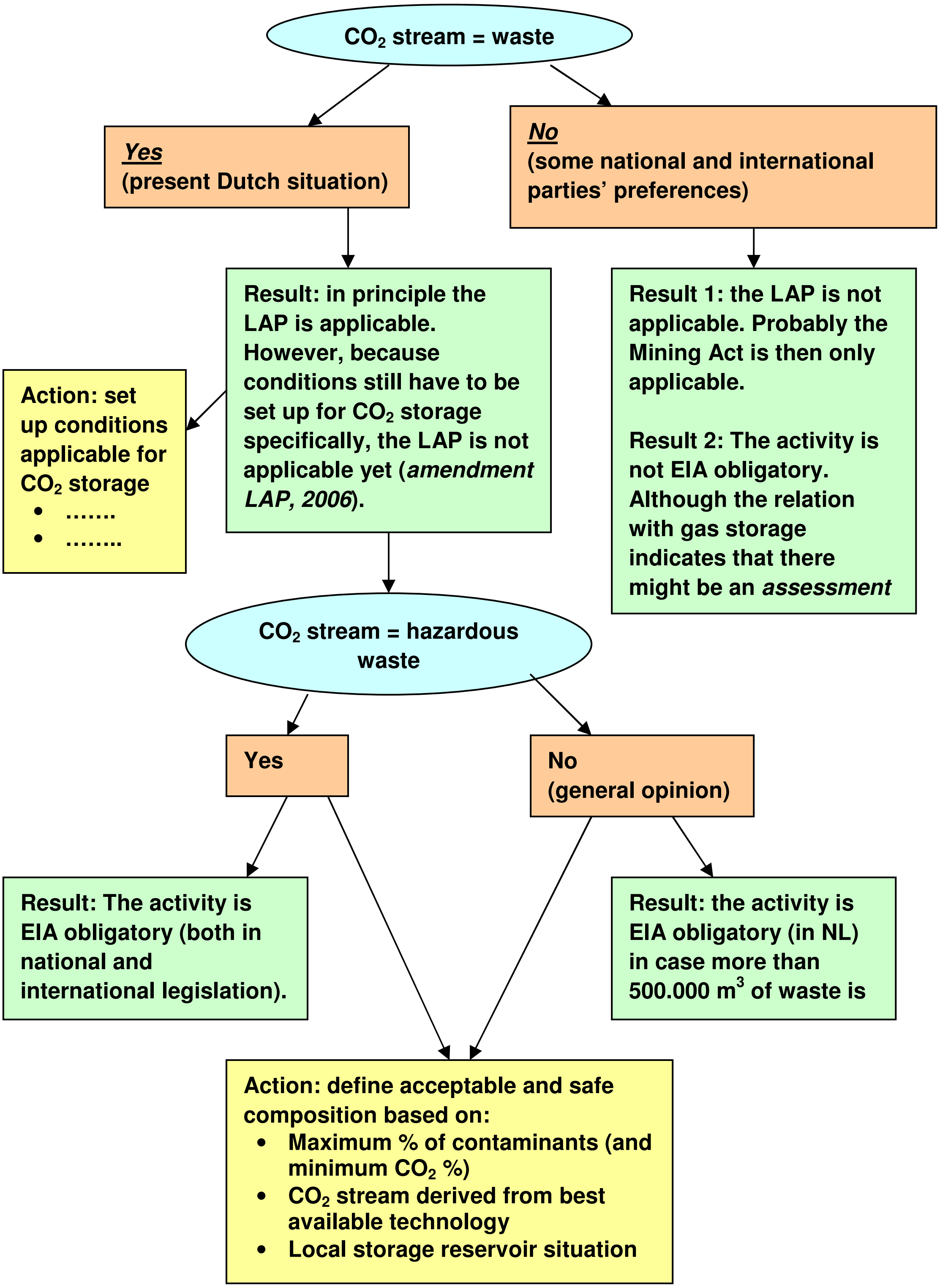


Figure 4.1 Summary of waste discussion

Since Min. VROM is the competent authority for the LAP, it seems logical that they should take the initiative in setting the criteria that are applicable for CO_2 storage in close cooperation with the Provinces as they are currently the responsible authority for waste from outside the mining work. Min. VROM is advised to make the recoverability criteria not applicable for CO_2 storage.

4.4.2 Responsibility in the long term

As explained previously, it is perceived as reasonable and preferable that the responsibility for a storage site will be transferred from the operator at some stage after the abandonment of the reservoir. Due to the very long time scales involved, it is essential that the responsibility is transferred to an enduring body. From this perspective, the long term responsibility can most sensibly be transferred to a governmental body, such as the Province or the national government. The participants of the expert meeting of March 12 (2007) have cautiously indicated a preference for the transfer of the long term responsibility to the government. This transfer would only take place after it is shown by the operator that the reservoir meets certain criteria which confirm a stable situation. These criteria still have to be defined.

To take a step ahead, it might be preferable to transfer the responsibility to the governmental body which prescribed the conditions for risk assessment, prevention and control in the first place (storage plan), which is Min. EA. This is the most experienced body in this context. It is might thus be recommended that after a certain period following site abandonment, the responsibility should be transferred to Min. EA.

As mentioned in the previous section the criteria for transfer of responsibility have not yet been established in the Dutch legislation. Two scenarios can be considered; in the first, responsibility is transferred when it is proven by the operator that the reservoir is stable, thus leaving only a very small risk in terms of safety and costs. The criteria for describing the stability of the reservoir need to be specified in this case. A second possibility is to transfer responsibility when a certain predetermined period has elapsed. This is currently applied for gas storage, for which the operator is still liable for hazardous events due to ground movement if it occurs within a (maximum) period of 30 years after abandonment (Burgelijk Wetboek). The period of 30 years is a maximum; the operator and the government can decide to transfer liability at any earlier stage.

When drawing up such criteria it is also important to take international legislation into account. At the moment the European Commission is working on drawing up criteria for the determination of risk related to (CO_2) storage. The current criteria and procedures for the acceptance of waste in landfills (2003/33/EC) might also play a role in establishing criteria for transferring responsibility.

Finally, (financial) arrangements need to be made for any aftercare activities, such as monitoring. Currently, it is the case with similar projects that the institute that is responsible for the after care becomes the exploiting party and hence should be held liable for the storage reservoir. A fund could be established by the operator that would be filled during the operational lifetime of the storage site. Since CO_2 storage for limiting climate change is an activity in the national interest, it might be reasonable to assume that the government would also contribute financially in one way or another, and this might influence the long-term aspects. This aspect is beyond the scope of this project.

Based on the preceding discussion, several actions need to be taken in the near future to make sure that all relevant aspects will be covered in regulations:

- Determine who will be responsible for the reservoir after transfer of the responsibility from the operator and incorporate this in legislation.
- Determine the criteria to be used for the timing of transfer and incorporate these into legislation.
- Determine the necessary (financial) arrangements for aftercare activities and incorporate these into legislation.

Several suggestions and recommendations have been made in this section on how to handle long term responsibility. It is up to the responsible authorities to take the initiative to work on the actions listed above and to incorporate the outcomes in the relevant laws and regulations. It seems appropriate that the actions related to long-term liability should be initiated by Min. EA, as this is the responsible authority for the MA. The Ministry needs to involve Provinces in this discussion, as they are currently the authorities responsible for granting an environmental permit for CO_2 storage (when it has originated from outside the mining work). The Ministry can be assisted by the State Supervision of Mines and by geological institutes to perform the necessary actions.

It should be noted that there is urgency in performing the above mentioned actions in order to facilitate the deployment of deep geological storage of CO_2 in the Netherlands. As stated previously, the basic principles are already contained in the MA (and the EMA), but it is unlikely that companies will initiate even pilot projects as long as the long term liability is not legally defined.

It is likely that pilot projects will provide the lessons which can be used to set up criteria such as those concerning long term responsibility. However, this will take time, leaving an uncertain gap in the meantime. Moreover, clarity is actually especially required for the first pilot projects, as these should also be show cases, in which it is shown to the general public that CO_2 storage is a save way of mitigating CO_2 emissions. For this reason it could be considered making temporary arrangements, applicable only to such pilot or demonstration projects, which would encourage companies to implement them. This could be seen to be in the national interest by assisting in combating climate change. Modifications found to be necessary in laws/regulations could then be made later, benefiting from the pilot project experience.

Role of the government

Finally, it should be noted that CO_2 storage can not simply be regarded as a commercial activity, in case CO_2 will not be used for enhanced recovery. Often the government participates in projects with such common interest. Therefore, it seems reasonable to assume that the government takes this common interest into account when adjusting legislation in the field of liability issues to facilitate CCS projects in the Netherlands.

4.4.3 One single (state) governmental decisive body

From the point of clarity and simplicity, it would be convenient if one governmental body is responsible for all activities associated with CO_2 storage. This was also decided for onshore pipelines, to accommodate all regulations at one Ministry (being Min. VROM).

On the other hand CO_2 storage concerns national and regional/local decisions, therefore, cooperation is necessary in all cases, no matter which governmental body will have the final say.

In any case the national government should draw up a long term national view on the use of the subsurface, including CO_2 storage. As CO_2 mitigation is in the interest of the whole nation, nation-wide targets have to be drawn up; including targets for CO_2 storage. For such a long term strategic document the Provinces have to be consulted on the possibilities within their territory. This is expected to lead to a better strategic spatial plan, which is supported by both the state and the Provinces; faster process of decision making and it makes sure that suitable locations for CO_2 storage are reserved for this purpose. A parallel can be drawn with the way wind turbine projects are arranged. For these projects, national targets are set and the provinces have to contribute to reach this target, but they can include these targets in their regional plans themselves (for which a Strategic Environmental Assessment has to be conducted). A similar arrangement might be suitable for CO_2 storage projects.

4.5 New international developments and discussions

4.5.1 Overview international law and regulation on CO_2 storage

This section provides an overview of the status and recent developments of the main European Union and international legal and regulatory issues with respect to CCS.

International law, like e.g. treaties, addresses the relationship between States, or the relationship between persons or entities in different States. In the context of carbon capture and storage (CCS), international law principles are implicated in two ways. First of all, industrial activities that generate carbon dioxide will have impacts beyond areas of national jurisdiction. Specific treaties to regulate direct or indirect CO_2 emissions are the UN Framework Convention on Climate Change, the Kyoto Protocol, and a number of EU Directives, which encourage the reduction of CO_2 emissions and encourage removals from the atmosphere in order to prevent dangerous climate change and reduce the impacts of greenhouse gases on the environment. Secondly, efforts undertaken to capture, transport and store carbon dioxide may themselves lead to damage to the environment in areas beyond the territorial limits of national jurisdiction. Agreements include the London Convention, the London Protocol, the OSPAR Convention (The Convention for the Protection of the Marine Environment of the North-East Atlantic), the Espoo convention (Convention on EIA in a Transboundary Context) and the Kyoto Protocol. Also on European level developments occur, e.g. in making provisions for adapting the Monitoring and Reporting Guidelines of the IPCC[73], inclusion of CCS in the European Trading Scheme (ETS), and in drafting policy and regulatory frameworks for enabling CCS.

From 2008 onwards, EU Member States are permitted to extend emissions allowance trading within ETS to activities, installations and greenhouse gases that are not listed in Annex I to the Directive. Conceivably, the storage of carbon dioxide might be regulated as a new activity, with storage sites regulated as a new category of installations. Next to provisions to get CCS accountable as an emission reduction option, CCS needs to comply with law and regulation to safeguard the environmental integrity of ecosystems.

[73] International Panel on Climate Change

In this section we describe the most relevant developments in international agreements with respect to the application of carbon dioxide capture and storage that could affect the developments of our national legislation for onshore CO_2 storage.

4.5.2 Transboundary issues and the Espoo convention

It is a general principle of international environmental law that States have the sovereign right to exploit their own resources, but also the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or damage to areas beyond the limits of their national jurisdiction[74]. In the context of transboundary environmental damage, this principle has two parts. First of all, a State has a responsibility to take measures to *prevent the occurrence* of transboundary environmental harm. Secondly, a State has a responsibility to *redress damage* if and when transboundary harm occurs. Numerous EU legal frameworks reflect and apply these international law principles in the areas of air pollution, groundwater pollution, marine pollution, waste management, land and marine transportation of hazardous and non-hazardous substances, and natural resource protection.

Espoo Convention

One of the international transboundary conventions is the Espoo convention[75] (EIA). It requires Parties to assess the environmental impact of certain activities at an early stage of planning. Member States have the general obligation to notify and consult each other on all major 'proposed activities' under consideration that are likely to have a significant adverse environmental impact across borders. The Espoo (EIA) Convention is based on earlier EU Directives (Sands: 814), which are discussed below.

'*Proposed activity*' is 'any activity or any major change to an activity subject to a decision of a competent authority in accordance with an applicable national procedure' (Art. 2(3)). '*Impact'* is defined as '*any effect caused by a proposed activity on the environment including human health and safety, flora, fauna, soil, air, water, climate, landscape and historical monuments or other physical structures or the interaction among these factors*.

'*Environmental impact assessment'* is defined as 'a national procedure for evaluating the likely impact of a proposed activity on the environment.

Parties agree to 'take all appropriate and effective measures to prevent, reduce and control significant adverse transboundary environmental impact from proposed activities' (Art. 2.1). They agree to take the necessary legal, administrative or other measures to implement the Convention – which include the establishment of a national procedure for public notice and participation, and the preparation of environmental impact assessment documentation for proposed activities listed in Appendix I that are *likely to cause significant adverse transboundary impact*.

If the Parties agree, the activity will be treated as an Appendix I activity (Art. 2.5). General guidance for identifying *criteria to determine significant adverse impact* is set forth in Appendix III, including size, location and effects. Furthermore, criteria suggest that the impacts of large-scale CO_2 geologic storage in sites that are either cross-

[74] Sands, P., Principles of international environmental law, (2nd ed. 2003), p. 183, citing Principle 21 of the Stockholm Declaration and Principle 2 of the Rio Declaration. See also the preamble to the 1992 UN Framework Convention on Climate Change, citing the Charter of the United Nations and the principles of international law.

[75] 1991 Convention on Environmental Impact Assessment in a Transboundary Context. In force in 1997

boundary, or close to national boundaries, should be the subject of discussion among concerned Parties.

4.5.3 2006 IPCC Guidelines

The 2006 Guidelines are the latest step in the IPCC development of inventory guidelines for national estimates of greenhouse gases. They may also be of use in more narrowly-defined project based estimates, although here they should be used with caution to ensure they correctly include only the emissions and removals from within the system boundaries. The new guidelines and source categories have been approved and accepted by IPCC plenary in Mauritius in April 2006. However, the Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nations Framework Convention on Climate Change (UNFCCC) still has not considered and concluded how to use the 2006 guidelines. These Guidelines provide emission estimation guidance for carbon dioxide transport, injection and geological storage (CCGS) only.

There are yet no national or international standards for performance of geological CO_2 storage sites and many countries are currently developing relevant regulations to address the risks of leakage. According to the guidelines, demonstration of monitoring technologies is a necessary part of this development. If one or more appropriate governing bodies that regulate carbon dioxide capture and storage exist, then the inventory compiler may obtain emissions information from those bodies. If no such agency exists, then it would be good practice for the inventory compiler to follow the methodology presented below. In the methodology outlined below, site characterization, modelling and assessment of the risk of leakage and monitoring activities are the responsibility of the storage project manager and/or an appropriate governing body that regulates carbon dioxide capture and storage.

They should:

1. Identify and document all geological storage operations in the jurisdiction.
2. Determine whether an adequate geological site characterization report has been produced for each storage site.
3. Determine whether the operator has assessed leakage potential at the storage site.
4. Determine whether each site has a suitable monitoring plan.
5. Collect and verify annual emissions from each site.

4.5.4 International offshore legislation: London Convention, London Protocol and OSPAR

The London Convention prohibits the dumping of industrial wastes. In April 2006, the London Convention Scientific Group (SG) Intersessional Technical Working Group on CO_2 Sequestration met to discuss possible amendments to the Protocol to allow for the storage of carbon dioxide in the sub-seabed. The amendment that has resulted from the 1st Meeting of Contracting Parties to the London Protocol (30 October - 3 November 2006), states that carbon dioxide streams may only be considered for dumping (into a sub-seabed geological formation), if it consists overwhelmingly of carbon dioxide (they may contain incidental associated substances derived from the source material and the capture and sequestration processes used); and no wastes or other matter are added for the purpose of disposing of those wastes or other matter. The changes to the London Protocol will in turn most likely lead to a revision of the OSPAR Convention, the North-East Atlantic's equivalent of the London Protocol, which combines the 1972 Oslo

Convention on dumping waste at sea and the 1974 Paris Convention on land-based sources of marine pollution.

The OSPAR Convention regulates the deliberate dumping of pollutants into the North-East Atlantic Ocean maritime area. The OSPAR Commission recently produced a report on *Placement of CO_2 in Subsea Geological Structures*. The report concluded that guidelines are needed to assess potential storage sites for their capability to store CO_2 long-term. Relevant factors include characterization of the reservoir, the cap rock/trapping mechanisms, geological stability and possible leakage-path routes. The report additionally concludes that:

- safe geological storage of CO_2 is technically feasible, provided sites are appropriately selected, managed and monitored;
- structures within the OSPAR maritime area have the potential to store most of the EU's CO_2 emissions from large point-sources for centuries;
- risks of stored CO_2 leakage must be evaluated against the risk to the marine environment posed by elevated atmospheric levels of CO_2;
- the capability of a site to store CO_2 in the long-term relates to the protection of the marine environment as well as climate change mitigation;
- appropriate monitoring/surveillance technology and methodology for the safe storage of CO_2 are available and should be used in a *site-specific* manner to monitor CO_2 storage (including proper injection), to detect and remediate any leakage, and to estimate emissions for inclusion in greenhouse gas inventories.

The OSPAR Convention is working toward producing guidelines or a framework to assess potential storage sites for their capability to store CO_2 long-term.

4.5.5 Development of policy and regulatory framework by the European Commission

The European Commission identifies CCS as an important technology in its 2005 Communication 'Winning the Battle Against Global Climate Change' (COM (2005)35 of 9 February 2005. CCS is also addressed in the Commissions' Green Paper on 'A European Strategy for Sustainable, Competitive and Secure Energy' (COP (2006)105 of 8 March 2006. The Green Paper identifies CCS as an opportunity for near-zero emissions power generation that can be particularly important for countries that choose to continue the use of coal as a secure and abundant energy source. It points out that, for this technology to be deployed, it needs the necessary economic incentives, as well as legal certainty for the private sector and guarantees for its environmental integrity. In June 2006 Working Group 3 of the European Climate Change Programme of the European Commission on CCS recommends that during 2007, the Commission produces a Communication outlining the major EU policy choices for CCS accompanied by a proposal for an EU CCS regulatory framework. It is recommended that those policy and regulatory framework should be in place as soon as possible.

The Commission is requested to address:

1. Permitting of geological storage sites, including risk management, site selection, operation, monitoring, reporting, verification, closure and post-closure.
2. Liability for leakage from storage sites during operation and post-closure.
3. Clarification of the role of CCS under EU legislation, in particular concerning waste and water, and propose appropriate amendments.
4. The recognition of CCS projects in the EU Emissions Trading Scheme.
5. The need and possible options for incentivising CCS in a transitional period.
6. The status of CCS projects under rules and guidelines for State Aid.

The workgroup advises that the policy and regulatory framework for CCS in the EU should:

- Ensure the appropriate management of the environmental risks associated with CCS and reduce environmental impacts associated with the CCS chain to an acceptable level, both over the short and long term.
- Provide clarity, coherence and stability, enabling market operators to invest in CCS facilities across the EU under comparable regulatory conditions.
- Provide appropriate incentives for the use of this technology, that are in relation to its actual GHG reduction benefits and do not unduly disadvantage the development and deployment other options, in particular in relation to energy efficiency and renewable energy.
- Address liability issues, in particular responsibility for remediation in relation to leakage from the storage site in the short and long term.

In addition recommendations were:

- Commission should provide interim guidance on the role of CCS in existing legislation, including the Emission Trading Scheme; and to explore and clarify the role of CCS under the legislation concerning waste and water, and propose amendments in case certain provisions would cause unwarranted obstacles.
- Commission should further explore the possible role of existing EU instruments such as the EIA Directive, the SEA Directive the Water Framework Directive, and the Integrated Pollution Prevention and Control Directive (IPCC).

At the moment, the Commission is preparing a policy and regulatory framework directive, which should be in a later stage be implemented in national law.

4.6 Carbon storage - an international perspective on regulations

The interest in using geological systems for the storage of surplus CO_2 is a significant change from the previous applications of injection in connection with the production of oil and gas products suitable for sale on the world markets. This change has resulted in some parallel activity in connection with the regulations needed for the CO_2 storage. In this section information is presented on the regulatory situation of CO_2 storage in several different parts of the world.

4.6.1 Sufficiency of existing regulations

Many jurisdictions have regulations that control the exploration and production of oil and gas resources, and injection of fluids, including carbon dioxide, into the subsurface. Regulatory reviews by the International Energy Agency (IEA) have indicated that, in general, the existing regulatory frameworks from other industries (mining, oil and gas) can be adapted for steps of the capture and storage process up to and including the point of injection. Further work and development were thought to be necessary in the areas of long term monitoring, ownership and of mitigation planning. In addition to technology and cost issues, health, safety, environmental and legal concerns also need to be addressed to ensure public support.

The situation in the USA appears to be particularly extreme in terms of regulatory decisions taken, even though there are currently several pilot projects in progress there. The government has reported to have taken the view that the Environmental Protection Agency (EPA) is not authorized to regulate CO_2, and that even if it is authorized the government has decided not to regulate it. This position was successfully challenged by some states before the Supreme Court. In practical terms the issue of CO_2 in relation to the pilot projects is considered to be one of protecting groundwater and there is a draft guidance document for this purpose.

Regulators and implementers in several countries have been asked to describe the position with respect to the existence of appropriate regulations. In a draft report to the International Energy Agency of Greenhouse Gas in August 2006 /1/ a number of tables were presented, one of which is reproduced below. In this table the respondents stated which of their existing laws are relevant to CO_2 sequestration projects, and they also commented on this information. The predominance of the assumed applicability of legislation from the petroleum industry is clear, as is the fact that in several cases there is a recognized necessity for modification or even for new legislation.

Table 4.2 Stenhouse et al. Role of Risk Assessment in Regulatory Framework for Geological Storage of CO_2. Feedback from Regulators and Implementers. Technical Report MSCI-2512v1

Country	Existing Relevant Laws	Comment
Australia	Combination of petroleum, environmental and safety legislation	Different legislations apply to different aspects of CO_2 storage. CCS projects approved on a case-by-case basis until CCS legislation is available
Canada *Saskatchewan* *Alberta* *British Columbia*	CO EOR and Acid Gas injection CO_2 EOR and Acid-gas disposal Regulations exist for small-scale projects Environmental assessment	Specific framework 2008+ No regulations specifically for CCS.Working towards legislation for 2008.
France*	Mining Act, Water Law, at least for pilot projects	Laws applicable only if pure CO_2.
Germany*	Mining Law	Date 'open' regarding legislation
Japan	None	Legislation possibly 2011-2016
Netherlands*	Mining Act Environmental Impact Assessment	Long-term aspect not yet covered
Norway*	Petroleum Law (CO_2 injection), Environment Protection Law (emissions)	Mostly covered by petroleum legislation
U.K.*	Only covering CO_2-EOR (Petroleum Act, Pollution Control Act *etc.*)	No set date for CCS-specific legislation
U.S.A.	Groundwater Protection Act; Clean Air Act; Underground Injection Control (UIC)	Assessing implications of adapting/modifying UIC

4.6.2 Long-term responsibilities

In oil and gas projects the ownership typically reverts to the state once the operator has completed any required abandonment measures at the depleted field. This may be perceived to be inappropriate for the long-term potentially hazardous condition of a full CO_2 repository. Although officials, e.g. in Canada, expect that the implementer will be responsible in the long term, there is nothing available there in writing which shows how this is to be achieved. Only for Australia a draft has been found which explicitly covers this issue. It concerns the 'Draft Guiding Regulatory Framework for Carbon Dioxide Geosequestration' prepared by the federal Department of Industry, Tourism and Resources, in which it is said: *'Responsibility and associated liabilities should remain with the project proponent until the relevant government is satisfied to a high degree of certainty that:*

- *Future land use objectives defined at the time of the project approval have been met; the residual risk of leakage and liability are acceptably low; and*

- *The ongoing costs associated with the site are acceptably low or are otherwise appropriately managed (for example through financial assurances, instruments and trust funds)*

Following closure, primary responsibility for the site will lie with the government, although some residual liability may remain with the proponent. The scope and nature of these residual responsibilities should be resolved upfront to the extent possible, recognizing that responsibility depends on individual circumstances of each case. These liabilities should be determined and negotiated with the proponent on a project-by-project basis. There may be a need to manage any residual liability that remains with the proponent e.g. through means such as ongoing indemnities, insurance policies or trust funds.'

4.7 Conclusions

CO_2 storage can play a potential important role in reducing the amount of CO_2 in the atmosphere. However, the current legal and administrative position in relation to CO_2 Capture and Storage (CCS) in the Netherlands is at some points unclear and some existing laws and regulation may need to be adjusted for the wide application of CO_2 storage projects. In this chapter an attempt has been made to detect these gaps in present laws and regulation in the Netherlands and to come up with suggestions to facilitate the realization of CO_2 storage. Next to the Netherlands regulatory framework, also the current state of international and European legislation with respect to CO_2 storage has been discussed.

In the introduction several questions were posed, concerning the responsible authority, the definition of CO_2 and associated legal consequences and the requirement for an Environmental Impact Assessment. In general, it can be concluded that despite the fact that the basic principles for CO_2 storage are already present in the current legislation and that it is reasonably clear what permits are required for CO_2 storage and on what basis a permit will be granted; some adjustments will have to be made before CO_2 storage projects will actually be initiated. Also from an international context, the predominance of the applicability of legislation from the petroleum and mining industry is clear, although it is also recognized that modification are probably necessary on certain topics. Currently, the most important aspect unclear in the Dutch Mining Act, is the issue on long term liability and the complementation and abandonment of a storage site. It is uncertain to whom and when liability is transferred, based on which criteria. Finally, nothing is (financially) arranged in legislation for aftercare activities. It is expected that operators will wait for more clarity, before they will start realizing (pilot) projects in the Netherlands. It is suggested that the long term responsibility should be transferred to the State, when it is shown by the operator that the reservoir meets certain criteria which confirm a stable situation. The criteria have to be established soon, thereby also taking international legislation into account.

Furthermore, in the current Dutch legislation, CO_2 is defined as waste, which means that in general the LAP is applicable and that the Provinces are the competent authority. However, the conditions for CO_2 storage specifically are not yet defined in the LAP. They will have to be drawn up by Min. VROM together with the Provinces, based on future pilot projects. This means that the Lap will not be applicable for these first pilot projects. Account should be taken for the fact that it seems that the international community chooses for another direction by not defining CO_2 as waste and by drawing up a separate directive for CCS. It would be very inconvenient and complicated when a national and EU legal documents both become applicable. Such a situation should be avoided.

It seems likely that CO_2 will be treated as non-hazardous waste in future legislation. However, the full CO_2 stream should be considered that might contain hazardous contaminants for human and the confinement layers. One of the consequences of the definition of CO_2 being waste is the fact that an EIA is required for hazardous waste both in national and international legislation and for non-hazardous waste (only in Dutch legislation) when the critical mass value is exceeded. It also seems preferable that an EIA should become obligatory for CO_2 storage projects, especially for the first projects. Furthermore, the Provinces do not have any other instrument at hand to determine the environmental impact of such activities. Finally, the societal discussion around CO_2 storage and the need for proper communication around it, encourage these thoughts even more. In case an EIA becomes obligatory for CO_2 storage, this also means that a SEA has to be conducted beforehand at a strategic level.

There seems to be a preference among Dutch experts present at the expert meeting in March (2007) to build upon existing legislation. However, for the competent authority there is a debate going on in the light of a few new regulations, about whether the provinces should remain the responsible authority or whether all legislative issues could be better accommodated under Min. EA. In any case it is in favour of CCS projects that continuous policy and clear legislation will be developed. It is suggested that a national strategic policy perspective on the use of the subsurface is developed in cooperation with Provinces and that Provinces remain responsible for deciding how and where these projects will be realized in cooperation with companies that are willing to take the initiative.

In the international arena it is also recognized that an EU CCS policy and regulatory framework should be developed as soon as possible. Currently, there are no national or international standards yet for the performance of geological CO_2 storage sites for example, and many countries are currently developing relevant regulations to address the risks of leakage. There are suggested methodologies including site characterization, modelling and assessment of the risk of leakage and monitoring activities, but they are not yet officially applicable. It is likely that a new directive will de drafted by the Commission, which should be in a later stage be implemented in national law.

Also transboundary legislation should refer to CCS, as efforts undertaken to capture, transport and store carbon dioxide may lead to damage to the environment in areas beyond the territorial limits of national jurisdiction. There are already numerous EU legal frameworks that reflect and apply these international law principles in the areas of air pollution, groundwater pollution, marine pollution, waste management, land and marine transportation of hazardous and non-hazardous substances, and natural resource protection, of which a few were described in the foregoing sections. Furthermore, international legislation has been developed for CO_2 storage offshore. The OSPAR Convention is for example working toward producing guidelines or a framework to assess potential storage sites for their capability to store CO_2 long-term.

It is clear from this chapter that there are indeed some gaps in existing national and international legislation that first need to be developed in order to facilitate CO_2 storage projects. In the Netherlands, the policy makers that will carry out the necessary actions are advised to take account of the international developments as well.

4.8 Issues in a specific project EIA

General issues for an EIA in chapter 4

Chapter 4 can be used to describe the laws and permits, regulations and policies. Usually the different levels of the relevant authorities are mentioned. There is a description of the policy on broad issues like energy and spatial development. More specific policies on water, ecology or archaeology are often discussed in the environmental impact chapter of this issue.

Specific attention to CO_2 storage in Chapter 4

Chapter 4 should be a state of the art overview for a specific CO_2 storage project. Since the regulation is complex and still unclear, a specific EIA might refer to the discussion in the AMESCO study and add the additional agreements. Special attention should be given to:

- An overview of general legislation rules (as presented here).
- Specific policy of the province concerned.
- Specific conditions from applicable national and regional policies.
- Different roles and responsibilities of the authorities, making clear the role of the province, Min. VROM and Min. EA (coordinated competent authority).
- Does CO_2 has to be recoverable.
- Who will be responsible for the storage in the long term?
- How will the reservoir be treated after abandonment?

5 ENVIRONMENTAL IMPACTS; GENERAL DESCRIPTION

5.1 Introduction

In Chapter 3 a description is given of the design and operation of a CO_2 storage system. This system is designed from an environmental point of view to minimise the environmental impacts. Still a CO_2 injection and storage system will have some impact.

This chapter gives an overview of the different types of environmental impact that are considered in a typical EIA. For each type of environmental impact the possible impact at a CO_2 injection and storage project is described. When determining possible impacts of a CO_2 storage system a distinction is made between:

- Expected impacts of normal operations
- Impact following a failure of the system

Both types of impact are to be described in an EIA. The descriptions of impacts from normal operations are related to planned activities. They are predictable from the experience of related projects, like water injection or gas injection.

For the impact following a failure of the system the situation is different. The possible failures have to be identified and for each type of failure an impact description must be made.

In this chapter first the project phases as described in Chapter 3 are characterized. Then in Section 5.3 a description is given of the subsurface hazards from normal operations. Section 5.4 describes the possible impacts on the surface. Section 5.5 describes the possible failures of the system (both surface and subsurface) and 5.6 gives an overview of the possible impacts of these failures. This will lead to Chapter 6 in which a description is given of the sensitivity of the biosphere to the possible impacts as described in this chapter. Chapter 7 continues with a more quantitative approach to the possible impacts.

5.2 Project phases of CO_2 storage

5.2.1 Storage as part of CCS

CO_2 storage activity is only possible if it is connected to a CO_2 capture and transport system. Therefore it could be argued that for a description of the environmental impact the whole (CCS) system has to be considered. This would give a complete picture for the option of storing CO_2. However it is expected that in the future there will be no direct connection between capture and storage of CO_2, when a pipeline network is used for transport from different capture sites to many different storage sites. In that case it is not necessary to perform an EIA of the whole system, but only of the different parts of the system.

For a CO_2 storage project it is important to fix the scope of the project-specific EIA. Within AMESCO we will use the area of the CO_2 injection site. Through a pipeline the CO_2 is transported from outside the area into the site. There may be an injection compressor in which the gas pressure is increased to the required pressure for injection. And of course there has to be a well, either an existing one or a well drilled for this purpose. Abandoned wells that will not be used but which penetrate the reservoir for CO_2 will have to be included in the project scope.

5.2.2 Stages of a CO_2 storage project

The stages of a project as used in this study are:

Phases						
Preparation phase			Storage operation phase	abandonment phase		
Activities						
Site selection & concession and permits	Design and construction of facility	Testing facility	Operation, CO_2 injection	Closing activities (Abandoning)	Transfer liability	Post closure
Monitoring						

5.3 Possible subsurface hazards by normal operations, related to CO_2 storage

If the CO_2 is stored as planned, the impact on the subsurface is limited. There will be a filled reservoir, and the pressure will be less than or equal to the original pressure. Therefore the impact of pressure is expected to be limited.

The injected CO_2 is different from the original gas. Therefore it is possible that chemical reactions will take place in the reservoir. There is limited knowledge about how the CO_2 (including possibly some impurities) will react with the material and other gases in the reservoir. So far there is no evidence that chemical reactions will take place on a large scale and substantially influence the reservoir.

There are two possible hazards that can be expected and estimated

- Induced seismicity, during CO_2 injection.
- rock deformation in and around the reservoir, during CO_2 injection.

There is, for example, experience with injection of production water in Borgsweer and Schoonebeek / Dalen and of temporary storage of gas in Norg. In these projects the EIA paid attention to possible ground tremors and possible uplift resulting from increasing the reservoir pressure. It is important to study these possible impacts, but for the EIA it is clear how these aspects should be considered, e.g. in a site selection process.

Brine displacement near reservoir
Although the CO_2 will be injected into a (nearly) empty reservoir, it is possible that the build up of pressure in the reservoir might cause movement in an underlying water reservoir. Brine displacement occurs when the reservoir is overfilled. Overfilling can be monitored and mitigated.

5.4 Possible impact by normal operations, related to CO_2 storage

5.4.1 Comparable projects

Projects to store CO_2 in onshore gas reservoirs are new for the Netherlands. Therefore the potential impacts and the assessments of such impacts are also new. However some of the impacts will be more or less predictable from comparable storage projects.

There are water injection projects for production water in the Groningen and in the Drenthe reservoirs and in the Western part of the Netherlands. These projects are designed to store the water without the objective of retrieving it. This purpose matches exactly with CO_2 storage.

NAM also has gas injection projects, but in these the gas is only stored for a relative short period of time, to have a buffer to meet high demands.

5.4.2 Surface

No standard construction impacts
The site is assumed to have been used for production of gas. Therefore considering some standard possible environmental impacts during the construction phase will not be necessary. No impact is expected on:

- Movement (transport) of soil.
- Drainage of groundwater or reduction of precipitation reaching the subsurface.
- Archaeological finds.
- Geomorphology.

Also, for the aspect of landscape, it might be expected that the installations for a CO_2 injection site will not be very different visually from the installations for gas production.

Possible contamination of soil and water
There might be some contamination of the soil or water during the construction phase (workover of the well and possibly the compressor), during CO_2 injection phase (especially during maintenance) and when the injection well is abandoned.

Ground movement – calculated uplift
During the injection phase there might be surface uplift from the deformation of the reservoir, reversing that from the gas production phase. This impact can be calculated and it is comparable with the impact of water injection in reservoirs, as is already being carried out in the Drenthe and Groningen fields.

Ground tremors
Ground tremors can result from induced seismicity during the injection phase and can be predicted by using the methods that are available for normal oil and gas operations. These methods are used for the preparation of standard 'winningsplannen' and 'opslagplannen'.

5.4.3 Noise, safety, use of energy

During the construction phase, injection period and abandonment, there will probably be some noise (e.g. from an injection compressor), traffic and waste. This might have impact on ecology, like disturbance of birds and other animals.

The CO_2 injection will take place in a close-system, without emission into the air. It seems possible to have hardly any impact from smell or light.

The safety issue will be strongly related to the possible impacts following a failure of the system, as discussed in the next section. For the surface facilities a QRA can be calculated comparable with water-injection projects. All these impacts are predictable, from the experiences of many other projects.

As part of the EIA it is important to calculate the energy balance. To store the CO_2 will cost some energy, for the injection. Also the use of materials has a cost of energy component. It is important to calculate the necessary energy and convert this into additional CO_2. This gives a CO_2 balance for the injection location. Of course the injection is only part of the activities; the capture and transport also have to be taken into account for a complete CCS system.

Table 5.1 gives an overview of the possible environmental impact related to CO_2 injection and storage.

Table 5.1 Normal operational activities

	Construction	Injection	Abandonment
Soil	1	0	1
Water	1	0	1
Ecology	1	1 (noise)	1
Archaeology	0	0	0
Geomorphology and landscape	0	0	0
Noise	1	1	1
Traffic and transportation	1	0	1
Smell / emissions	0	0	0
Light	0	0	0
Safety	0	1	0
Waste	1	0	1
Ground movement	0	1	0
Ground tremors	0	1	0
Use of energy	1	1	1

Explanation Table 5.1

0 = no impact related to CO_2 storage expected

1 = possible impact related to CO_2 storage, but impact assessment is well known from other activities

2 = possible impact related to CO_2 storage, but little or no direct previous experience

5.5 Possible failures, related to CO_2 storage

Considering the environmental impact of CO_2 storage, there are a number of possible failure sources:

- Surface facilities failures
  - Pipeline system (construction, maintenance).
  - Compressor (during construction and operation).
  - Well (possibly drilling, maintenance, closure).
- Subsurface failure
  - Loss of containment (leakage).

In any project EIA these elements will have to be addressed. Evaluating the environmental impact of some of the abovementioned sources however is not new, because they are part of other gas and oil projects. Therefore they should be considered and studied, but within the context of the AMESCO study we will focus our attention on the new aspects that are specific to underground storage of CO_2.

5.5.1 Surface facilities

At the surface facilities possible failures can be:

- Leakage in pipe system or compressor. These are failures that are not exclusive to a CO_2 storage system. In an EIA they will have to be addressed in a Qualitative Risk Assessment (QRA).
- During construction and abandonment the risks of failure are also comparable to those of existing systems.

5.5.2 Subsurface failure

Subsurface failure is related to loss of containment, i.e. unwanted leakage out of the reservoir up to the biosphere. The sensitivity of the biosphere to CO_2 is thoroughly described in chapter 6, while chapter 7 describes the possible leakage mechanisms and their impact on the biosphere.

5.6 Possible effects from failure of the system, related to CO_2 storage

5.6.1 Effects from surface failures

Blow out
Just like in normal well operation a blow out can occur. The probability of a blow out can be calculated. Also mitigation measures are standard in drilling operations.

Noise
Additional noise could occur as a consequence of a failure. For normal operations noise levels can be calculated and tested with the standard procedures.

Traffic and transportation
Additional transport at the surface level might take place following a failure, but as already mentioned with the impact of noise, a standard method is available to include the impact in an EIA.

Smell
During normal operations, no smell is expected. Only in the case of leakage, there is the possibility of smell. CO_2 does not have a very strong smell. However, as mentioned before, after or during CO_2 injection, not only CO_2 might leak but also some other gases. These gases might have a strong smell. Since this would be an indication that something is wrong, there should not be a smell for a long period of time.

Light
As with noise and traffic, there is no specific light impact expected from CO_2 storage even in the case of a failure. When the site at surface level uses light the same rules will apply as for any other activity.

Safety
There will be high pressures needed to inject the CO_2 and the injection itself can be seen as a safety risk associated with modes of potential failure. However, this is not a new activity and models and legislation exist for this purpose.

Waste
Additional waste could arise as a result of measures taken following a failure.

Use of energy
It is unlikely that a system failure would result in an increase in the use of energy.

5.6.2 Effects from subsurface failure

If CO_2 leakage occurs and the CO_2 reaches the biosphere, there will be impact on both health and environment. The impact depends on:

- Amount of CO_2, the flux.
- The sensitivity of humans and organisms to CO_2.
- Current natural CO_2 concentrations and fluxes.

The possible flux and concentration of CO_2 is discussed in Chapter 7, while the sensitivity and current concentrations are described in Chapter 6. Health impact on humans is considered extensively in both chapters. In this section we take a closer look at the different aspects of the EIA to see what may be influenced by a failure of the storage system.

5.7 Issues in Chapter 5 of a specific project EIA

Usually the different alternatives to be compared in the EIA are described first, before an overview of the impacts is given. This means the findings of Chapter 8 from this report should be expected before the findings of Chapter 5.

General issues for an EIA in Chapter 5
This chapter in a specific EIA will contain an overview of the relevant environmental issues, including a table of how the impact will be described (toetsingstabel). The issues may be calculated and quantitatively determined, or there may be a more qualitative description. In addition, a classification table is presented, describing the different levels of significance, for example from '- - - ' to '+ + + '.

Then for each environmental issue a description of the impact is given and the resulting classification. A background document is usually available to give a detailed account of how the impact will occur and all the desktop study or field data that has been used.

Specific attention to CO_2 storage in Chapter 5
For CO_2 storage projects the same approach is possible. In this study a distinction is made between impact from normal operation and possible unexpected impact, which might occur after a long period of time. For the impact under normal operational conditions the standard EIA approach will be useful. For the possible unexpected impact a risk-based approach is suggested. Chapter 7 of this study addresses how this could be done.

Possible unexpected impacts could be caused by CO_2 leakage from the reservoir. How and when is unpredictable, however it is possible to give an indication of the possible impact if leakage occurs. In that case impact could occur to groundwater, organisms living in the soil, underground construction material and also, if CO_2 enters the atmosphere, to human beings. The risk of leakage and the possible impact will be the focus of the next chapters.

6 GEOGRAPHICAL DESCRIPTION - SENSITIVITY TO CO_2 RELEASES

6.1 Introduction

As discussed in the previous chapter, there are different possible kinds of environmental impact. Impacts under normal operational conditions are predictable and can be compared to any other project. In this study the focus in the next chapter will be on the impact of unexpected situations. As mentioned in Chapter 5, this concerns especially leakage of CO_2.

In an EIA the geographical description of the study area contains all relevant local and regional information for the possible environmental impacts. In this case no specific area has been selected. Therefore the important geographical elements are described here in more general terms (Section 6.2). To determine which are relevant aspects for CO_2 storage, the focus will be on sensitivity to CO_2 concentrations. In this chapter information is given on the levels of CO_2 concentration that different groups are sensitive to and CO_2 levels in different circumstances (Section 6.4) are also described (Section 6.3).

6.2 Description of the Dutch geographical situation

6.2.1 Surface

The Netherlands is a geographically low-lying country. A remarkable aspect of the Netherlands is the flatness. Hilly landscapes can only be found in the central part, in the south-eastern tip of the country and where ice-sheets pushed up several hilly ridges such as the Hondsrug in Drenthe, the stuwwallen near Nijmegen, Salland, Twente and the Utrechtse Heuvelrug. The country can be divided into 2 areas:

- The low and flat lands in the west and north. These lands, including the reclaimed polders and river deltas, make up about half of the surface area and are less than 1 metre above sea level, with much of it actually below sea level. An extensive array of seawalls and coastal dunes protect the Netherlands from the sea, and levees and dikes along the rivers protect against flooding from rivers.
- The higher lands with minor hills in the east and south. Even this portion is mostly flat, only in the extreme south of the country there are some foothills of the Ardennes mountains. This is where Vaalserberg is located, the country's highest point at 322.7 metres above sea level.

Substantial parts of the Netherlands, for example, all of the province of Flevoland (containing the largest man-made island in the world) and large parts of Holland, have been reclaimed from the sea.

6.2.2 Land use

The Netherlands is a densely populated country, with 395 inhabitants per square kilometre - or 484 people per square kilometre if only the land area is counted, since 18.4% is water.

There are no cities with a population over 1 million in the Netherlands, but the four cities areas of Amsterdam, Rotterdam, The Hague and Utrecht can in many ways be regarded as a single conurbation, the Randstad ('rim or edge city'). The Randstad has about 7 million inhabitants and an agricultural 'green heart' (het Groene Hart). The unity of this conurbation can be illustrated by the current idea of creating a circular train system connecting the four cities. The four cities in the Randstad mentioned above are also the four largest cities. The population of the Randstad makes up more than 45% of the total Dutch population and its surface only 25% of total Dutch land area.

Other population centers of far lower numbers of inhabitants are the Brabantse stedenring, the urban population centre in Twente (Hengelo, Enschede) and the area of Meppel, Emmen and Hoogeveen.

Land use: (1996 est.) is approximately:

- arable land: 25%
- permanent crops: 3%
- permanent pastures: 25%
- forests and woodland: 8%
- other: 39%

The category ‘other’ refers to settlements and infrastructure and the percentage mentioned illustrates the density of human activities. The population density leaves little room for natural areas, which are mainly concentrated in the centre (Veluwe, Utrechtse Heuvelrug) and the eastern part of the country (Graafschap, Overijssel[76], Drenthe[77]) as well as the Waddenzee. Detailed maps with occurrence of valuable natural habitats are presented in figure 6.1. Most natural areas outside these regions are of very modest size.

Another aspect of land use in the Netherlands resulting from the high population density, but also from the fact that trade is a significant part of Dutch economy, is the high density of major infrastructural connections. These are used both for passenger and goods transport, including connection to the hinterland in mainly Germany and Belgium. The main infrastructural routes have a west to east orientation or a west to south-east orientation following the rivers Rhine and Maas or Schelde from the coastal region to the hinterland.

For the regions particularly relevant for this study - the ones containing gas fields - a more detailed description and an indicative description of the developments in land use is given below.

- ***South Holland region***
  The Delfland and IJsselmonde regions are two of the most densely populated areas in the Netherlands. Gas reservoirs in these regions are located directly under or near population centers, specifically Barendrecht, Rotterdam and Pernis, Botlek, Spijkenisse, De Lier, Monster, Delft, Maasdijk, ‘s Gravenzande, Berkel, Rijswijk and Naaldwijk. Monster is a popular resort and it lies above a gas field.

  Transportation in the region is intensive with several highways and railways, e.g. the motorway and railway line between Rotterdam and Hoek van Holland traversing areas with natural gas reservoirs beneath. There is also a high density of persons

[76] Twente, Sallland, Weerribben
[77] Dwingeler veld, Foechteler veen

working in glasshouse horticulture and in industry in the vicinity of the existing gas reservoirs.

The current development in these regions is an ongoing increase in the area occupied by housing. Tens of thousands of houses are to be built in the next decade in the region between Rotterdam and The Hague, partly at the expense of greenhouse horticulture area. It is not clear whether these expansions will be realized on top of gas reservoirs.

Valuable natural reserves and parts of the so-called ecological main structure in these regions above or near to gas reservoirs are:

- the dunes along the coast between Hoek van Holland and Monster
- probably also De Vlietlanden and Ackerdijkse Plassen.

The dune area is a Natural Protection Law Area.

- ***North-Holland region***

  Gas fields in this region are located partly underneath the Alkmaar urban district (Alkmaar, Bergen, Heiloo, Heerhugowaard) and partly in the rural area of the Beemster, Wormer and Schermer polders.

  The urban district is densely populated and part of the Dutch main infrastructure runs through it, e.g. motorway and railway from Amsterdam to Den Helder. The district will grow as a result of lack of space in the area around Amsterdam. The town of Bergen is a popular resort.

  The rural area is sparsely populated with a population density in most locations below 100 persons per km^2.

  Several gas fields are located in the vicinity of valuable natural reserves:
  - Gas fields under the dunes near Alkmaar are in a Natural Protection Law Area
  - The gas field of Middelie is located in the vicinity of a Habitat guideline area and a Bird guideline area.

- ***Twente***

  In the Twente natural gas system area only a few population centres are located e.g. Oldenzaal, Tubbergen and Denekamp. Population density outside these centres is low, often below 25 persons per km^2.

  The rural countryside contains a number of sizeable ecological main structure area and Habitat guideline areas that coincide with locations of natural gas fields e.g.: the Springendal nature reserve.

  In the more rural areas area planning is primarily aimed at conservation and restoration of valuable landscapes.

- ***South-east Drenthe region***

  Gas fields in this region are located around towns such as Meppel, Hoogeveen, Emmen and Coevorden. The population of the countryside between Meppel and Hoogeveen is moderately dense and the main infrastructure consists of a railway and a motorway between both towns. The area around Emmen and Coevorden is less densely populated with many areas having a population density of less than 25 persons per km^2. Development in the area is further intensification of housing, industrial activities and transportation since these four towns are the centres of focus for economic development of the region.

The area around Coevorden and Emmen is also a major recreational concentration area because of the beauty of the landscape. The area between Meppel and Hoogeveen and between Hoogeveen and Emmen also contains a significant number of locations that are part of the Ecological main structure or are classified as Habitat or Bird life guideline areas.

In the more rural areas, planning is primarily aimed at improvement of agricultural structure (land consolidation a.o.) and in the vicinity of Hardenberg on intensification of agriculture.

- ***North Drenthe, Friesland and parts of Groningen***
  In this region too, a number of gas fields is situated in the vicinity of urban centers, such as Assen, Leeuwarden, Drachten, Sneek and Harlingen. Main infrastructure crosses areas with gasfields, e.g. the A31, A7 and A32 motorways and the railway from Groningen via Leeuwarden to Harlingen. Recreational activities are limited, except in the vicinity of Assen. Valuable nature reserves (Habitat and Bird life guideline reservoirs) are located in the vicinity of Leeuwarden, near Bergum, gas storage facility Norg, Assen and Lauwersmeer. Planning for this region varies from location to location, between conservation or restoration of valuable landscapes and improving agriculture.

6.2.3 The Dutch atmosphere[78]

The relevance of the atmosphere lies in the potential distribution and dilution of CO_2, if it escapes from a storage reservoir. The Dutch atmosphere is very much part of the North Atlantic meteorological zone and is significantly influenced by the vicinity of the North Sea. Wind direction is (increasingly) primarily south-west in the colder half of the year, resulting in mild winters and springs (see Figure 6.2). In the warmer part of the year (May - October) the wind direction is south-east (inland wind) approximately 45% of the time and more westerly orientated in the rest of the period.

[78] Sources: http://www.gewiekste.nl/MolenOntw_Alg.htm http://www.pyrosolar.nl/html/rekenvoorbeeld.html http://www.knmi.nl/kenniscentrum/de_toestand_van_het_klimaat_in_Nederland_1999/waarnemingen.html#Windrichting

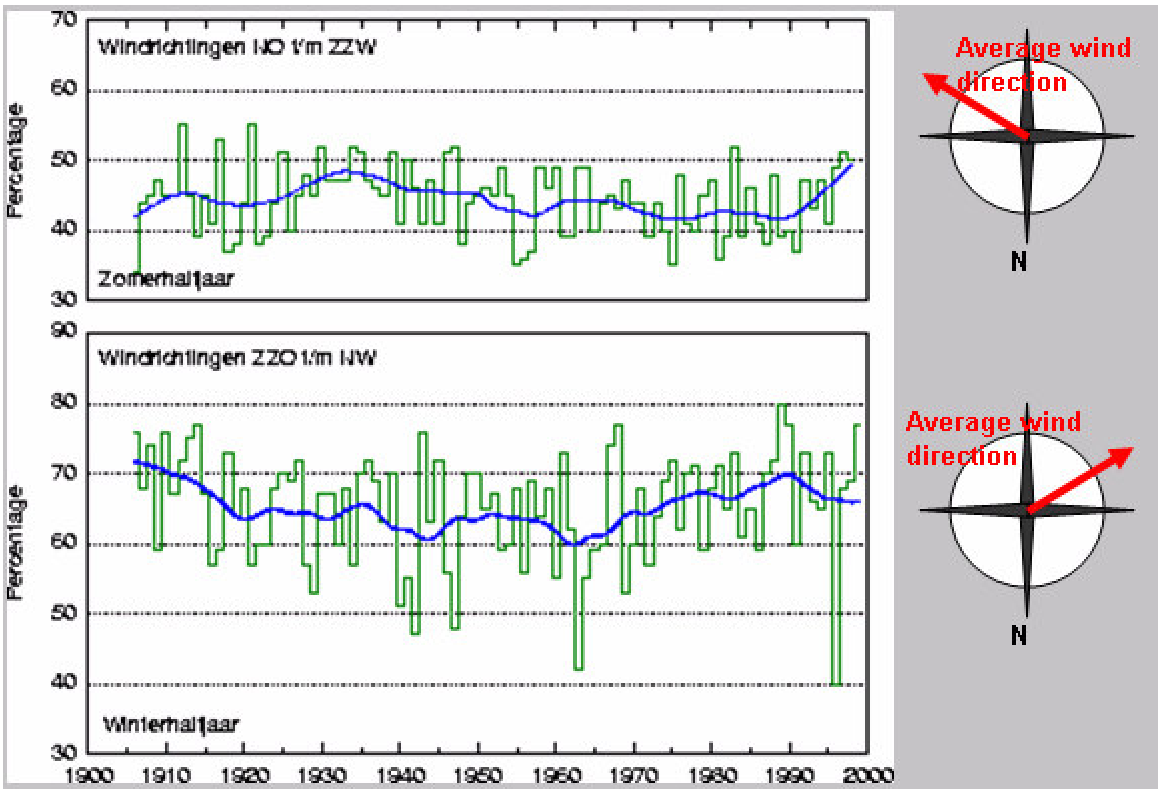


Figure 6.2 Average yearly wind velocities at 10 metres height for the period 1971-2000

Wind speed is lowest 2 to 3 hours after sunrise and strongest 3 to 4 hours after the sun reaches its summit. Wind speed at lower levels can be estimated using the relation:

$$V_{height\ x} = \frac{\ln\left(\frac{60}{0{,}03}\right)}{\ln\left(\frac{60}{R}\right)} \cdot \frac{\ln\left(\frac{height\ x}{R}\right)}{\ln\left(\frac{10}{0{,}03}\right)} \cdot V_{height=10\,meters}$$

In which R is the roughness factor, representing the friction wind experiences from the landscape at the considered location.

Table 6.1 An overview of roughness factors

Roughness factor	Description of landscape
0.001	Ice, open sea or lake
0.03	Pasture/grassland, large open area
0.2	Open landscape with trees, hedges, few buildings
0.25	Rough landscape
0.5	Village centre
1	Cities, woods
2	City centre with many high buildings

Application of the relation, roughness factor values and average wind speeds for the provinces with gas fields indicates that in most of Groningen, Drenthe and Overijssel average wind speed at a level of 1.5 meters above ground is lower than 1 m/s in villages and more intensely built-up areas or woods (see Figure 6.3).

The lowest part of the atmosphere is referred to as the planetary boundary layer (PBL) and its behaviour is directly influenced by its contact with the surface. The layer is typically several hundreds of meters thick during the day at the latitudes of the Netherlands, but shrinks during night-time because of cooling of the atmosphere. Because of the friction of the earth's surface the layer is turbulent by nature and because of the turbulence the layer is almost homogeneously mixed during daytime.

Exchange fluxes with the overlying free troposphere are good during daytime, but may be almost negligible during night-time in the case of a temperature inversion. Normally the temperature of PBL is higher than that of the free troposphere and fluxes go upwards because of this gradient. Under certain conditions the normal vertical temperature gradient is inverted such that the air is colder near the surface of the Earth.

In this case there is no transport of substances from PBL upwards into the overlying free atmosphere and substances released in the PBL accumulate there. An inversion can occur when, for example, a warmer, less dense air mass moves over a cooler, more dense air mass. This type of inversion occurs in the vicinity of warm fronts, and also in areas of oceanic upwelling such as along the coast. The effects of inversion on CO_2 concentrations in the atmosphere will be discussed in Section 6.3.

Rising smoke forms a ceiling over a valley due to a temperature inversion. The smoke rises up to the boundary between Planetary Boundary Layer and overlying air layer and subsequently disperses horizontally

6.2.4 Current and future use of the subsurface

Use of the subsurface takes many forms and there may be concerns about different applications at the same depth (see Figure 6.4).

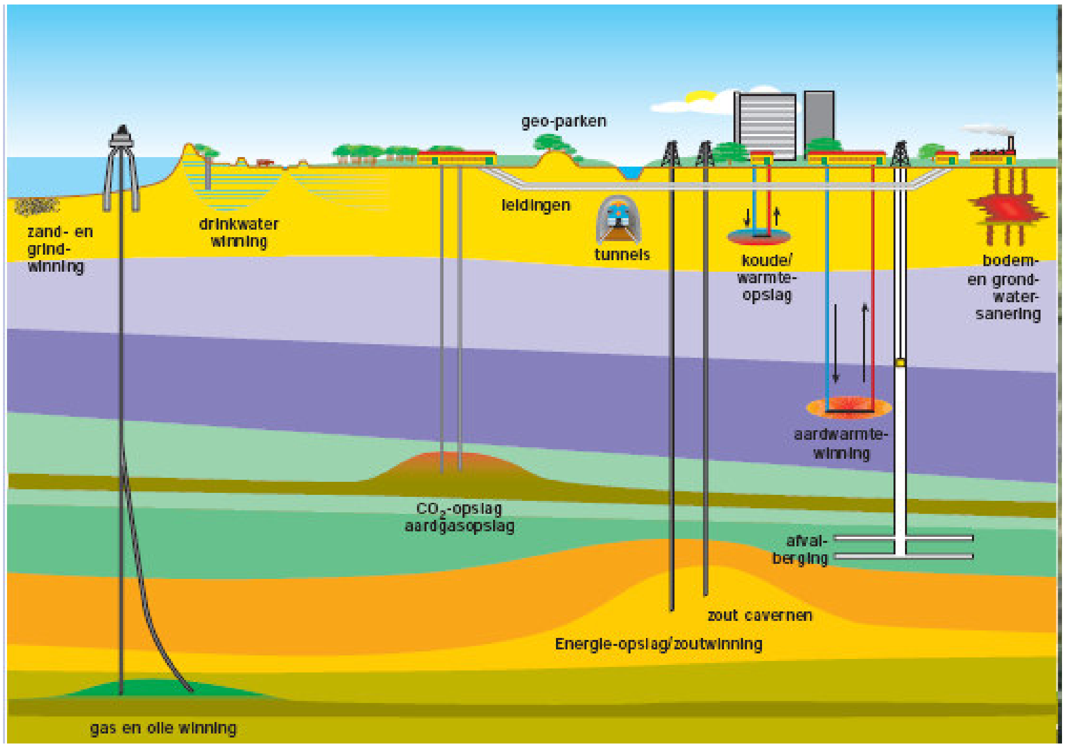


Figure 6.4 Schematic visualisation of different use of the subsurface (vertical and horizontal scales are different)

Shallow subsurface

In the top layer a network of cables, sewers and pipelines is present, especially in built-up areas. Positioning of older local distribution pipelines and cables is not always known since mapping was not a priority several decades ago and probably still is not[79]. The shallow subsurface in inner cities is also used for car parks and road or tram and train tunnels. A relative new phenomena is the construction of subsurface shopping malls such as ' de koopgoot' and 'de groen passage' in Rotterdam.

A common perception is that use of the shallow subsurface will intensify because of the low availability of room above ground. TNO-NITG estimates the value of the Dutch subsurface for construction and infrastructure for transport at a gross 40 billion € for the next 50 years[80]. At present there is no vision document, scenario study or policy concerning future use of the shallow subsurface for construction and infrastructure. However the Min. of VROM is developing a vision document for the Dutch underground. The AMESCO study will be used to complete this underground vision document.

[79] See for example 'Beleidsverkenning Duurzaam Gebruik Ondergrond'

[80] See 'Vooruitblik op een duurzaam gebruik van de ondergrond van Nederland voor de komende 50 jaar', http://www.nitg.tno.nl/ned/pubrels/jaarv2002/jv2002nl2.pdf

Use of tunnels or subsurface infrastructure (both railway and road) is applied increasingly as a mitigation measure for reduction of the impact of infrastructure on its surroundings. Examples are the part of the A27 highway near Amelisweerd, Utrecht and part of the 'Betuwelijn' railway in the Alblasserwaard.

Another use of the shallow subsurface is the use of raw materials, such as:

- sand for construction, concrete and sand-lime bricks;
- gravel for construction and concrete;
- clay for ceramic products;
- groundwater for drinking water production, cooling water or process water in industrial applications or irrigation water in agriculture.

Groundwater

Groundwater is extracted from depths up to 50 meters (see figure 6.5). However, in the south of the Netherlands potable groundwater aquifers are present at depths of up to 400 meters (IWACO, 1994)[81]. It is not clear if potable water is produced from these deep aquifers. Total consumption amounts to 0.8 billion m^3, compared to an annual natural influx of 2.6 billion m^3 and a reserve of 800 billion m^3.

The shallow groundwater aquifers are also and increasingly used for storage of warm and cold water. Presently 600 open and an unknown number of closed systems are applied, storing warm and/or cold water at depths of typically between 20 and 250 meters and containing an energy content of up to 2 PJ. Although not explicitly defined in any policy, on the 'milieucentraal' website a goal for 2020 of 15 PJ is mentioned[82].

Deep subsurface - supplier for raw materials

The deep subsurface (below 500 meters) is at present a supplier of raw materials (salts) and fuels (oil, gas). Salts (NaCl, $MgCl_2$) are produced in the provinces of Overijssel, Drenthe, Friesland and Groningen from depths of 1,500 meters for $MgCl_2$ and 2,500-3,000 meters for rock salt in Friesland and at only several hundreds of meters in Twente in Overijssel. Production amounts to 3.6 Mton per year, of which approximately 0.3 Mton is $MgCl_2$.

Natural gas is produced from depths of 1,000-4,000 meters at an annual rate (onshore) of approximately 40 billion Sm^3/year. Total remaining onshore reserves are estimated at approximately 1,200 billion Sm^3. Onshore oil production is negligible at the moment, but will increase if oil production is resumed at the Schoonebeek oilfield.

Deep subsurface - storage of natural gas

The deep subsurface is currently also used for natural gas storage in Alkmaar, Norg and Grijpskerk and new storage facilities are planned or under construction in Zuidwending and Waalwijk. Except for Zuidwending, all storage facilities are depleted gas fields transformed into storage reservoirs. The Zuidwending facility is a peak-lopping facility based on salt caverns.

[81] S. Seinen et al; 'CO2-verwijdering: milieu aspecten'; IWACO, 's Hertogenbosch, juli 1994.
[82] See: http://www.milieucentraal.nl/pagina?onderwerp=Energieopslag-MC

Deep subsurface - storage of residual water flows

A third application is permanent storage of residual water flows from oil production making use of depleted gas fields in Groningen, Drenthe and planned in Overijssel.

Both storage of natural gas and residual water flows in deep subsurface compete with the CO_2-storage in depleted gas fields considered in this study.

There are also ambitions for geothermal energy production from deep aquifers (1,000-4,000 meters). Scenarios estimate 30-300 installations producing 3-30 PJ of heat for space heating[83]. Since the target is aquifers, there is little possibility of competition with CO_2-storage in gas fields. Most likely locations for realisation are in the north of the Netherlands where the warmest aquifers are located, as shown in figure 6.6.

6.3 CO_2 levels in the biosphere

6.3.1 Atmospheric levels, levels in air

Average atmospheric concentrations

CO_2 is a gaseous component of the earth's atmosphere with an average residence time in the atmosphere of 100 years. Because of its long residence time and its chemical relative inactivity most of the CO_2 emitted at the earth's surface from natural and anthropogenic sources is transported upwards into the free troposphere and higher atmospheric layers and distributed equally among these layers and around the globe. The above means that CCS in the Netherlands is as effective in mitigating greenhouse gas emissions in the Netherlands as it is in China.

The distribution of CO_2 can also be illustrated by the annual average column CO_2 concentration as determined by the Carbon Tracker program[84]. The graph (figure 6.7) concerns data for 2005 and shows the average CO_2 concentration (in ppmv) in a column of the lowest 100 kilometres of the atmosphere. The fact that the variation in values is only 4 ppmv (part per million in volume, 0.0001 vol%) underlines the almost uniform distribution of CO_2 in the atmosphere. Regions with high anthropogenic emissions (USA East coast, Europe, South-East Asia) show slightly higher average concentrations.

[83] Smart Energy Mix, presentation by Victor van Heekeren, Platform Geothermie
[84] http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/maps.php?type=glb&prod=columns

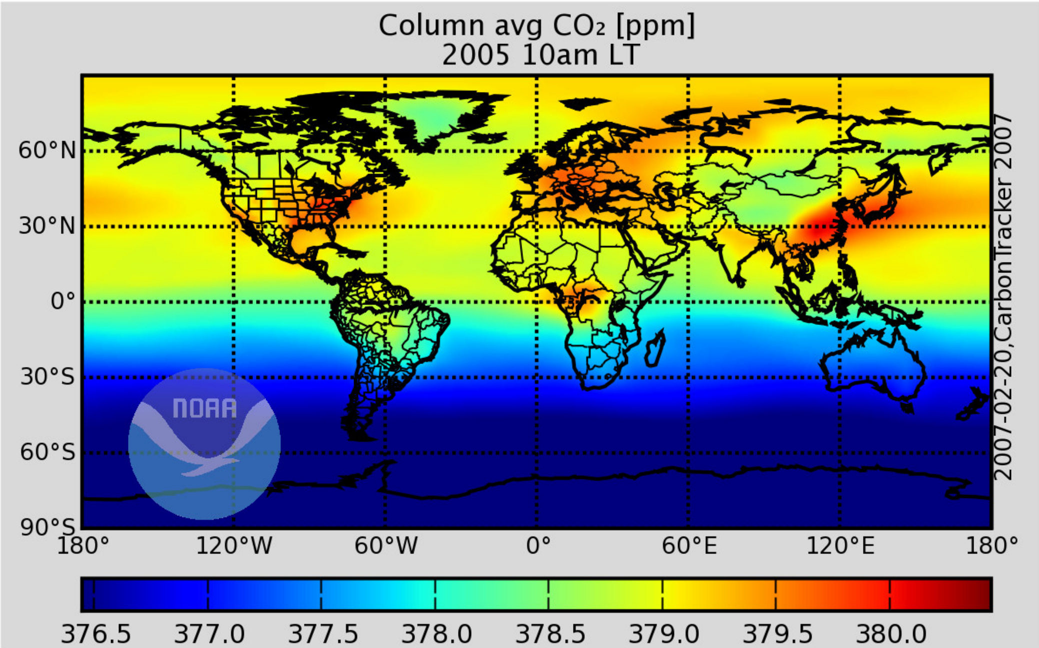


Figure 6.7 The average CO_2 concentration (in ppmv) in a column of the lowest 100 kilometres of the atmosphere[85]

There are modest concentration fluctuations in the hemisphere and especially in the PBL (planetary boundary layer). Atmospheric concentrations in the PBL vary during the day by several tens of ppmv because of absorption of CO_2 by plants during daytime and emission of CO_2 by vegetation during the night-time. An example of CO_2 concentration fluctuations in a pine forest as function of height (vertical axis) and time of the day (horizontal axis)[86] is shown in Figure 6.8. Temperature inversion can result in limited accumulation of CO_2 in the PBL up to levels of 500-600 ppmv (0.05 vol% - 0.06 vol%) with low wind velocities[87].

In uneven terrain such as exists in the most southern part of the Netherlands, but also in several regions in the Netherlands with gas fields (Twente, dune zone in Zuid-Holland and Noord-Holland) the possibility of inversion and accumulation is higher due to the roughness of the terrain.

[85] http://en.wikipedia.org/wiki/Carbon_dioxide
[86] http://www.lenntech.com/stoffen-test.htm
[87] Oral information from Fred Bosveld (KNMI) and Alex Vermeulen (ECN)

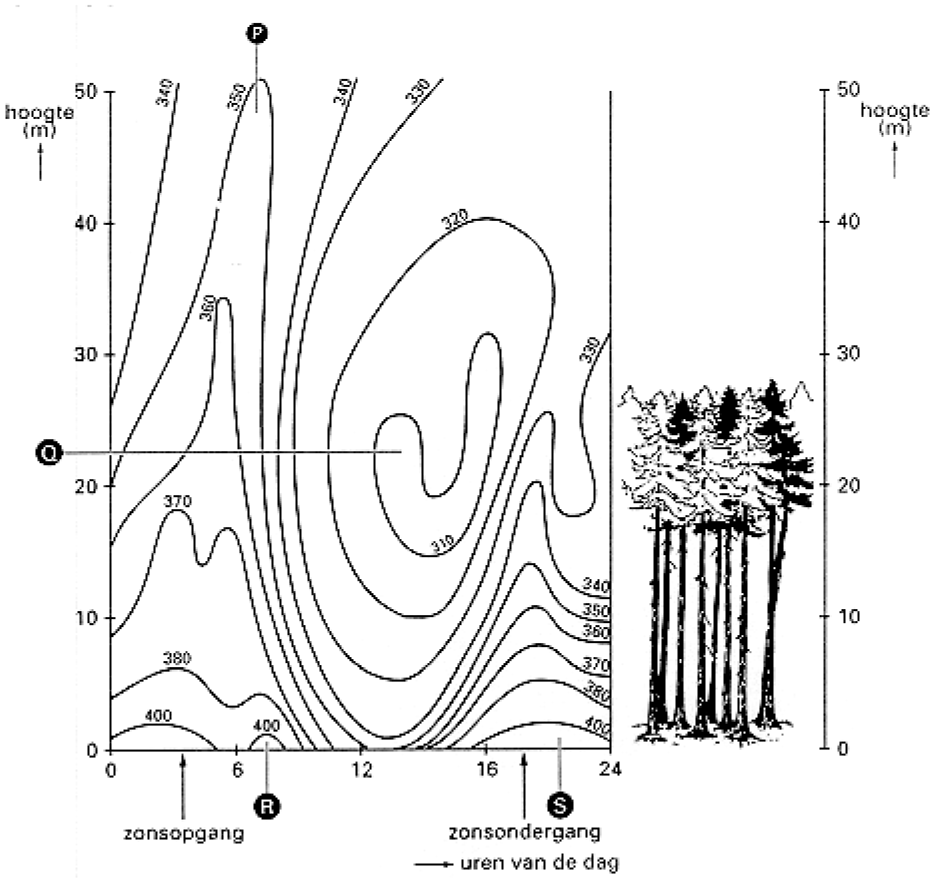


Figure 6.8 CO_2 concentration fluctuations in a pine forest as function of height (vertical axis) and time of the day (horizontal axis)

There is also an annual variation in atmospheric concentration because the northern hemisphere contains more vegetation than the southern hemisphere. The result is that in the northern hemisphere growing season more CO_2 is taken up by vegetation in the northern hemisphere than is released by vegetation in the southern hemisphere, where it is autumn and winter.

The net annual fluctuation is approximately 6 ppmv (part per million in volume, 0.0001 vol%). However, exposure levels may be significantly higher than the average, both due to emissions from natural sources and emissions from anthropogenic sources.

Increased atmospheric concentrations

For comparison with exposure levels related to possible CO_2 leakage from reservoirs, an inventory of exposure levels for anthropogenic CO_2 - emitted in connection with human-related activities - in confined spaces can be used. In these activities CO_2 is produced by respiration (office, airplane cabin, school, submarine), combustion of fuels (horticulture, tunnel) or anaerobic conversion of organic material (beer cellar). In the figure 6.9 the full range of measured concentration levels is given for the considered confined spaces.

In most spaces CO_2 concentration will initially be comparable to atmospheric concentration level prior to any activity taking place in them but the concentration will eventually accumulate to the maximum levels given in the figure due to limited ventilation. The two exceptions (tunnel and horticulture) concern spaces in which activities do not stop.

Figure 6.9 shows that most humans will be used to higher then average concentrations up to 2,000 or 2,500 ppm. In extreme situations concentrations of up to 11,000 ppm are possible.

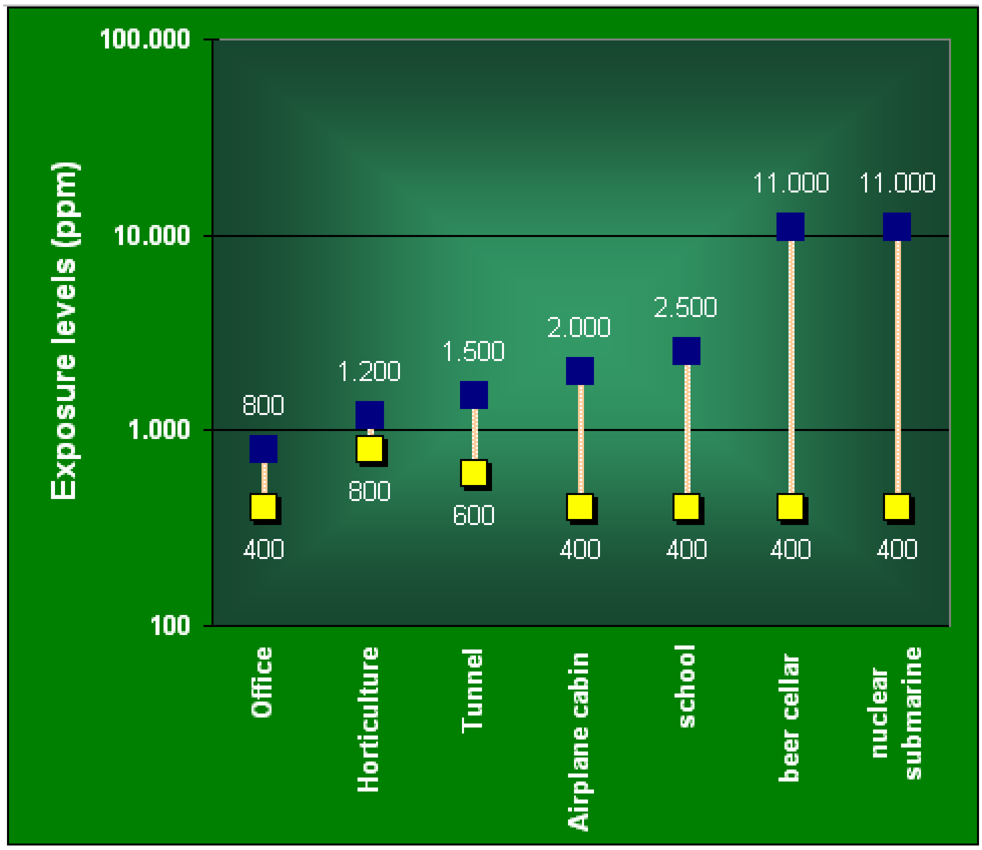


Figure 6.9 Exposure levels for anthropogenic CO_2 from various human activities

Extreme natural releases

Exposure to CO_2 from natural sources is related to volcanic activities or systems, or to spontaneous releases from natural reservoirs in sedimentary basins. Volcanic events or systems will probably not occur in the Netherlands given the limited geological activity of the subsurface. Releases of CO_2 from such systems or events and the subsequent exposure to CO_2 does however give an indication of the relation between size and speed of fluxes and exposure levels - if the situation is comparable with that in the Netherlands - and for that reason information concerning these 'un-Dutch' situations has been included. Releases from reservoirs in sedimentary basins would not be unrealistic in the Netherlands, where several gas accumulations exist with very high concentrations of CO_2.

Exposure to CO_2 due to large releases from CCS storage facilities could occur in case of a so-called well blow-out or in case of acute releases of shallow subsurface accumulation of CO_2 that escaped from the storage reservoir (see Chapter 7). An indication of emission rates from well blow-outs during injection can be derived from CO_2 well blow-outs related to oil and gas exploration. An example is the Crystal Geyser in Utah, USA. It developed from an oil exploration well drilled in the nineteen thirties that proved to be in connection with CO_2 charged water. Emission rates from the bore hole are estimated at 220-500 ton CO_2 /day.

Table 6.2 Characteristics of model simulations and natural geothermal systems and reservoirs in sedimentary basins (IPCC, 2005), (Lewicki, 2005)

	Diffuse release fluxes (g/m²/day)			max soil vol% CO_2	pathway for leakage	type of release	Fatalities?
	average	maximum	ref flux				
Solfatara crater, Italy	1,500	75,000			faults and fractures	diffuse and vent	No
Albani hills, Italy	1,164			93%			Yes
Poggio dell'Ulivo, Italy		22,000			faults and fractures		No
Poas volcano, Costa Rica		140		16%			No
Arenal volcano, Costa Rica		290		7%			No
Oldoinyo Lengia volcano, Tanzania		1,350		90%			?
Yellowstone	90	30,000		90%			No
Dixie Valley, USA		570	7				No
Mammoth mountain, USA	1500 - 2100	> 10,000	25	90%	faults and fractures	vast, diffuse, vent and sping	Yes
Shrub mud volcano, USA	400	5,600	10	25%	faults and fractures		No
Miyakejima volcano, Japan		18,150					?
Laacher See, Germany	4				lake turnover	diffuse	No
Mátraderecske, Hungary	300	1,700			faults and fractures	diffuse, vent and sping	Yes

Eruption
An indication of exposure levels can also be derived from the experiences at Crystal Geyser. Measurements in the area surrounding the geyser indicate that during eruptions background CO_2 concentrations are reached within 25-100 metres from the eruption point. Because of the eruptive nature of the release, concentrations are below human health and safety concerns within a few metres of the geyser. Since the geyser emits pressurised CO_2 from a standard borehole the exposure levels are comparable to possible emissions from CO_2 storage facilities.

Slower releases
In case of slower releases, such as from faults, exposure levels or concentrations in air depend significantly on the receiving space. This can be illustrated by fluxes and fatalities found for geothermal systems and sedimentary reservoirs around the world. Experiences at the Azores, Mammoth Mountain, Albani Hills and Mátraderecske show that CO_2 can accumulate in unventilated confined spaces, such as cellars and kitchen cupboards, pits and snow caves up to harmful levels, even at limited fluxes of several hundreds of ppm. Even in the Mátraderecske area with its relatively low emission flux fatalities have occurred from accumulation in basements.

On the other hand, in case of emission to well-ventilated spaces or to free air, the emitted CO_2 is dispersed by the wind and exposure levels remain below harmful levels. This effect can, for example, be found in geothermal areas in Italy where local residents tend to keep the doors and windows of their houses open for ventilation and fatalities have never occurred despite the relatively high average emission flux.

Emissions from leaking gas fields applied for CO_2 storage may be comparable with natural emissions from leaking natural CO_2 gas fields and geothermal systems.

In de TS IPCC report some figures of emissions are given. It is stated that a fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years.

It is also concluded in this report that to make such impermanent storage valuable for mitigation of climate change, a fraction retained in the order of 90-99% for 100 years or 60 – 95% for 500 years is sufficient.

As mentioned, the expected maximum amount of the stored CO_2 leaking into overlying layers amounts to 1% for a period of 100 years. Given the fact that on average Dutch gas fields can store 10-100 Mton of CO_2 and assuming that all of the leaked CO_2 reaches the surface this would result in an average emission of:

- 0.1-1 Mton in a period 100 years;
- 1,000-10,000 ton per year during a period of 100 years.

Such emission rates are smaller than or at most comparable to emissions from natural systems, which are often in the range of tens of kilotonnes per year.

6.3.2 CO_2 in surface water, groundwater and soil

CO_2 is present in surface water and groundwater both dissolved and as bicarbonate and carbonate. In natural systems alkalinity (concentration of calcium and magnesium), pH and CO_2 concentration/bicarbonate concentration are in chemical equilibrium with each other. The distribution of CO_2 between CO_2 and bicarbonate is determined by pH with all inorganic carbon present as CO_2 at pH = 4.2 or less and as bicarbonate at pH = 8.4 or higher. Alkalinity is approximately linear with bicarbonate concentration. The distribution of inorganic carbon between bicarbonate and CO_2, the concentration of inorganic carbon and pH determine the aquatic vegetation and sorts of fish and other organisms present. CO_2 concentrations can amount to several hundreds of mg/liter in low pH and anaerobic waters, such as exist in areas with peat soil.

In deep layers the concentration in formation water at depths of 2,000-4,000 meters depends on the chemical composition of the base rock. In formation water in Rijswijk and formation sandstone under De Lier, for example, the bicarbonate concentration is in the range of tens of milligrams per liter. Formation water in Borgsweer and Schoonebeek contain 100 and approximately 750 mg/l of bicarbonate respectively.

Concentrations of CO_2 in soil air are higher than atmospheric concentrations, ranging from 0.2 vol% to up to 4 vol%, depending on time of the day and season.

Vegetation produces CO_2 itself in the soil via ‘respiration’ through the roots and from decomposition of organic material in the soil. The CO_2 flux from plants and decomposing materials amounts to approximately 25% of gross biomass production and natural fluxes amount to 10-25 g/m^2/day.

6.4 Sensitivity to CO_2

Exposure to CO_2 can result in adverse health effects to all life forms in the biosphere (vegetation, mammals, birds, fish, insects). As indicated in the previous section the concentration can vary in natural circumstances from 370 ppm (0.037 vol%) on average to 2500 ppm (0.25 vol%) or even 11,000 ppm (1.1 vol%). The maximum level for a working environment in the Netherlands is 5000 ppm (MAC level is 0.5 vol%).

In this section an overview is given of the sensitivity of:

- different types of organisms;
- (construction) material;
- soil and groundwater in subsurface layers.

CO_2 in itself is not classified as a toxic substance. However, exposure can result in adverse effects.

Humans and animals are sensitive to even short periods of elevated levels of CO_2, humans and fish more than mammals and birds. In the most extreme cases, e.g. being exposed to clouds of pure CO_2, death occurs rapidly.

Plants can tolerate short periods of high concentration levels but die when exposed for periods of several days. Adverse effects in this case are not so much related to air concentrations as to elevated concentrations of CO_2 in the soil.
For plants, insects and burrowers concentration levels in the case of chronic exposure will be much higher than for humans and larger mammals as CO_2 is denser than air and accumulates in the soil gas. Effects of CO_2 leakage from reservoirs will therefore be more severe for these organisms.

6.4.1 Toxic effects for humans

For humans tolerance levels and toxic effects are mentioned in several literature sources[88] with some typical values shown in Figure 6.10.

[88] see chapter 14

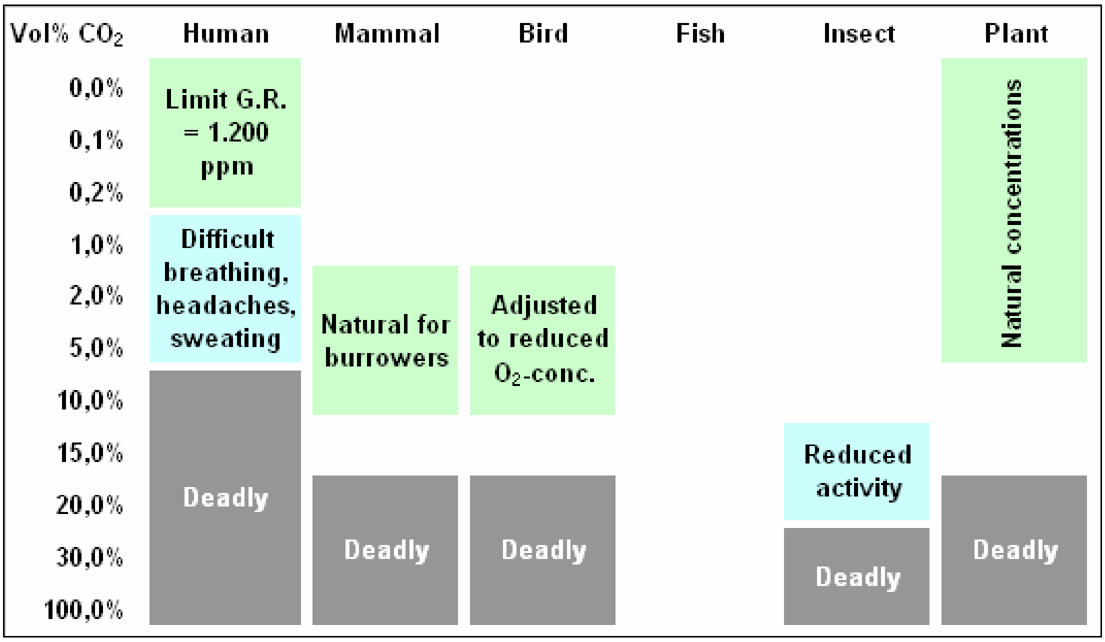


Figure 6.10 Human tolerance levels, impacts from acute exposure as a function of concentration[89]

Maximum allowable levels in working environments are given in Table 6.3.

Table 6.3 Maximum CO_2-concentrations allowed in working environments

Country/ Institution	Level %	Level mg m^{-3}	Averaging Period
EU	0.5	9,000	8 hour TWA
UK	1.5	274,000	15 min
	0.5	9,150	8 hour TWA
USA	3	540,000	15 min
	>0.5	9,000	8 hour TWA
	0.5	9,000	10 hour TWA

http://www.truthout.org/issues_06/071106EC.shtml

In Table 6.3 a distinction has been made for a short period of time (until 15 minutes) and a more continuous situation (8 hours). In Europe as in the UK and USA a level of 0.5% is the maximum for the continuous situation. For a period of 15 minutes UK legislation allows 1.5%, while in the USA the level is 3 vol%.

6.4.2 Toxic effects for other organisms

Mammals
The sensitivity of mammals depends on the species. Burrowers, inhabiting tunnels, expose themselves to CO_2 levels of 2 vol% - 9 vol% without adverse effects and concentrations in dens of hibernating animals can even amount to 13 vol%.

Insects
Insects become paralysed at concentrations between 20 vol% and 50 vol%.

89 G.R. = Gezondheidsraad, Dutch national Health Council http://www.gr.nl/index.php?phpLang=en.

Birds

For birds no exposure limits were found, however in (IPCC, 2005) the indication is given that birds can far more easily sustain high CO_2 levels and reduced O_2 levels compared to humans because of their ability to produce high energy output at reduced O_2 concentrations during flight at altitude.

Vegetation

Because roots are exposed in natural conditions to elevated CO_2 vegetation is somewhat less sensitive to exposure to increased CO_2 concentrations than humans and other mammals. However, long-term exposure to concentrations higher than 5 vol% can cause retardation of vegetation. Long-term exposure to concentrations higher than 20% causes die off through phytotoxic effects and root hypoxia.

Seepages of CO_2 from CO_2 reservoirs are likely to cause damage to vegetation at the location the CO_2 reaches the surface. Since CO_2 is heavier than air it tends to accumulate in the soil at the point of emission.

In theory, vegetation production is increased by increasing concentrations of CO_2. But this is only true in the case of sufficient nitrogen in the soil and if the concentration increase is limited, as is indicated by the slightly increased level applied in greenhouses. Upward fluxes from CO_2 storage reservoirs might result in significantly elevated concentrations in the vadose zone, as indicated by modelled soil concentration values. Even relatively moderate increases compared to the natural flux - such as the maximum fluxes measured in Costa Rica - result in doubling or quadrupling of the soil concentration and exceeding the limit of 5 vol%. Increase is high even at these moderate fluxes because of the limited exchange of air in soil with the atmosphere. This means that little air is introduced into the soil so that the upward CO_2 flux is not diluted. This mechanism is illustrated by model simulations conducted by Oldenburger et al (Oldenburger, 2004).

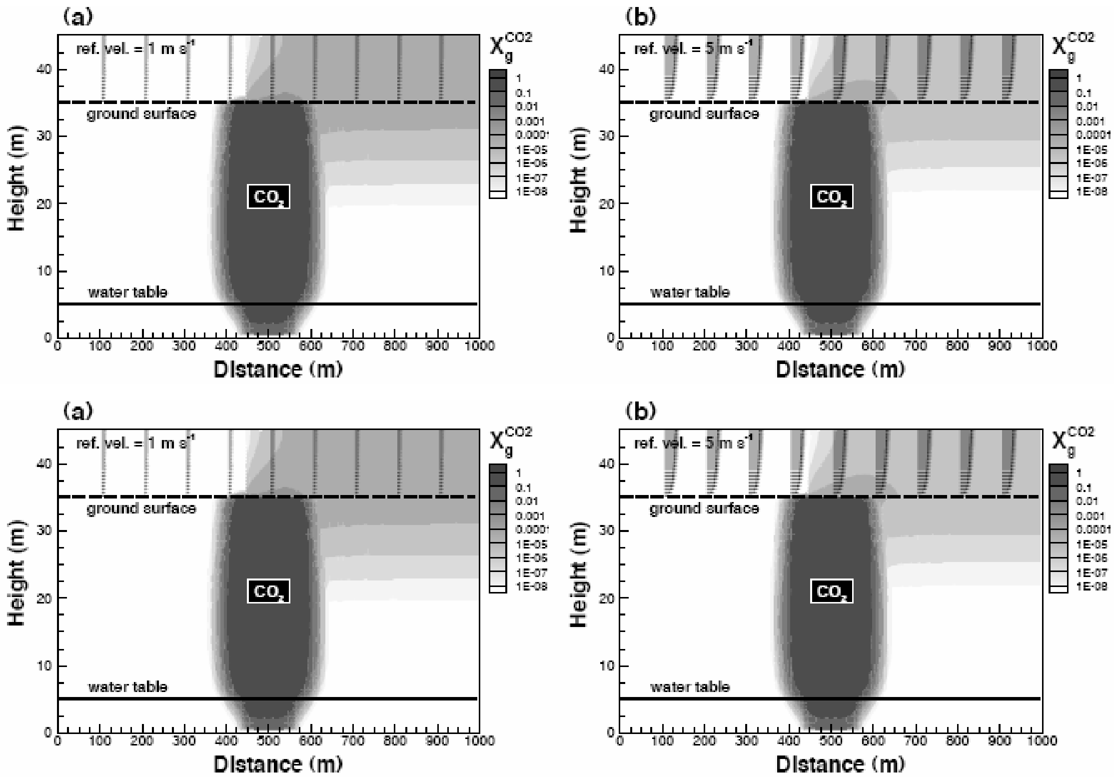


Figure 6.11 Exposure levels (mol fraction CO_2) for a diffuse 1,100 g/d/m^2 CO_2 emissions from an 100 x 100 metres area at an average wind speed of 1 m/s (a) and 5 m/s (b) – from (Oldenburg, 2004). Emissions amount to 11 ton/day and 4,100 ton/year for the entire emitting surface

Figure 6.11 also illustrates the principal mechanism of distribution of diffuse emissions in vadose zone and atmosphere. Due to limited exchange with the atmosphere, soil CO_2 concentrations will increase dramatically from average values of <1 - 5vol% up to 95%. In the atmosphere however, emitted CO_2 is quickly mixed and diluted with ambient air, even at a relatively low wind speed of 1 m/s. In (Oldenburger, 2004) maximum mol fraction from emitted CO_2 in ambient air flowing over the emission zone of 100 x 100 metres at a wind speed of only 1 m/s is 0,1 vol% - 0,01 vol%, corresponding to a maximum concentration of approximately 60 - 70 ppm. Concentration quickly reduces to 0.01 vol% - 0.001 vol% within a few metres from the emission area. In case of maximum release rates of up to 50.000 g/d/m^2 the atmospheric concentration will – in case of linearity with flux – amount to a maximum concentration of 5 vol% - 0,5 vol%.

Fish

Fish in potable aquatic environments seem sensitive to CO_2 dissolved in water. Lethal concentrations mentioned for some species are:

- 140-150 mg/l for perch;
- 190-230 mg/l for roach.

Small increases in CO_2 concentration in water make fish significantly more vulnerable to pH decreases. A combination of low pH (4.5-5.5) and elevated CO_2 concentration (>20 mg/l) is deadly for perch.

6.4.3 Impact on (construction) materials

Increased CO_2 /HCO_3/CO_3 levels in groundwater and resulting lowering of pH will result in deterioration of materials quality. Primarily affected are corrodible metals (e.g. steel) and products containing portland cement such as concrete.

Steel will corrode as a result of acid attack and this results from the exchange of electrons between originally electrically neutral iron and the hydrogen ions resulting from dissolved CO_2 conversion to carbonic acid.

Corrosion is a familiar phenomena in oil and gas production and is mitigated by applying oxygen scavengers, corrosion inhibitors, lining of surfaces with unreactive materials (e.g. certain plastics) and by applying good quality steels, for example steel containing several percent of Cr formed in such a way that a very dense microstructure results.

The primary effect of any type of acid attack on concrete is the dissolution of the cement paste matrix. Free carbon dioxide can dissolve calcium carbonate. Water containing CO_2 acts by acid reaction and can attack concrete and other portland cement products whether they are carbonated or not [90]. In concrete with siliceous gravel, granite or basalt aggregate, the surface attack will produce an 'exposed aggregate' appearance. However, in concrete with limestone (calcium carbonate) aggregates, the aggregate may dissolve at a rate similar to that of the cement paste and leave a smoother surface. There are several other negative carbonation reactions. Craze cracking at concrete surfaces is enhanced (particularly at high water-cement ratios) because of the piggybacking of carbonation shrinkage onto normal drying shrinkage. Also, if the carbonation front reaches embedded steel, the steel can corrode. Good concrete design and construction requires steel to be located deeply enough to ensure the carbonation front will not reach it during a structure's expected lifetime[91].

The positive effects of carbonation are seldom mentioned. For instance, carbonation usually strengthens concrete surfaces, increases wear resistance, and makes it less permeable. The rate of attack depends more on the rate of water movement over the surface and on the quality of the concrete, than on the type of cement or aggregate:

- Acidic groundwater that is not mobile appears to have little effect on buried concrete.
- Mildly acidic (pH above 5.5) mobile water will attack concrete significantly, but the rate of attack will be generally slow, particularly if the acids are primarily organic in origin.
- Flowing acidic water may cause rapid deterioration of concrete, therefore high quality concrete is needed[92]

The exact level of deterioration is difficult to predict and the mechanisms resulting in materials deterioration are not always well understood or predictable - see also deterioration of casing and cementing of injection wells (discussed in Chapter 7). The level and speed of deterioration also depends on factors as product composition - e.g. quality of steel and alkalinity of concrete. Some indications can however be given. According to http://www.ocpa.com/manual/perform_frame.htm lowering of pH from 7 to 4 will result in a 10 times higher deterioration speed.

90 http://www.cement.org/tech/cct_dur_acid.asp
91 http://www.encyclopedia.com/doc/1G1-121280315.html
92 http://projects.bre.co.uk/sd1/pdf/PartBv6.pdf

6.4.4 Effect on groundwater and surface water

Groundwater and surface water composition and quality may alter as a result of even small fluxes of CO_2 to the biosphere (IPCC, 2005). CO_2 influx in groundwater and surface water will result in lower pH due to the formation of carbonic acid.

In areas with natural CO_2 seepage low pH water can leach toxic minerals from rock or soil. Acidification of groundwater may result in:

- Decreased biological availability of phosphorous, magnesium, molybdenum.
- Increased washout of potassium and calcium.
- Excessive concentrations of manganese, aluminium and iron ions.
- Reduced microbiological activity.

These impacts will in turn result in reduced productivity of vegetation and crops. Areas with clay or peat soil are generally less sensitive to these effects due to the buffering capacity of the soil. This is illustrated by the higher sensitivity of sandy soils to atmospheric deposition of acidifying compounds.

In surface water acidification will result in increased ecological pressure on fish, vegetation and other organisms.

The fact that even very small influxes can have a significant effect on water quality can be illustrated by the facts that:

- Natural concentrations in surface water and groundwater are several hundreds of mg/liter at most;
- Potable water bodies in the first water containing layer in the shallow subsurface have a thickness of 20-60 meters and a current of 5-20 meters/year

This means that - assuming a thickness of 50 meters and an average current of 12 m/year - an influx of approximately 400 g/m^2/day will result in exceeding the CO_2 limit of 250 mg/liter for fish (not taking into account buffering effects from bicarbonate - CO_2 - Ca equilibrium).

Deterioration of the quality of groundwater does not necessarily mean that it will no longer be suitable for production of drinking water. Groundwater in areas with high diffuse emission fluxes from geothermal systems is often still potable (IPCC, 2005). Secondly, drinking water production facilities already apply several different water cleaning technologies, such as reverse osmosis. Quality deterioration will however make drinking water production more expensive.

Deeper lying potable aquifers that are connected to leaking CO_2 reservoirs in sedimentary basins show increased bicarbonate concentrations of several hundreds of mg/liter and produce sparkling water from carbonated springs. Many of these carbonated springs are exploited by the sparkling mineral waters industry (Chaudfontaine, Perrier, Gerolsteiner and other Eifel springs),

6.4.5 Findings

Humans seem to be the most sensitive organism as far as acute exposure is concerned. Maximum concentrations for even short term exposures should not exceed 1,5 vol% - 3 vol%. A direct relation with a flux can however not be given since exposure level not only depends on flux, but also on the 'ventilatievoud' of the receiving space. As illustrated by Crystal Geyser and geothermal systems in Italy, no negative impacts will occur even at high fluxes of thousands of g/m^2/day as long as ventilation is sufficient for diluting the emitted CO_2.
On the other hand, in case of slow but chronic releases that do not accumulate, humans have less to be concerned about since influxes into the biosphere compartment they live in (air) will be diluted quickly in general.

Vegetation and organisms in water on the other hand will be exposed to harmful concentrations at influxes of only several hundreds g/m^2/day. Based on measurements of fluxes and soil CO_2 concentrations in Costa Rica a first indication of a possible maximum acceptable flux for vegetation would be approximately 50 g/m$^{2/}$day, several times natural flux levels. Maximum acceptable flux will probably vary with coarseness of soil particles and will probably be higher for sandy soils and lower for clay due to differences in permeability of the different soil types.

Based on the above conclusions one could argue that it would be appropriate to define a permitting policy in which storage is prohibited for potentially crowded areas (including busy infrastructure and tourist attractions) and areas with high natural value. Such an approach would leave the possibilities for storage effectively limited to agricultural areas with low population density.

The above conclusions could also be used as an argument to keep wellheads of CO_2 injection boreholes after abandonment accessible and to prohibit residential areas or other forms of built-up areas in the direct vicinity of the well head – since the wellhead is regarded to be the most vulnerable part of a CO_2 storage reservoir with respect to potential leakages. This would be a deviation from current abandonment policy for gas and oil production; that demands return to a green field situation and allows any activity on top of the former well head[93].

However one must be careful considering such 'solutions' since such a policy is relevant only for current land use. The fact is that the entire geopolitical situation in Europe has changed again and again in the past 2000 years – thereby resulting in changing responsible authorities[94] - and that the location of many abandoned landfills is presently unknown. This raises the question of whether such a policy would actually guarantee that in some future era there will not be a valuable natural area or residential area in the direct vicinity of a former wellhead.

This uncertainty about future land use and awareness of former wellhead locations might be an argument for requiering a 'fail safe' CO_2 storage facility with a guaranteed

[93] According to article 8.5.2.7 of the current mining law the well head and tubing must be cut off at a minimum depth of 3 meters below ground level and the upper part of the remaining tubing must be filled with coarse material down to 20 meters below ground level to make further removal of tubing more easy in case of construction of underground constructions such as car parks or tunnels.

[94] See eg: 'Nuclear waste disposal,:options and realities', presentation given by Hans Codée of COVRA N.V. at Clingendael International Energy Programme nuclear energy workshop, 24 January 2006 (http://www.clingendael.nl/ciep/events/20060124/20060124_Codee.pdf).

maximum risk of leakage for a certain period of time, with maintenance included or excluded. Such an approach is consistent with for example:

- permit requirements for landfills in the Netherlands (10,000 years, intermediate maintenance taken into account - 'eeuwigdurende nazorg');
- IPPC BAT for tailings reservoirs (5,000-10,000 years for high hazard dams);
- US permit demands for uranium tailings (5,000 years, no intermediate maintenance taken into account).

Aftercare will require creation of a fund. For this aspect too a number of analogues can be mentioned:

- Funds for final storage for high activity nuclear waste in the Netherlands, financed through the Covra gate fee.
- Funds for 'eternal aftercare' for Dutch landfills, financed through landfill gate fees and landfill taxation.
- Possibility for Ministry of Economic Affairs to demand a guarantee fund under the current 'Mining Law'.
- Possibilities for a permit authority to demand a guarantee fund under the 'Environmental Management Act'.
- The voluntary 'Bodemdalingsfonds'.

6.5 Land use and vulnerability to negative impacts from CO_2 storage

The risk of negative effects from CO_2 leakage and other events depends on the probability of vulnerable entities being in the vicinity, and this depends on the land use.

On the basis of the information given in this chapter it is considered that humans, larger mammals and foraging birds will be less affected by slow CO_2 releases from reservoirs than plants, insects, burrowers and fish. As pointed out, CO_2 concentrations in the vadose zone and at the surface may be high, but they will rapidly decrease with altitude. Accumulation of CO_2 in confined spaces could result in additional risks for humans.

One way of dealing with these risks is by site selection considering land use. The different types of land use distinguished in a regular EIA or in special planning are:

- Agricultural areas, including more specific types of area such as:
  - Characteristic valuable landscapes.
  - Archaeological valuable landscapes.
  - Other forms of cultural heritage.
- Natural areas, including more specific types of area such as:
  - Bird and habitat guideline areas.
  - Areas under the nature protection law.
  - Ecological main structure areas.
- Areas with high concentrations of humans, such as residential areas, industrial areas, main infrastructure, recreational areas.
- Areas with a specific function: water collection areas, military training grounds, landfill sites.

A first selection criterion could be low population density, a second the absence of valuable ecosystems and natural areas.

On this basis the best sites would be in agricultural areas. Agricultural areas can be characterised as having a low population density and limited natural value. The main adverse effects could be on crop yield, on livestock health due to direct exposure to CO_2 and on groundwater and soil composition and quality. A summary of the relevance of the risks for the different types of regions is given in Table 6.4.

Table 6.4 Overview of the relevance of risks from CO_2 leakage for different types of regions

	Adverse health effects	Adverse effects on important natural values	Adverse effects on crops and vegetation
Agricultural areas	X	X	XXX
Natural areas	X	XXX	?
Residential areas and other areas with high concentrations of people	XXX		

6.6 Issues in Chapter 6 in a project-specific EIA

General issues for an EIA in Chapter 6

The geographical setting of the project area is generally described in the form of population density, areas of special interest because of nature or archeology, infrastructure etc. Apart from the general description attention will be paid to specific aspects that may be vulnerable to impacts from the proposed activity.

Specific attention to CO_2 storage in Chapter 6

As described in previous paragraphs, exposure to CO_2 from storage reservoirs poses risks for especially humans, vegetation and animals living in the ground. This means that in an IEA for a specific project the presence in the vicinity of the location of humans and high value natural areas are of concern:

- Sensitivity of an area, overview of activities near the wells.
- Overview of subsurface activities, like groundwater abstraction.

Sensitivity

From the different ranges it appears that humans are more sensitive to higher CO_2 concentrations then other organisms. Therefore, as long as concentrations are acceptable for humans, they also will have limited impact on the other organisms. Since the humans are the most critical, testing should be done on human conditions.

Possibly affected

However humans, larger mammals and foraging birds will be less affected by CO_2 releases from reservoirs than plants, insects, burrowers and fish, because due to the wind concentrations are not very likely to build up. CO_2 concentrations in the vadose zone and at the surface may be high, but they will rapidly decrease with altitude. Accumulation of CO_2 in confined spaces could result in additional risks for humans.

7 POTENTIAL HEALTH, SAFETY AND ENVIRONMENTAL (HSE) IMPACTS AND RISKS FROM CO_2 STORAGE IN DUTCH ONSHORE GAS FIELDS

7.1 Introduction

Unlike man-made structures, the natural subsurface system is only very sparsely and approximately known. Because of these poorly known subsurface properties, leakage of CO_2 cannot be excluded completely. This chapter discusses potential hazards that could affect the integrity of the subsurface storage reservoir and any adverse effects on health, safety and environment (HSE) that may result from such events. As discussed in chapter 5, CO_2 leakage from the containing depleted gas reservoir is regarded as being the most specific hazard involved in underground subsurface storage. Ground movement, induced seismicity and brine displacement are not discussed in this chapter as they are relatively well understood. When storing CO_2 in depleted gas fields one can expect that leakage will not take place as long as safe injection practices are applied. Nevertheless, it cannot be excluded that at some point in the future leakage will take place. Alternative leakage options are explored in this chapter, in order to discuss which types of impact are possible.

First the possible mechanisms underlying leakage are listed and described in Section 7.2. Leakage along or through boreholes appears to be potentially the most significant leakage scenario and is therefore discussed in more detail in Section 7.3.

CO_2 migration through the overburden is described in Section 7.3. The possible CO_2 fluxes through the overburden, depending on the type of leakage, are discussed based on available real and hypothetical case studies. The simulated overburden fluxes from a flow model can be directly translated into exposure (concentration of CO_2 multiplied by the duration of this concentration) and, if impact models are available, the exposure can be translated into impact (see also the Appendix to Chapter 7).

Leakage from CO_2 storage could have undesired consequences for the health and safety of humans and other life forms, for the existing infrastructure in the soil, for shallow groundwater reserves, and for buildings. The construction, operation and post-operation phases of the storage facility should be designed such that these impacts do not exceed acceptable levels. This chapter deals with the question of how to determine what acceptable levels of leakage are and how it is possible to adjust a design.

The potential impact of increased CO_2 concentrations in the shallow subsurface and atmosphere on health, safety and environment is discussed in Section 7.4.

For man-made installations, a quantitative risk assessment (QRA) is usually performed to evaluate the potential impact of possible events. In the case of subsurface CO_2 storage, a scooping quantitative assessment of what-if (worst-case) scenarios should be considered for those elements that can be quantified (conforming to the specifications for assessing the external safety of industrial installations; see Safety.nl). Establishing a full QRA with the knowledge available at one point in time (e.g. at time of license application) is possible, but rather meaningless as risk assessment in systems with unknown or poorly known properties, such as the subsurface, should be seen as a dynamic learning exercise where subsequent assessments are performed to update the quantitative models with the most recent information and insights acquired. This dynamic learning aspect is typical of projects involving subsurface systems and is aimed at managing the project and at understanding the relative *improvement* of the risk profile, rather than predicting any absolute risk performance. To calibrate the models used, risk assessments will also depend on the experience in analogous activities like gas storage or injection of other fluids. The experience with CO_2 storage in other countries and offshore regions shall also be used if monitoring and modelling data are available. These findings shall be subsequently translated to the situation in the Netherlands. Risk evaluation is explained in more detail in Section 7.5. The risk evaluation methodology uses the principle of the bow tie: the bow tie shows the hazards on one side, an event (natural or man-made) is placed centrally, and on the right hand sight the impact is described. If the probabilities of the hazards and of the events can be estimated, and if the acceptance limit is known, then the 'risk' can be quantified. This is the cumulative probability of exceeding the limit, multiplied by the average impact of those cases that exceed the limit.

The proposed approach in specific projects is described in Section 7.6. This can be read as a 'recipe' how such approach should be filled in. Finally, in Section 7.7 recommendations on assessment of risk and HSE-impact for underground CO_2 storage are given with respect to a site-specific EIA.

When reading this chapter one should bear in mind that the proposed method is based on the current state-of-the-art. In the years to come new findings and practical experiences with subsurface CO_2 storage may lead to alternative approaches.

7.2 Mechanisms of leakage

In order to assess the potential HSE-impact of CO_2 leaking out of the subsurface storage, the possible leakage mechanisms from the reservoir and subsequent flow pathways to the surface must be considered. In general, the Dutch subsurface is composed of clastic sedimentary sequences, consisting of sandstones, shales and claystone, and finally by unconsolidated clays and sands. Salt layers of the Zechstein form a perfect cap rock for hydrocarbons. Gas reservoirs consist mostly of fault-bounded graben blocks below the salt. Exploration and production wells, both operational and abandoned, are widely present. Four potential leakage mechanisms (Figure 7.1) are envisaged to apply generically to storage sites in Dutch onshore depleted gas fields.

- Leakage through the cap rock (Section 7.2.1).
- Leakage along the reservoir spill-point (Section 7.2.2).
- Leakage through or along geological faults (Section 7.2.3).
- Leakage through or along wells (Section 7.2.4).

It is important to note that possible combinations of the above mechanisms should be considered (Section 7.2.5). For each mechanism it is necessary to identify the hazards that may cause leakage, the resulting fluxes out of the reservoir that may occur over time, and the possible leakage pathways through the overburden. Hazards are defined as system properties or (sequences of) events that may lead to CO_2 escaping the storage reservoir. These may be different for the various phases of the storage and, therefore, should be considered separately. The operational phase of the storage site (injection phase) should be distinguished from the post-operational phase of the storage site (post-injection phase).

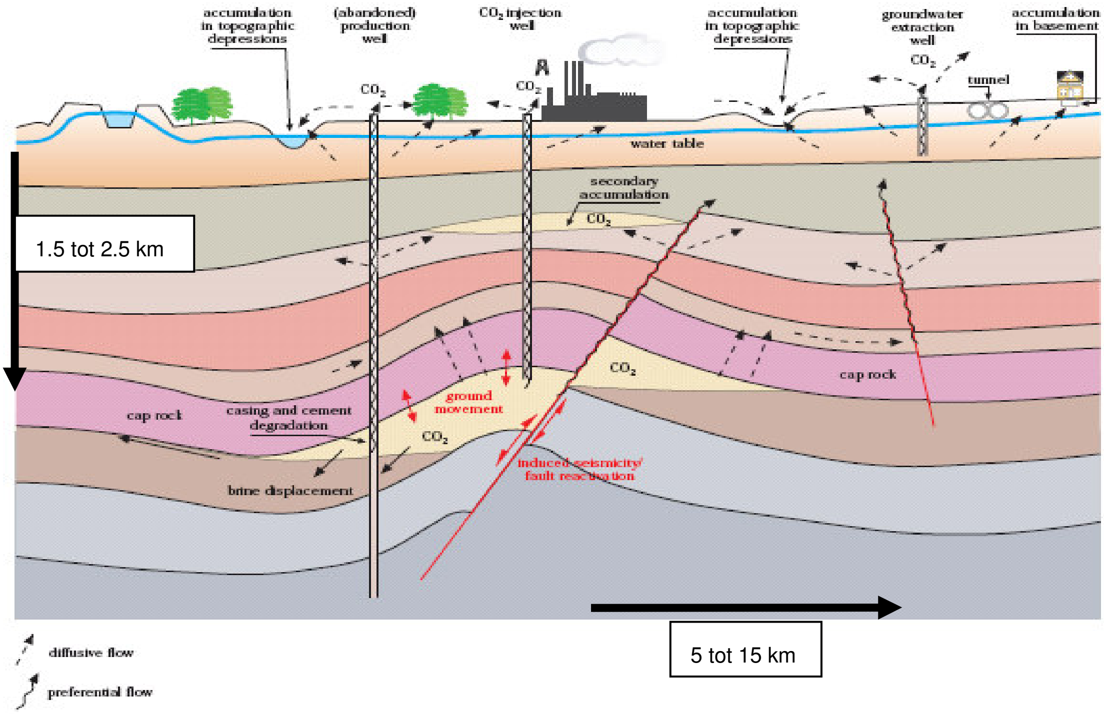


Figure 7.1 **Main leakage paths for CO_2 to move towards the surface: cap rock leakage; spill leakage; fault leakage; well leakage (TNO, 2007)**

It is necessary to consider the possible influence of impurities in the CO_2 stream on the integrity of the seal, well and reservoir. Xu et al. 2004 concluded on the basis of modelling studies that the co-injection of CO_2 with specific impurities like SO_x and NO_x would lead to a larger extent of the injected fluids and stronger acidification The radial extent would be 100 m with impurities and only 20 m with CO_2 alone. The pH would go down to 0.6 with impurities and to 3.4 with CO_2 alone. Xu et al. 2004 studied the impact of impurities in saline aquifers where the role of free water is dominant. The amount of free water in a depleted gas reservoir is significantly different and therefore the conclusion of Xu et al 2004 is only valid in parts of depleted gas fields that contain free water. Johnson et al. (2004) concluded that CO_2 waste-stream impurities (e.g., CH_4, H_2S, SO_x, NO_x concentrations), exert only a secondary influence on geochemical alteration processes, meaning that impurities have only a minor effect. Therefore impurities (especially SO_2) in the CO_2 stream could only have an effect on the reservoir and well integrity in the case of a depleted gas reservoir with strong water influx.

It should be noted that the natural original occurrence of CO_2 and other impurities in the reservoir and in contact with the caprock demonstrates the long term chemical integrity of the reservoir and the seal.

7.2.1 Cap rock leakage mechanism

The sealing cap rock is the geological layer that traps buoyant liquids or gases in the reservoir. In the Netherlands, the reservoir rocks predominantly consist of sandstone, such as the sandstones of the Rotliegend.

Caprocks are characterized by an extremely low permeability and a very high capillary entry-pressure. In the Netherlands they commonly consist of either claystones (shales) or evaporites (rock salt, anhydrite). The caprocks may interact with the CO_2 or other gases injected in the reservoir. Depending on their mineralogical composition, this can result in either permeability enhancement, possibly leading to leakage, or permeability reduction, leading to improved sealing integrity.

The leaking cap rock scenario describes CO_2 leakage and flow through the caprock due to geochemical or mechanical deterioration of this seal. Fluxes through the caprock depend on the increased permeability of the cap rock resulting from these degradation processes. For the Dutch gas reservoirs, this pathway generally has the lowest probability of occurrence when compared to other pathways. Therefore, leakage through the caprock constitutes the smallest expected impact from CO_2 leakage. After all, the adequacy of the cap rock performance has been demonstrated by the storage of natural gas for millions of years.

However, the cap rock properties may be affected mechanically during the production of the gas. Mechanical alteration of the reservoir prior to and during the injection phase needs to be addressed in any CO_2 storage risk assessment. Also, the flow properties of supercritical CO_2 are different from those of gas and oil. As the capillary entry pressure for CO_2 is lower than for hydrocarbons, CO_2 will start to enter the cap rock material at lower pressures than CH_4. The fact that CH_4 gas has been trapped for several million years is no guarantee that CO_2 cannot seep through the same seal. In this respect it should be noted that this process is mitigated by lower pressure build up in the reservoir for CO_2 relative to natural gas. In addition, the result of temperature changes during the injection phase may have an effect on the phase of the CO_2 which in turn may have an impact on the swelling and shrinkage of any clays in the seal, changing its sealing properties. Their integrity should be specifically evaluated.

Furthermore, compositional changes and precipitation of salts (scaling) may reduce the injectivity of the injection wells, which may lead to local pressure build-up and, hence, cap rock deterioration. Injection pressures around the well should be kept below the mechanical rock strength of the seal, as established during formation leak-off tests below the casing shoe. Another difference from gas containment is the chemical behaviour of CO_2. In combination with formation water, CO_2 will form an acidic solution that is capable of dissolving carbonate minerals, thereby enhancing the permeability and reducing the mechanical stability of carbonate-bearing cap rock. This effect is possible if the shale cap rock contains carbonate streaks. Salt seals are insensitive to chemical degradation due to CO_2 and will form an appropriate cap rock for CO_2.

Although highly unlikely, it is therefore possible that CO_2 will leak at relatively small constant fluxes from the reservoir through the seal. As explained above, this process depends on the pressure development in the reservoir and on the potential for mineral, dissolution in the seal.

7.2.2 Spill leakage mechanism

During injection, and depending on the prevailing reservoir properties, CO_2 may reach the reservoir's spill point, thereby spilling CO_2 into the same stratigraphical layer which is water-bearing beyond the spill point. Spill leakage of CO_2 could occur if the total injected volume of CO_2 exceeds the volume of the trapping structure. This would result in uncontained flow of CO_2, similar to the results of cap rock leakage. The probability of occurrence of this scenario could be reduced by using a detailed characterization of the storage reservoir. Using pressure data, seismic data and other information gathered during the gas exploration and production process, an accurate model of the containing structure and its extents should be prepared. With this information together with monitoring the probability of spill leakage during operation can be limited. Furthermore the effects of spill leakage will be reduced by the dissolution of CO_2 in the ambient formation water.

An alternative cause of spill leakage is CO_2 migrating out of the reservoir by formation fluid flow when the reservoir is part of a dynamic fluid system. High permeability zones may enhance this behaviour. This effect can be mitigated by keeping the depleted gas reservoir under sufficient pressure so that formation water cannot flow into the reservoir. Dutch gas fields rarely show influx of formation water after depletion, leading to the suggestion that in most cases this phenomenon will not occur. However, fluid flow systems are less predictable, especially over longer periods of time. Flow regimes may change due to other human impacts on the larger subsurface system.

A further alternative is when the CO_2 is injected at high rates and that reservoir heterogeneities plus dynamic effects together result in the CO_2's channelling preferentially to the spill-point. If the structural relief is low and the reservoir is relatively heterogeneous, with a low vertical:horizontal permeability ratio, this hazard may not be negligible. Such effects can be assessed through reservoir simulation studies.

7.2.3 Fault leakage mechanism

Faults are planar zones at which strata or layers are discontinuous and displaced. Faults through shales probably have a low permeability, while faults in carbonate rocks are likely to be open conduits. Faults in sandstone depend on the throw and shaley layers surrounding it. There are no faults running through salt due to its self healing capacity.

This displacement, and subsequent alteration of the displaced rock, can result in changes (increase or decrease) of the permeability in the fault zone. Due to deformation of the reservoir during production of hydrocarbons or injection of CO_2, faults can also be reactivated (Mulders, 2003; Van Eijs, 2006). It is unlikely, however, that these reactivations would cause an increase of the permeability over a large length as maximum displacements during these reactivation events are within the centimetre range.

In case of enhanced permeability in the fault zone CO_2 could leak along these fault zones out of the reservoir and reach the overburden. It may even form a short circuit to the shallow subsurface. The fault zone permeability and width are the dominant parameters governing both the CO_2 flux and the cumulative release along a fault zone (Wildenborg et al., 2003). It remains questionable, however, that a fault system would have an enhanced permeability over its total length but, it is not possible to determine with confidence the permeability of the entire fault. This property can be deduced locally from core material taken from the fault or it can be estimated from field observations such as the pressure behaviour of the reservoir during production.

Large faults in the subsurface can be detected by seismic investigations but smaller faults, or faults with hardly any displacement, are difficult to detect. It is however not plausible that this type of faults will make a connection (short circuit) between the reservoir and the ground surface in the Dutch situation. First the timing of faulting per definition restricts the vertical extent of faults to formations that were in place at that time. Moreover, the unconsolidated sediments that cover practically the entire Dutch surface are not prone to brittle deformation and therefore generally faults will not reach the ground surface at all.

Similarly to the case of the cap rock integrity, any faults involved have proven their capability of containing hydrocarbons over geological timescales, and the risk of fault leakage appears to be limited. However, the presence of (precipitated) carbonate or calcite minerals in the fault zone would pose a leakage risk. Pathways could be opened due to chemical reactions between the carbonate and an aqueous solution of CO_2. Moreover, as discussed above the capillary pressure of CO_2 is lower than that of gas and, as a result, a containment layer is capable of holding a smaller pressure of CO_2 in comparison with those for oil or gas.

7.2.4 Well leakage mechanism

Well integrity has been the most important cause of leakage in underground gas storage facilities. Benson et al. (2002) concluded that failure of an injection well in most cases results from the use of construction materials that were incompatible with the injected waste, leading to excessive corrosion of the well casing. Generally, repairing or reconditioning the wells fixes this problem. Other common causes are inadequate monitoring of the annulus pressure to detect leaks (and, therefore, taking no remedial action), lack of early detection of fluid migration behind the well casing (ditto), and injecting waste at excessive pressures. Over time, as engineering practices have improved and regulatory monitoring activities have grown more stringent, fewer incidents have occurred. Together with improved procedures this has rendered underground natural gas storage a relatively safe and effective operation (Benson et al., 2002).

Large scale industrial storage of CO_2 leads to new potential problems regarding well integrity issues. The primary difference between natural gas and CO_2 is that in combination with water CO_2 tends to form a slightly acidic solution that may chemically interact with the well material (mainly steel and cement). In order to prevent leakage of CO_2 through or along the well, the applied materials require a high resistance to both short-term and long-term degradation processes.

The cement is used both for sealing off the spaces between the casing and the surrounding rock formation, as well as for constructing closure plugs over certain intervals inside the casing. To prevent leakage of fluids and gases from the reservoir through or along the well, a cement matrix is applied that has the minimum possible permeability, mostly in the μD-range (Economides, 1990). In principle all communication of the reservoir to other formations should be prevented in this way. However, several physical phenomena can take place that may lead to the formation of thin continuous flow channels along the well trajectory.

Construction quality
Several factors relating to the well construction and abandonment stages will affect the well integrity with respect to CO_2 storage. A poor cement placement or plugging job results in unsatisfactory isolation characteristics and may even lead to direct migration routes for CO_2. Inadequate mudcake removal, for instance, will leave parts of the clay-like mudcake in place, potentially leading to preferential flow paths. Furthermore, cement shrinkage after drying may have an effect on the overall permeability of the cement sheath. Nowadays also cements are available and used that expand slightly after placement, which would prevent shrinkage cracking.

It should be noted however, that current Dutch mining legislation requires the applied plugs to be pressure tested for their isolating capability. These casing pressure tests should be carried out such so as to prevent deformation and cracking of the cement around the casing. The quality of the primary cement sheath in the annulus can be assessed using a Cement Bond Log (CBL). Annular pressure measurements at the Xmas tree may also give confidence that no hydraulic vertical communication to the surface exists.

In case of stacked reservoirs one should ascertain that uncompleted gas-bearing zones are also adequately sealed by a cement plug above those zones.

Mechanical degradation
The production of gas may have had an effect on the mechanical integrity of the wells. A pressure change in the reservoir could lead to compaction and possible shear deformation of the well on the interface layer between reservoir and seal. The deformation may have an impact on the cement where it could degrade mechanically. Temperature changes due to the production of gas could have resulted in deformation of the casing and cement due to the different expansion coefficients for the different materials (i.e. metal, cement, rock). This in turn may result in weakening of the cement bond and potentially to the formation of narrow pathways. The production of sand or acid fluids also may have lead to erosion of the casing.

Changing stresses, pore pressures or temperatures during CO_2 injection in theory will cause deformation of both the well cement and the casing, but preliminary evidence indicates that this is not expected to result in leakage problems (Orlic, 2007).

Chemical degradation
Pure and dry CO_2 is not an aggressive substance. However, in contact with formation water, CO_2 will form carbonic acid that can trigger chemical degradation of both the cement as well as of the casing. For this reason well sections close to and below the original gas-water contact (GWC) can experience relatively large degradation and corrosion rates. When CO_2 is injected or channels below the GWC and forms acidic brine with the formation water, large sections of the well may be affected by degradation and corrosion. In specific cases consideration needs to be given also to the presence of non-CO_2 components of the injected gas, such as H_2S, NO_x or SO_x, that may significantly affect the degradation rate. One should also assume that the injected CO_2 will mix with the residual gases in the reservoir and that the resulting mixture is the relevant substance when considering the degradation and corrosion rates (chemical potential) and the composition of the leaking gas.

Cement degradation involves the progressive consumption of portlandite [$Ca(OH)_2$] and Calcium Silicate Hydrates (CSH) to produce carbonates (aragonite, vaterite and/or calcite), amorphous silica gel and water (e.g. Barlet-Gouedard et al. 2006). The progressive dissolution of CSH creates a high-porosity zone that infiltrates the cement. Carbonates form at the carbonation front, which leads to a reduction of the porosity. Subsequently the newly formed carbonates are dissolved by the CO_2-brine ('dissolution back-front'), increasing the porosity and resulting in a strong degradation of the cement governed by the amount of communication with the formation (i.e. speed of transport of reactants to and from the formation). The replacement of the original cement constituents by amorphous silica gel also has large negative effects on the mechanical strength of the material.

Degradation rates can be derived from experimental work. Although conditions applied in laboratory tests in general will differ from natural reservoir conditions degradation rates which were established in this way still provide valuable information. Under the assumption that the cement degradation process is governed by diffusion of CO_2, chemical degradation rates of cement *plugs* is too slow to be an issue. Even under extremely high temperature conditions (204ºC; 69 bar) 10,000 years of exposure of Portland class G cement to CO_2 would result in some 12.5 m of degraded cement (Shen and Pye, 1989). Cement plugs usually have a thickness of several tens of metres or more. However, it should be noted that the presence of cracks or other pathways in the cement may highly accelerate the degradation process. Furthermore, these reaction rates will cause pervasive lateral degradation of the thin (i.e. 1-2 inch) *primary cement sheath* when subjected to CO_2. At other p-T conditions CO_2 penetration depths in cement range from some centimetres in 10,000 years at atmospheric pressure and room temperature (Duguid et al., 2006) to 7.28 m after 10,000 years at 400 bar and 80ºC (Van Gerven et al., 2004).

Steel (casing) degradation involves the corrosion through electrochemical reactions resulting from the presence of CO_2 in solution. Severe pitting or perforation of the casing can occur over relative small time spans. This process is strongly dependent on local physical conditions (pH, pressure, temperature, presence of water, presence of catalyzing ions). In principle corrosion rates of steel casing can be very high, i.e. in the order of tens of mm per year. This implies that casing corrosion in theory can degrade the entire casing over many tens of meters within 10,000 years, creating an annulus that bypasses the cement plug and caprock. However, at certain conditions at the reaction surface $FeCO_3$ can precipitate (Chokshi, 2004) thereby strongly reducing the corrosion rate. A protective $FeCO_3$ film can only form at pH values above 5, while conditions immediately after injection of CO_2 generally will show lower reservoir pH. Furthermore, precipitation of a protective film starts at temperatures above 60ºC, but only above 150ºC a complete, adhesive $FeCO_3$ layer will form given pH>5 (Burke, 1984; Palacios and Shadley, 1991). It should be noticed that the casing steel generally is enclosed between a cement plug and primary cement sheath at the caprock level. Although the process is not yet fully understood, most probably this will lead to accelerated increase of pH as a result of the cement buffering capacity (Cailly, 2005). Even if pervasive casing corrosion would take place, creating a thin, approximately 1 inch wide channel, transport of reactants and products is likely to be reduced due to the increasing length between the reaction front and the reservoir. This is expected to seriously hamper reaction rates. The corrosion of the casing in not already abandoned wells will definitely be managed when the casing with the cement sheath will be milled out and a pancake plug is emplaced.

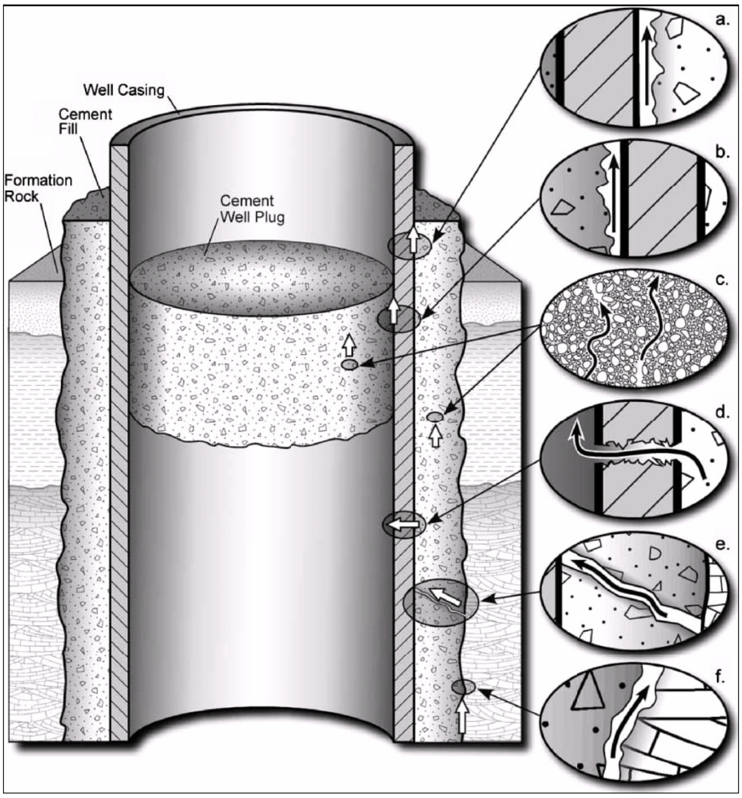


Figure 7.2 Schematic representation of possible leakage pathways through an abandoned well: (a) between casing and cement; (b) between cement plug and casing; (c) through the cement pore space as a result of cement degradation; (d) through casing as a result of corrosion; (e) through fractures in cement; and (f) between cement and rock. From Gasda et al. (2004).

By means of these processes leakage pathways can develop along the contact of the cement sheath to the casing or the surrounding formation rock, between the cement plug and the casing, through the cement matrix or casing material, or along fractures in the cement (Figure 7.2). Release of CO_2 through these channels is expected to be a relatively slow process (tens to hundreds of years). However, in the case of plugged and abandoned wells, potential leakage could also result from large portions of the casing being uncemented (Pirkle and Jones, 2006). In such cases CO_2 only has to degrade a few inches of cement sheath and casing, before it can enter the open borehole. Similarly, lost well segments can form open conduits in the subsurface. These structures would form migration corridors that enable rapid transport of significant amounts of CO_2 to the next cement plug, which is often present at much shallower levels.

Legislation and regulation for the abandonment of wells has developed in recent years so that nowadays wells are designed and constructed using the latest technology. Older abandoned wells have been subject to less stringent regulations and, consequently, may result in a substantial risk of leakage due to different kinds of degradation. Many depleted fields contain operating production wells with outdated construction designs (Figure 7.3). Well repairs and well workovers have been common and led to specific modifications that were not always properly recorded. The adaptations required to ensure safe well abandonment need to be assessed for each individual case.

Potential leakage via the well or along the well is regarded to be the major concern for storage of CO_2 in depleted gas fields in the Netherlands. It should be noted that this is only valid under the assumption that other mechanisms of leakage are not likely to occur, i.e. that the type of cap rock prevents any leakage (likely for thick Zechstein salt seals), no spill leakage occurs and faults are not prone to permeability enhancement by chemical reactions or mechanical causes. Still these mechanisms should be evaluated for specific CO_2 storage sites.

7.2.5 Combined pathway leakage mechanisms

In the preceding sections individual leakage scenarios have been discussed. However, actual leakages may involve a combination of the different pathway scenarios.

A variant to the short-circuit scenario, where CO_2 leaks from the reservoir via continuous flow channels through or along a well all the way to the atmosphere, is that a continuous column of gas at some level inside the well leaks through the casing and enters a permeable formation in the overburden. The density of the gas is much lower than that of water and with decreasing depth the pressure drop of the gaseous phase is much lower than that of the water column. This means that at some point the threshold entry pressure of some high conductivity formation is exceeded and the gas can move laterally, far away from the well rather than releasing CO_2 only near the well head. This possibility of uncontained flow through the overburden makes the design of monitoring schemes a complicated job (Van Eijs et al., 2005).

Similarly, leakage from the reservoir along a fault zone with relatively high permeability could result in more disperse migration of CO_2 through adjacent permeable formations at shallower levels of the overburden. In the Dutch situation this seems more probable than leakage through a fault zone all the way to the atmosphere, as the surface is practically entirely covered by unconsolidated sediments that are not susceptible to brittle faulting.

The opposite effect could also take place when uncontained CO_2 migrating through the overburden would come upon wells or well segments that are open to infiltration, e.g. shallow groundwater extraction wells or corroded parts of deeper wells. These structures could form open conduits and transport CO_2 further upward at high speed. Release to shallower levels in the subsurface or even to the atmosphere then may occur in high concentrations at large distances from the injection facility.

7.3 Fluxes to biosphere

7.3.1 Trapping mechanisms in the overburden

After leaking from its containment reservoir in most cases the gaseous CO_2 phase has to travel through a thick overburden with all sorts of mechanisms that can either prevent or enhance this upward migration. Potential flow of CO_2 towards the shallow subsurface or atmosphere can be classified in *gradual leakage*, by dispersive migration through the overburden, *incidental leakage*, comprising relatively sudden releases of CO_2 from the reservoir, and *shallow accumulation* below secondary entrapment structures in the overburden (i.e. gas pockets).

As practically the complete Dutch surface is covered by unconsolidated Quaternary sediments, any CO_2 migration along geological discontinuities is very likely to disperse and dissolve or mineralize in the overburden well below the surface. As a result of the loose sediments, potential CO_2 flow will show dispersive behaviour in the upper levels of the subsurface which will lead to decrease of fluxes to the atmosphere. An exception would be corroded wells forming high permeability conduits that may directly reach the atmosphere. Dispersive CO_2 flow through the overburden may be prevented from reaching the shallow subsurface by several trapping mechanisms which possess different degrees of trapping efficiency and operate on different time scales (Figure 7.4), i.e. structural and stratigraphic trapping, residual trapping, solubility trapping and mineral trapping.

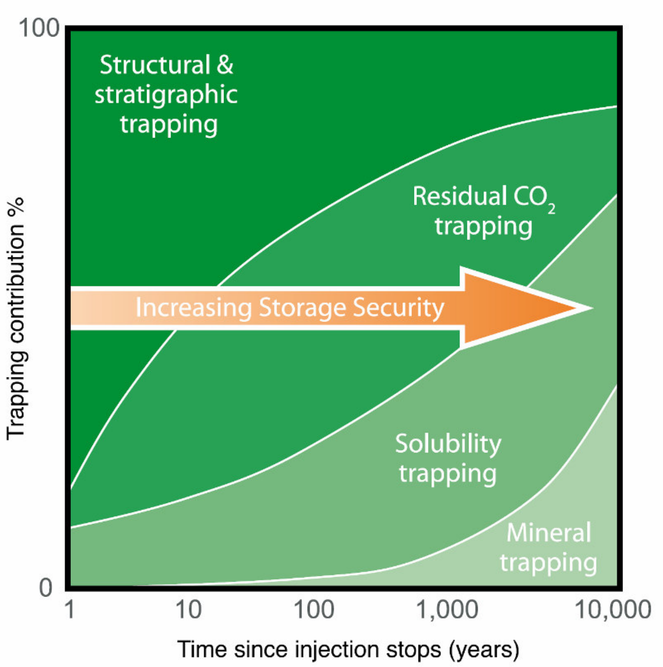


Figure 7.4 **Storage security depending on a combination of physical and geochemical trapping. Over time, the physical process of residual CO_2 trapping and geochemical processes of solubility trapping and mineral trapping increase (From: IPCC, 2005).**

Structural and stratigraphic trapping involve physical containment of CO_2 within geological structures. This is an important mechanism, especially in the early stages of sequestration. In the shallow overburden of the Netherlands the gaseous CO_2 can become trapped below local clay seals. The CO_2 phase will accumulate until the entry pressure of the sealing layer is exceeded or other pathways with lower entry pressures are found. CO_2 accumulating at shallow levels may escape through cracks or channels after building up pressure, leading to secondary release to the atmosphere of large amounts of CO_2 in short periods of time.

Natural gas pockets occur in the Dutch coastal provinces. In historical sources dating back to Roman times spontaneous eruptions of shallow gas accumulations are mentioned (Stuurmans, 2001; Obdam, 2001). In the same provinces there are gas-tight horizontal peat and clay layers at 30-50 metres depth, which can act as traps for gas generated underneath.

Another trapping mechanism is entrapment of part of the CO_2 in the pore space of a formation, which is called residual trapping.

The results of a sensitivity simulation by Svensson et al. (2005) for flow through the overburden at the Schweinrich site indicate that the total CO_2 release and the maximum CO_2 flux could be significantly reduced by CO_2 going into solution in the aqueous phase. The significance of solubility trapping increases with time. Once dissolved in the pore water, CO_2 no longer exists as a separate buoyant phase. Also, the increased density of the pore water containing CO_2 is favourable for sequestration. Solubility trapping has limited effect in Dutch gas reservoirs, because of the relatively low water saturation in these reservoirs. This trapping mechanism could play a significant role if part of the CO_2 were to leak into an overlying aquifer.

An even more permanent mechanism for retaining CO_2 is mineral trapping, but this will occur to a significant extent only a considerable time after injection (hundred to many thousands of years).

7.3.2 Flow along preferential pathways in the well zone

Results of numerical simulations of CO_2 flow along preferential pathways are available from the literature but are not representative for the setting of the Dutch gas fields. An example is the work performed by Svensson et al. (2005) and Van Eijs et al. (2005) for an aquifer in Germany. Representative fluxes for specific sites can only be estimated by applying the local characteristics and properties of the storage reservoir and overburden.

Injection of CO_2 in an aquifer will lead to systematically higher pressures than the reservoir pressures resulting from CO_2 injection in depleted gas fields. In general the results of simulations for other sites or observations from other locations should be treated with caution when applying them to other settings, such as the gas fields in the Netherlands.

Svensson et al. (2005) analysed several leakage scenarios for an aquifer in Germany, one of which is the well leakage scenario. Several processes were not included in the model:

- Dissolution of CO_2.
- Capillary pressure effects.

Exclusion of these process leads to an overestimation of fluxes to the biosphere.

Furthermore, the data input was conservative:

- Mean final permeability of cement: 156 mD for a diameter of 2 m, which is equivalent to 10 D for a well diameter of 0.25 m.
- Mean degradation period of cement: 400 years.

In particular the permeability is very conservative as it assumes that this high permeability holds for the whole well.

The model constraints and conservative assumptions lead to an overestimation of the resulting fluxes, which are expected to be well above representative values for a well in a Dutch gas field. The maximum value for the fluxes near the well in the German aquifer case is 350 tons/m^2/year, which is equal to about 950 kg/m^2/day. The simulations show a first breakthrough after several decades to hundreds of years. Maximum fluxes are reached after many hundreds of years to 2,000 years (Svensson et al., 2005). Special attention to the quality of the plugs will minimize the risk of well leakage in the longer term.

The amount of CO_2 released per unit of time in the case of an injection well blow-out at a CO_2 storage facility will probably be of the same order as injection rates. Studies for CO_2 sequestration in De Lier and figures for water injection give an indication of the potential injection rate per well, ranging from approximately 650 tons/day for CO_2 sequestration in De Lier to approximately 1,000 tons/day in case of injection rates as applied for water injection at Borgsweer. An early study by Shell of CCS in the Netherlands gives an injection rate of 2,500 tons/day per well. It is expected that a blow-out will be under control within days and the total emission resulting from a blow-out will thus be limited. A blow-out can only occur during the injection phase of a project. Risk methods and mitigating measures are industry standard.

7.4 Consequences

The possible HSE-impact of exposure to CO_2 should be assessed for soil mineralogy, groundwater chemistry and for the biosphere. For this purpose the possible build-up of CO_2 concentration resulting from CO_2 leakage needs to be determined for shallow aquifers and the biosphere, which consists of the soil, surface and atmosphere. Furthermore, the hazards that may arise from secondary accumulations of CO_2 in the overburden (e.g. future unintentional drilling into secondary CO_2 accumulations) should be assessed. Also attention has to be paid to the presence of impurities in the leaked gas and the possible leaching of harmful minerals.

Chapter 6 discussed the impact of the exposure to CO_2 of shallow aquifers and the biosphere. Possible HSE-impacts are reflected in soil mineralogy and groundwater chemistry, including the impact on hydraulic properties of shallow aquifers, on subsurface infrastructure (such as pipelines, foundation of buildings etc.) and on (subsurface) flora and fauna (including humans and livestock).

7.4.1 Exposure in the shallow subsurface

As pointed out before, leakage through wells is expected to represent the highest risk. For the very conservative simulation of the German aquifer (see Section 7.3.2) the estimated maximum CO_2 concentration in the shallow subsurface is close to 30% (Van Eijs et al., 2005). Such concentrations would result in lethal effects for terrestrial ecosystems (Saripalli et al., 2002). Results of the leaking well scenario in the SAMCARDS project show that the lateral extent of the high CO_2 concentrations at the surface is limited, affecting areas of 1,000 to 30,000 m^2 (Wildenborg et al., 2003).

As this is a very conservative estimate for gas fields the maximum concentration for gas fields in the Netherlands is probably lower. Subsurface organisms generally can cope with concentrations of 10%; a concentration of 20% or more is lethal for life forms in the soil. Leakage in the shallow subsurface can also influence groundwater quality by increasing the acidity and mobilising heavy metals. The heavy metal concentrations. will however not exceed the existing Dutch norms (Wildenborg et al. 2003). A soil monitoring system is well capable of detecting enhanced CO_2 concentrations and its chemical effects (see Chapter 9).

7.4.2 Exposure in the atmosphere

Depending on the emission rates, the CO_2 may eventually migrate via the unsaturated zone in the soil to the atmosphere or in the case of a well blowout may be vented directly into the air. In the Dutch setting, where drains intersect areas covered by meadows, this may result in concentrated emissions in the drains and other depressions in the land surface (basements etc). In stable atmospheric conditions (situations with low wind speeds and low inputs of solar radiation) it will not be rapidly dispersed and may accumulate. In most instances however gases will be effectively dispersed in the atmosphere.

The effect of releasing CO_2 to the atmosphere was assessed by Van Eijs et al. (2005) for the German aquifer case. The assumed maximum CO_2 flux into the atmosphere was about 950 kg/m^2/day over an area of 100 m^2, which is equal to 95 tonne per day for an area of 100 m^2. The assumed weather was classified as 'very stable' (Pasquill stability class F) and the wind speed at 10 m height was 1.5 m/s. The dispersion calculations were done for a height of 1.5 m, which is the normal breathing height of an average human being. The maximum concentration that can be reached is about 4 g/m^3, which is 25 times below the dangerous level of 100 g/m^3. So, this case of well leakage does not pose a threat to human safety.

These concentration levels refer to ambient air and to well-ventilated spaces. Experience shows that CO_2 can accumulate up to harmful levels in unventilated spaces, such as cellars and kitchen cupboards, pits and snow caves. Next to this, windless conditions do occur even in the flat country of the polders, for example on cold nights when water vapour forms mist over ditches and slowly spreads across the surrounding countryside. Under such conditions CO_2 could accumulate close to the ground and form clouds with dangerous concentrations of CO_2.

7.5 Methodology: establishing the risks for a specific project

7.5.1 Risk assessment of the subsurface system

As noted in Section 7.1, unlike operators of man-made industrial process plants, CO_2 sequestration site operators will have to manage an unknown, or poorly known, system. Surface installations have been designed by man, performance experience is available and can therefore be analysed using Quantitative Risk Analysis (QRA) when applying for a license: all the system properties are known, allowing design specifications to govern the risks. Geological storages, however, have not been designed by man and are therefore subject to large uncertainties in the system properties. Risks (probability of occurrence multiplied by the undesired impact) are only partly governed by the system design, and a major part can be attributed to the unknown system properties. Regarding the latter, the *modelling*, including of risks, is aimed at *learning* about the system during the construction, operational and post-closure phases of the site, rather than predicting the absolute value of the risks at any point in time.

This *dynamic* objective of modelling is the reason why it is considered meaningless, at the time of licensing, to relate the calculated risk to some absolute norm. This is the case in all systems that deal with the subsurface. Calculated risks based on poorly known subsurface parameters should be regarded as having an indicative and relative value in a learning process, not as being an absolute value.
Although a full QRA is not feasible at the time of the licensing, limited quantitative assessment of what-if (worst-case) scenarios can support the licensing process. This evaluation should be performed in line with the specifications for assessing the external safety of industrial installations (see Safety.nl).

The models improve one's understanding of the system and allow comparison of alternative courses of action. During this learning process, the design, operational and monitoring activities can be adjusted in order to mitigate the risks. As time and knowledge of the system evolve, absolute model predictions may be used with increasing confidence. At some stage it may become meaningful to relate the calculated risks to some absolute risk acceptance norm.

In conclusion, the *dynamic learning process* during the life cycle of a site is fundamental to how one should perceive the value of subsurface models. Using subsurface models to make absolute predictions at some point in time (e.g. at time of license application) is not considered meaningful as such a 'snapshot' approach is not considered appropriate to a poorly known system that is going to unveil (some of) its properties only gradually in time.

7.5.2 Purpose of modelling

As already noted above, anyone dealing with the subsurface will have to face large uncertainties in the system properties. Using models of the system behaviour, these uncertainties can be translated into uncertainty in the predicted impact and, hence, into 'risk'.

The uncertainties in the model predictions are due to:

- the subjectivity in defining the conceptual framework within which quantitative subsurface models are constructed (this framework should be regularly updated during the course of the subsurface asset's life time);
- within this framework, the subjective choice and definition of the quantitative parameters to be estimated;
- the choice of how to model the uncertainty around those parameters;
- the choice of the simulation model to be used, which mostly is subject to an unknown modelling error (for example the choice of the flux simulator, or whether to use geochemical models)
- poorly understood upscaling rules to reduce the size and number of the grid blocks in the model. This may result in an unknown modelling error.

Quantitative models definitely should be constructed (see below), but should not be seen as tools to make *absolute* statements about the predictions made. Rather, the added value of modelling is in the *learning* during the course of the injection and post-injection phases. This should allow the operator to manage the system so as to optimise it within certain constraints (e.g. improving the risk profile in time as new information is acquired). Both optimisation objectives and constraints are subject to change as new information is revealed over time. Monitoring programmes also need to be updated and re-focused as the new information becomes available.

Quantitative models are useful to establish a data acquisition (monitoring) strategy. Moreover, a model can be useful to study possible extreme (i.e. highly unlikely) scenarios at the time of license application. If these do not result in significant HSE impacts, or only after some extremely long period, then such models may provide some confidence in the planned activities, although one should always be conscious of the many assumptions in these scenarios.

7.6 Approach: establishing the risks in specific project

7.6.1 Recommended approach

Rather than doing a QRA on geological storage, based on possibly unrealistic and rather uncertain models during the license application period it is recommended that:

1. The operator carries out a qualitative hazard identification analysis based on a check list to be issued by the competent authorities optionally supported with quantitative modelling of what-if leakage scenarios.
2. The operator submits a plan in which the role of modelling is explained in terms of its contribution to mitigating risks. The plan should explain how during the operational and post-operational phases of the site monitoring combined with modelling is used in a formal learning framework. In particular, the verification of explicit and implicit assumptions, and updating of mental frameworks should be addressed.
3. The operator submits a risk management plan which includes inputs from modelling and monitoring. This should also explain how the updated models are continuously used to make predictions and steer the operational activities accordingly, *inter alia* to avoid or mitigate those risks that may *increase* in time (as new information is being revealed) and at some stage become unacceptable. In this way a quantitative, updated model is always available to test various mitigation options in case a leak is suspected.

7.6.2 Conclusion

- A full QRA on geological storage as part of a license application is considered meaningless. Quantitative assessment will be limited to the analysis of what-if leakage scenarios. This should include differentiation of leakage mechanisms, as individual leakage mechanisms could have different impacts.
- A qualitative hazard identification study based on a check list established by the competent authorities is considered meaningful and should be mandatory.
- A robust monitoring plan should be submitted as part of the license application. Such a data acquisition plan should cover the construction, injection, and post-injection phases and explain the role of quantitative models as part of a formal learning process. The plan should address the verification of past (modelling) assumptions and explain the rationale of acquiring new data in terms of how this will update the risk profile of the site. The demonstration phase in the deployment of CCS will probably include more demands on the size and components of the monitoring system.

- In the transition to full-scale deployment of CCS and building on the experience from the demonstration phase the extent of monitoring could be reduced but still meet minimum regulatory requirements.
- Should a suspicion of leakage arise, models may serve as a basis for designing targeted additional data acquisition. Such modelling studies may be instrumental in deciding under which conditions a sequestration license is to be prolonged.
- The license holder should be made liable for any possible HSE impact until the transfer of liability. In extreme situations the competent authority should have the power to demand recovery of the injected CO_2. This should give the license holder a clear interest in applying all due diligence when designing and operating the site. In case of a (suspicion of a) leak, the license holder will do his utmost to 1) identify and plug the leak, 2) predict the possible HSE impact of the leakage, 3) to establish a formal tracking and learning (modelling) process that enables him to test various operational alternatives (model predictive control).

7.7 Recommendations for a site-specific EIA

General issues for an EIA in Chapter 7
This chapter has been dedicated to considering possible leakage from the gas reservoir and the impact from CO_2 in the biosphere. This is not a regular EIA issue, but a specific item for CO_2 storage projects.

Specific attention for CO_2 storage in Chapter 7
The key function of Chapter 7 in a project-specific EIA is to provide the basis for the management of risk related to CO_2 leakage. Using the detailed project description in Chapter 3, the hazards and the resulting potential impacts must be collated for all the leakage scenarios which cannot be excluded in the project-specific case.

Each leakage scenario should be considered, taking account of the sensitivities at the particular location (from Chapter 5), and taking account of the different types of impact (from Chapter 6). Each case should evaluate the various possible impacts, as these will govern the programming of the data acquisition / monitoring activities as part of the wider risk management plan.

Well integrity has been the most important cause of leakage in underground gas storage facilities. Benson et al. (2002) concluded that failure of an injection well in most cases results from the use of construction materials that were incompatible with the injected waste, leading to excessive corrosion of the well casing. The corrosion of the casing in not already abandoned wells will definitely be managed when the casing with the cement sheath will be milled out and a pancake plug is emplaced.

Besides effects of CO_2 injection itself, changes in the reservoir system resulting from gas production during the pre-injection phase may represent a hazard when commencing CO_2 injection. The seal, reservoir, faults and wells may have been exposed to some deformation as a result of seismic events that may have triggered fault reactivation. Any event that occurred during production and prior to injection therefore has to be assessed in order to obtain an appropriate understanding of the containment condition at the start of injection and changes in the system relative to the exploration phase.

Furthermore, long-term risks should be considered. The main drivers after injection are buoyancy forces, chemical reactions and the pressurized reservoir, which will continue to exert forces on reservoir, cap rock and well.

8 OPTIONS FOR HSE IMPACT REDUCTION AND MITIGATION

There are a number of basic possibilities for the deep geological storage of CO_2 but in this report (see Ch. 1) only onshore former reservoirs for natural gas are considered. In this chapter the potentially available options for impact reduction and mitigation are presented for the case of a specific project to store a defined quantity of CO_2 in such a reservoir. For each option the relevant advantages and disadvantages are discussed. These may be relevant at different stages of the project, from construction through to the post-closure, long-term condition. The preferred characteristics for each aspect or property of a potential reservoir are indicated in a summary table.

Available options
There are three groups of options which may be considered. The first group concerns the features of the potential sites and would be considered during a site selection stage. The second group relates to the options available for the injection system at a particular site. Within the third group the properties of the injected CO_2 are considered. Monitoring options are discussed in Chapter 9.

8.1 Reservoir selection

In principle, for any selected storage reservoir alternative reservoirs may be present that could have been selected instead. The reservoir properties considered during the site selection process are discussed below. Table 8.1 gives an overview of the discussed items.

Existing and former penetrations

- As leakages from reservoirs are most often associated with old wells their presence increases the probability that impacts will occur, although not necessarily the size of any impact. It is important to consider the age, particularly the date of abandonment, of any existing or former penetrations. Technological and regulatory changes affecting the Dutch oil and gas industry have resulted in lower risk levels for newer wells. It is therefore advantageous to select a reservoir with fewer older penetrations.
- There may be cost implications associated with the presence of penetrations if it is necessary to carry out work on them to ensure that they are safe. For this reason too it is advantageous to select a reservoir with fewer older penetrations.

Reservoir depth

- As there are depth-related costs associated with drilling wells, and potentially also with the injection process, a shallower reservoir has some advantages. Below a certain depth – approximately that at which the stored CO_2 will be in a supercritical condition, i.e. about 800 m - there is little benefit in terms of increased storage capacity to be obtained by choosing a deeper reservoir option.
- A disadvantage of a shallow reservoir is that in the unlikely event that any leakage occurs there is a higher probability that this will result in surface or near-surface impacts. In a deeper system there are more likely to be intervening strata which will trap the CO_2 as it travels upwards.
- Injecting CO_2 into the reservoir will generally result in an increase in the reservoir volume and this may be sufficient to cause uplift at the ground surface, with potential implications for surface water management. In this context a deeper reservoir could be advantageous, as the uplift spreads over a larger area.

Faults

- Faults appear not to be much of an issue in the Netherlands. The mentioned possibility of faults is still important to give a complete overview.
- Numerical studies indicate that CO_2 may travel upwards along permeable faults. Even though leakage of CO_2 is very unlikely it is advantageous to select sites with fewer faults and with low-permeability faults.
- If faults are present then it is advantageous if they do not extend over a substantial part of the overburden thickness. In that case there are more likely to be intervening strata which will trap any CO_2 as it travels upwards.

Cap rock

- It is advantageous for the sealing layer - the cap rock - to have a low permeability and also for this property to be insensitive to disturbances resulting from the development and use of the reservoir. Because of its self-healing characteristics and extremely low permeability rock salt is considered to be the best material. Claystones are also considered to be suitable if they have a low permeability.
- It is advantageous in terms of sealing performance and risk levels to have a thicker rather than a thinner cap rock.
- To demonstrate that a reservoir will store the CO_2 satisfactorily it is useful to be able to show that this occurred previously over a sustained period. For this reason the fact that there was a higher percentage of CO_2 in the gas produced from the reservoir can be considered to be advantageous in terms of chemical reactivity.

Reservoir rock

- It is more cost-effective if a given amount of CO_2 can be injected into the reservoir rock at a lower tubing head pressure (lower compression costs).
- Potential reservoir rocks in the Netherlands include sandstones and carbonates. Especially in the latter case, in the presence of water, the injected CO_2 in the form of carbonic acid may react with the rock. This might affect injectivity or result in displacements. For this reason it is considered advantageous to select a reservoir in sandstone.
- Under certain in situ conditions the injection of CO_2 may result in small seismic events. Although the consequences of such events are unlikely to be large it is advantageous to select a reservoir in which such events are not to be anticipated.

Residual reservoir gas

- In the unlikely event that gas leaks from or is released from the reservoir, the presence of contaminants within it is likely to be disadvantageous in terms of impacts or handling costs. For this reason it is advantageous to select a reservoir in which the residual gas contains low quantities of the typical natural-gas contaminants in the Netherlands such as H_2S and BTEX.

Surface features and uses

- Even though it is unlikely that CO_2 will leak from a reservoir there are advantages in selecting a location in which the impacts would be smaller if it did occur. For this reason agricultural areas are to be preferred over nature reserves, and these in turn over urban areas. Similarly, it is advantageous for any vulnerable objects, perhaps an occupied building, to be relatively distant from any identified potential leakage paths, such as a well.

Various aspects of reservoirs for the storage of CO_2 have been discussed above considering their advantages and disadvantages, and which conditions are to be preferred if a choice is available. On the basis of this information it is possible to envisage developing a decision support tool, to be used when evaluating or comparing potential reservoir locations or potential uses for a given reservoir.

One application could be to determine which reservoirs in a province are most suitable for CO_2 storage. In Table 8.1 suitability criteria are listed with what would be considered to be good characteristics or values in each case. The values have been colour-coded from green - best - through to red - worst. These take account of safety and potential for environmental impact, as well as of cost and operational aspects. It should be noted that in a real case it is unlikely that one field will be the best for all criteria and that to reach a decision it will be necessary to weight the criteria appropriately.

Table 8.1 Suitability of depleted gas fields for CO_2 storage

CRITERIA	Reservoir characteristics				
	Good		Medium		Poor
Existing and former penetrations					
Number of wells abandoned before 1985	0	0	1	2	3
Number of abandoned wells in total	0	2	4	7	>10
Number of wells to be abandoned	4	8	20	40	100+
Reservoir depth					
Depth of reservoir (m)	>2.500	1.000-2.500	800-1.000	500-800	<500
Faults					
Fault approach to surface (m)	>1.000	1.000 - 500	500 -150	150 - 10	< 10 (surface)
Number of faults	0	1-5	> 5	> 5	> 5
Assessed fault permeability	uniformly low		very uncertain		uniformly high
Cap rock					
Cap rock	salt	claystone (low permeability)	claystone (medium permeability)	other	other
Cap rock thickness (m)	> 100	50-100	30 - 50	< 30	< 30
CO_2 in original gas phase in reservoir (%)	20	5	0	0	0
Reservoir rock					
Reservoir injectability	very good		medium		very tight
Reservoir rock	sandstone	carbonates	other	other	other
Earth tremor likelihood during injection (%)	0	10	50	100	100
Residual reservoir gas					
H_2S and BTEX in reservoir gas phase (%)	< 0.5	0.5 - 1.0	1 - 5	5 - 10	> 10
Surface features and uses					
Land use above reservoir	agricultural		nature reserve		urban
Proximity of vulnerable objects to potential leakage paths from the reservoir (m)	>100	50-100	25-50	10-25	<10

CRITERIA	GOOD CHARACTERISTICS
Existing and former penetrations	
Number of wells abandoned before 1985	As few as possible
Number of abandoned wells in total	As few as possible
Number of wells to be abandoned	As few as possible
Reservoir	
Depth of reservoir	More than about 800m, but not much deeper
Water in reservoir	As little as possible
Faults	
Fault approach to surface	As deep as possible
Number of faults	As few as possible
Assessed fault permeability	Uniformly low
Cap rock	
Permeability	As low as possible
Self-healing potential	High
Thickness	As large as possible
Reservoir rock	
Injectability	High
Porosity	High
Chemical reactivity	Low
Homogeneity	High
Earth tremor likelihood during injection	Low
Reservoir gas	
CO_2 in original gas phase in reservoir	High proportion
H_2S and BTEX in reservoir gas phase	Low proportion
Surface features and uses	
Land use above reservoir	Agricultural
Proximity of vulnerable objects to potential leakage paths from the reservoir	As far as possible

8.2 Injection system

Options are available in principal with respect to the materials, the configuration, the operation and the final closure of the injection system. The relevant advantages and disadvantages are discussed below.

Re-use of production wells

- There are obvious cost advantages in making use of suitable existing wells for injection rather than constructing new ones. The suitability of existing wells will depend on factors such as their injection capacity in comparison with the planned CO_2 injection rate and on the selected injection strategy (see below).
- Even if the materials used in the casing and the cementation of an existing well are not ideal for the modified use (e.g. injection, monitoring) it may still be advantageous in terms of costs to upgrade an existing well.

Number of injection wells

- Multiple wells may be used to obtain a sufficiently high injection rate without exceeding a given pressure. However this has the disadvantage that it increases the (low) likelihood of a well-related impact occurring. It also has cost disadvantages if new wells have to be constructed.
- An advantage of the use of multiple wells is the availability of back-up in the event that problems arise. Moreover, a multiple well setting introduces an additional possibility for redundant process control and safeguarding.

Construction and materials

- For the purposes of risk reduction it is advantageous to select the well-casing materials (the type of steel and any surface treatment) and those used in sealing between the casing and the surrounding ground (typically cement-based), and within the casing in the case of closure (steel or cement-based) from the options available to be sufficiently resistant to degradation during operation and during the very long post-closure period. The selection needs to take account of the natural subsurface conditions and of the modifications of these resulting from the injection process (e.g. uplift) and from the presence in the system of the injected CO_2 and impurities. (See also Chapter 3).
- Also in the interest of risk reduction it is advantageous to take appropriate quality control measures during construction to ensure that each well complies in all respects with the design objectives. As well as checks on the compliance with the specification of supplied construction materials measures could include confirmation of the consistency between the design assumptions and the encountered strata and, ideally post-construction, that zones of cementation or injection have the required minimum dimensions.

Injection strategy

- A lower injection pressure will reduce the costs of injection, but at the expense of a lower injection rate per well.
- If there is a risk of damage to the reservoir rock or the cap rock this may anyway result in a limit being imposed on the maximum injection pressure. Mind that the fracture gradient (a limit for fracturing the rock during drilling and injection) is lowered due to production phase of the gas field.
- To reduce the risk of impacts which would result from leakage the pressure at the end of injection should not be higher than the pressure which was found in the reservoir before the natural-gas was removed.
- In a reservoir there may be the option of injecting into a water-filled zone, e.g. into a water-leg. This would have the advantage that additional trapping mechanisms could operate there (solubility and residual saturation - see Ch. 3) and thus reduce the quantity of CO_2 which could be released. Most of the Dutch reservoirs were filled with gas to the spill point, which means that there is no opportunity for the gas to move upward to highest point of the depleted gas field when it would be injected in the aquifer. One other disadvantage is that the injection rate (for a given pressure limit) is likely to be lower or that injection costs are likely to be higher. Another negative aspect is that the potential for the CO_2 to degrade the steel and cementitious components of the injection system is significantly higher when water is present. Another consideration is that injecting into water would reduce the proportion of the injected CO_2 which is ultimately retrievable, if this were to be required for some legal reason.

Final closure

- Although there are, in principal, options available for the details (see Ch. 3) and the timing of the final closure this critical aspect will be governed by the relevant regulations. To avoid future impacts this closure system must prevent any possibility that the stored CO_2 can escape in the future and therefore has to be tested and quality checked appropriately after placement on its integrity.
- Placement of a 'pancake' abandonment plug is considered to be the safest option for final closure of a well. This involves milling out of the casing, the cement sheath and part of the surrounding rock over a length of at least 30 m. A mechanical bridge plug is placed about 10-25 m below the milled section and cement is then used to fill the created cavity under a pressure of about 50 bars. As a result cement is filling the casing from 10-25 m below the milled section, the milled out cavity itself, and some 50 m of casing above this cavity. A pancake plug eliminates the potential of annular leakage pathways between cement and casing.
- CO_2-resistant cement and steel types and corrosion inhibitors in the well fluids above the plugs could further reduce the chemical reactibility.

8.3 Injected material

Depending on the source of the injected CO_2 it may contain impurities (see Ch. 3). Such impurities could influence impacts in the event that the gas is released. SO_2 in the presence of water could increase somewhat the likelihood of impacts by increasing the acidity of solutions within the reservoir system. Potential effects include chemical reactions with the reservoir rock, especially in the case of carbonates. It could also increase the rate of degradation of cement-based seals in and around the wells. Therefore, this must be taken into account in their design. In this respect using purer CO_2 could be advantageous, if it were available, but is not necessary to ensure a sufficient level of safety.

8.4 Issues in Chapter 8 of an EIA for a specific project

General issues for an EIA in Chapter 8

This chapter discusses the possible alternatives and variants. Usually in an EIA this is done before the description of environmental impacts. The different realistically possible alternatives are studied and the impact will be compared with the proposed activity.

Specific attention to CO_2 storage in Chapter 8

This chapter shows that many options are to be considered within a practical CO_2 storage project. Some of these have the potential to modify the likelihood and or the extent of impacts, although not their nature. Some also have cost implications, for construction and operation. Possible options are the choice of the storage reservoir itself and the details of the injection system and process and the procedure for final closure.

9 MONITORING PLAN

9.1 Introduction

Monitoring objectives
The overall objective of monitoring is to gain increasing evidence that the CO_2 storage is not leaking. Monitoring also helps to identify priorities in data acquisition and, if a leak has been identified, to take timely remedial action. Within the framework of a storage project, monitoring can be performed for many other reasons, ranging from meeting regulatory obligations and certifying CO_2 storage for emission trading schemes to informing the public and testing of new monitoring technologies. The intensity of monitoring for safety can be increased or reduced depending on the fit between modelled and actual behaviour of the storage site throughout the life of the project from the pre-operational phase through to the post- closure phase.

Monitoring in order to update the risk assessment models
If the objective of monitoring is to gain *increasing* evidence that the CO_2 storage is not leaking, then the role of modelling as part of a learning and monitoring programme should be discussed. As part of the monitoring programme, quantitative models should be constructed (see Chapter 7), but should not be seen as tools to make absolute statements about the predictions made. Rather, the added value of modelling is in learning during the injection and post-injection phases. This should allow the operator to steer his activities so as to optimise his operations within certain constraints (e.g. improving the risk profile in time as new information is acquired). Both optimisation objectives and constraints are subject to change as the new truth is continuously being revealed in time (i.e. through the monitoring activities). Monitoring programmes also need to be updated and re-focused as the new information is being revealed. The quantitative models are also useful to establish the priorities of a data acquisition (monitoring) strategy by 'Value of Information' (VoI) analyses. A VoI analysis predicts the impact of the storage operations with and without the information gained, assuming that the value of any new information entity is determined by how it impacts on subsequent decision-making (e.g. timing of remedial action). According to the VoI approach, if new information has no impact on the decision-making, then the VoI is zero.

Current status
It should be emphasised that techniques to monitor CO_2 storages are still under development. Current techniques are derived mainly from monitoring systems of oil and gas production and their applicability to CO_2 storage is not fully known. Current storage projects have become operational only recently and, consequently, should still be regarded as research and development. Experience needs to be gained in monitoring frequency, duration and intensity. The monitoring frequencies and periods of time that are given below should be considered as suggestions, rather than firm numbers. As the first dedicated storage projects become operational, best-practice monitoring procedures will be collected and used in future updates of this document.

9.2 Monitoring systems

Injectivity and capacity
First of all, injection monitoring is of prime importance and should be standard practice. This includes the measurement of pressure, temperature, gas flow rate at the injector well. This is required to prove that injection is proceeding as planned and to estimate

when the reservoir is filled. The conditions at bottom hole are derived from those at the top of the well through a well model. At regular intervals, the pressure build-up in the reservoir is to be tested, by shutting in the injector and measuring pressure versus time for a short period of time (days). This gives the equilibrium pressure in the reservoir; the pressure data can be used to fine-tune the reservoir model. At this time, the well model can also be calibrated.

Containment
The remaining monitoring efforts are aimed at detecting leakage and, if a leak is suspected, to decide which remedial action is most effective. A number of leakage pathways related to leakage out of the storage reservoir along the wellbore can be identified:

- along the well, through pathways between cement, casing and formation;
- casing failure and subsequent leakage through the casing;
- along the well and into geological formations, away from the well.

Table 9.1 lists these leakage pathways, along with monitoring techniques that can be used to detect the CO_2. The techniques are described in some detail in Section 9.4. The pathways are discussed below, along with related monitoring techniques, in the different phases of a storage project.

9.3 Leakage along the well

Leakage along the well can take place as soon as the injection program starts. As the CO_2 migrates along the interfaces between casing, cement and formation, it will replace existing fluids and change rock properties locally. Existing well logging tools can be used to detect these changes. The CO_2 decreases seismic wave velocity, which can be measured with sonic logs. Saturation (neutron) logs can detect the displacement of formation water by CO_2. Both logging tools can be run in cased holes and their ability to detect CO_2 has been proven in pilot CO_2 injection programs. CO_2 rising along the wellbore will also cause temperature anomalies (Joule-Thomson cooling), which provides an opportunity for detection with existing logging tools.

For this effect to occur, there must occur a pressure differential in the order of such a magnitude that well integrity already has been compromised. Moreover, logging tools give room for several interpretations as their results are diverted from various of physical properties being measured. This accounts for instance also for the Clement Bond Logging which not always provides the exclusive answer.

In addition to the tools mentioned above, the cased hole dynamics tester can take fluid samples behind casing, drilling through the casing and plugging the hole afterwards. The tool can also measure annulus temperature, where lower temperature can indicate CO_2 leaking behind the casing (the gas cools as it expands on its way up). As an alternative, the casing section in the cap rock can be fitted with sensors for continuous casing temperature monitoring, providing the earliest possible detection of CO_2 leakage along the well. This technique is in use.

Well logging tools cannot be used to quantify leakage rates, as the relation between logging data and CO_2 concentration and flow rate is not straightforward and non-unique. To optimise detection probability, it is advised to use more than a single tool. Time-lapse monitoring is a useful method to detect changes in the log responses. Well log monitoring should be performed on a regular basis from the start of injection.

9.3.1 Casing failure

Pressure increase can affect the well integrity as it leads to well completion deformation, which in turn could cause CO_2 leakage at plugs, cement or casing. In addition, the injection of CO_2 increases the risk of casing corrosion. Monitoring casing integrity is necessary in order to prevent this type of leakage. As with CO_2 leakage along the wellbore, this type of leakage can occur from the start of injection and monitoring is to be conducted on a regular basis during injection.

Current well logging techniques can be used to monitor well integrity. The casing integrity log (CIL) can be used for the casing, while the bond between casing, cement and formation is tested with a cement bond log (CBL). The latter tool measures the response of casing plus cement to sound waves. Other tools measure casing corrosion, using ultrasonic sources.

9.3.2 Leakage into geological formations

CO_2 leaking from the well can invade formations, which are in direct or indirect contact with it. Detailed modelling prior to injection will show whether a pathway into a formation is likely for a specific project (see also Chapter 7) so that a dedicated monitoring system can be designed. CO_2 can migrate via aquifers and faults to shallower zones where it can be secondarily trapped below low permeable layers or can seep to the biosphere.

CO_2 leakage into formations could occur as soon as there is a possibility for the CO_2 to migrate outside the casing and/or cement of the injection well. This implies that from the first moment of CO_2 injection there is a possibility for leakage of CO_2 from the well into geological formations and thus monitoring for this type of leakage is required from the start of injection. This type of monitoring can cease once the well is safely and effectively plugged at reservoir cap rock level and abandoned.

Monitoring: seismics
Seismic methods (see Section 9.4.2) are a good way to measure large quantities of gas in otherwise water-saturated rocks. We can distinguish between several types of seismics. At the Sleipner project, 3D time-lapse surface seismics is successfully used to monitor the presence and migration of CO_2 in an aquifer (Arts et al., 2004). Acquisition of seismic data involves the use of heavy equipment and, in some cases, the use of small subsurface explosions.

Monitoring: resistivity
Resistivity measurements (see Section 9.4.3) are capable of detecting CO_2 leakage into geological formations. As for seismics, there are several ways to perform resistivity measurements. The impact on the environment varies with the method used. An advantage of resistivity methods over seismics is the absence of heavy equipment.

Monitoring: fluid samples
Another way of monitoring for leakage is the analysis of samples of formation water likely to have taken up leaked CO_2. Samples could be taken from monitoring wells in the vicinity and additionally they could be ordered from nearby drinking water facilities that

produce from wells. The presence of leaked CO_2 could be indicated by tracer molecules (as being used in the EGR project at K12-B) or possibly by the isotopic composition of the CO_2 (the $\delta^{13}C$ isotope). In the latter case, the isotopic composition of the injected CO_2 must be known and constant throughout the injection program. This may pose a problem for injection projects with a variable source of CO_2. Tracer molecules provide a way to mark the injected CO_2; in addition, tracer molecules are known to migrate through the subsurface faster that CO_2, providing an early warning of imminent elevated CO_2 fluxes. The impact of this monitoring method on the environment would be minimal, especially when existing wells are used. New observation wells should preferably not penetrate the cap rock above the storage reservoir.

Table 9.1 CO_2 leakage paths along wellbore and related monitoring techniques

Leakage path	Monitoring techniques	Application in monitoring phase
Pathways between cement, casing and formation	Logging tools (CBL, CIL etc.)	Preparation, operation, closure
	Soil gas sampling at the surface near the well.	All
Casing failure and through well	Logging tools, well fluid samples	Preparation, operation, closure
Pathways along well, into overburden	(Time-lapse) seismic surveys	Preparation, operation, post-closure
	VSP, reverse VSP	Preparation, operation, post-closure
Pathways along well, into overburden and to surface	Groundwater fluid sampling; soil gas sampling Resistivity methods at surface	All

Monitoring: CO_2 flux measurements

A final way to monitor leakage into formations into which the CO_2 migrates away from the well is to measure the CO_2 concentration, composition and flux at or near the surface. This could be done in areas where seepage to the soil via preferred migration paths would be expected. Impact of this type of monitoring on the environment would be minimal.

9.4 Practical applicability

9.4.1 Casing and cement integrity tools

Casing integrity and cement-casing-formation bond integrity monitoring is required to ensure continued containment.

Casing corrosion

Casing corrosion can cause CO_2 leakage and can be monitored by using for example an Ultrasonic casing imager (UCI) tool. It locates and quantifies casing damage or corrosion. The design is specifically engineered for high-azimuthal-resolution images and detailed examination of both the inner and outer surfaces of casing ranging from $4\frac{1}{2}$' to $13\frac{3}{8}$', resulting in improved echo detection. Full azimuthal coverage with a 2 MHz focused ultrasonic transducer is used to analyze the reflections. Signal arrivals are analyzed to provide the casing thickness and surface condition images, and even small defects on both internal and external casing surfaces are quantified. Measurements can also be performed in horizontal wells.

Cement integrity
To prove that the storage will not leak and also to set baseline conditions, it is necessary to monitor the cement and casing integrity. Sonic and ultrasonic tools are available that measure the bond between casing and cement:

- In the presence of cement, the signal is weak because the cement attenuates the vibration of the metal.
- In the absence of cement, the casing vibrates freely, generating a strong signal.

Factors that affect the quality of the cement bonding before or during CO_2 injection are:

- Compressive strength of the cement in place.
- Temperature and pressure changes applied to the casing during injection.
- Epoxy resin applied to the outer wall.

CO_2 flow behind casing
Well logging tools exist to sample formation fluids behind the casing. An example of such a tool is the cased hole dynamics tester. It is a technologically advanced tool capable of measuring multiple pressures and sampling fluids behind a cased wellbore. It has the unique ability to drill through a cased borehole and into the formation, perform multiple pressure and temperature measurements, recover fluid samples and then plug the hole made in the casing. Its main applications are:

- evaluation of old wells for bypassed hydrocarbons or CO_2;
- reduced-risk alternative to open hole formation testing under difficult conditions;
- pressure monitoring during water, steam and CO_2 injection.

Its ability to monitor the annulus temperature profile it can identify flow behind casing and therefore any well integrity failure.

Impact on operations
The impact on operations of monitoring well integrity is that injection is required to be interrupted for a period of time. Some tools require the tubing to be lifted.

Monitoring frequency
Baseline tests are to be performed as part of the site preparation phase, with the results from these tests providing baseline data. Monitoring frequency is suggested to be once a year, at least for the pilot projects. A lower frequency can be used, depending on experience with CO_2 and injection effects on casing and cement.

9.4.2 Seismic methods

Seismic methods provide the possibility to image a large subsurface volume, with a high resolution. The Sleipner project shows that seismic methods provide a clear view of the CO_2 plume in the subsurface. However, seismic waves cannot be used to monitor CO_2 inside a (depleted) gas field, as the contrast between gas–saturated and CO_2–saturated rock is small. Once CO_2 leaks from a reservoir, seismic methods can be used to monitor its progress.

When the overburden analysis suggests that CO_2 leaking along the well may follow spill paths into the overburden, seismic methods can be used to monitor the CO_2 plume. This monitoring may be required when the CO_2 is expected to arrive at the surface in sensitive areas. The detection threshold of surface-based seismic methods is of the order of $1 \cdot 10^4$ m^3 of CO_2–saturated rock at depths of about 1000 m, for realistic survey parameters (Wilson & Monea, 2004). This illustrates the high resolution that can be reached with seismic surveys. Seismic waves are relatively insensitive to the level of CO_2 saturation and the amount of CO_2 that leaked out of the reservoir can be estimated only with a large uncertainty (Arts et al, 2004).

An alternative to surface-base seismic method, well-based methods (VSP or reversed VSP) provide a higher resolution in the subsurface, as either source or receivers are located close to the zone of interest. For CO_2 leakage originating at the well, well-based seismics will provide a clear image of the CO_2 near (but not at) the well.

At the Sleipner storage project, time-lapse seismic surveys are performed at roughly 2 year intervals, to monitor the progress of the CO_2 plume inside the aquifer. For gas fields in the onshore Netherlands subsurface there is no need for this level of monitoring when the storage capacity is known and the injection is limited. If CO_2 is expected to be distributed in the overburden and hazards are high, then time-lapse surveys at 5-year intervals are probably sufficient to follow the CO_2 plume.

The impact of seismic surveys is considerable, for the short duration of the survey. In the case of VSP or reverse-VSP, the well needs to be cleared. Seismic sources can be chosen to minimise effects on existing infrastructure. The noise level in densely populated or industrialised areas can be a limiting factor to the resolution in the seismic data.

9.4.3 Resistivity measurements

Ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. Electrical resistivity surveys have been extensively used for environmental surveys. The resistivity measurements are normally made by injecting current into the ground through two current electrodes and measuring the resulting voltage difference at two potential electrodes. From the current and voltage values, an apparent resistivity value is calculated.

The resistivity of ground water varies from 10 to 100 ohm·m depending on the concentration of dissolved salts. When water dissolves CO_2 its resistivity changes, which makes the resistivity method a useful technique for mapping these kinds of anomalies.

The depth and vertical resolution of the method is related to electrode spacing and resistivity contrast while lateral resolution depends on the electrode density, the type of array used and the resistivity contrast.

When elevated CO_2 concentrations occur in the shallow subsurface, surface-based resistivity measurements could be used to detect and monitor CO_2. As is the case for the resolution, the threshold for resistivity measurements to detect CO_2 concentrations depend on the distance of the CO_2 from the electrodes, the type of array used and the resistivity contrast in the subsurface.

The surface-based resistivity measurements generally have a limited depth range. Alternative methods of resistivity measurements could be used to overcome this shortcoming. These include cross-hole resistivity surveys and downhole-surface resistivity measurements. These latter types of measurements could also give a much higher resolution compared to surface-based surveys.

The impact of resistivity measurements on the surrounding differs in the way the measurements are taken, ranging from only minimal disruption and relatively low costs during a surface-based survey to a more disruptive and costly cross-hole or downhole-surface operation. Besides the presence of the equipment there is no further hinder because resistivity measurements create no noise or unwanted effects.

9.4.4 Surface measurements of CO_2 concentration and fluxes

Direct (near) surface measurements can determine CO_2 concentrations and CO_2 fluxes. Further, they can be used to ascertain if there is CO_2 leaking to the surface by measuring an increase of the CO_2 concentration or flux, by measuring the isotopic composition of CO_2 or the presence of tracer molecules. More densely spaced measurements, either or both in time and space, should be taken where preferred leakage pathways surface. Locations like these can be identified by geological studies of the reservoir overburden. A measurement of radon concentrations at the surface can identify the location of subsurface faults, as a refinement and validation of the overburden analysis.

CO_2 concentration and flux measurements
Low cost CO_2 sensors, based on infrared detection of CO_2, can be buried in shallow monitoring wells in high-risk areas (preferred pathways) or below sensitive buildings. These sensors are only capable of measuring absolute CO_2 concentrations; it is necessary that historic data is available, including daily and seasonal trends to determine the level and variation in CO_2 concentration. For a more detailed and complete analysis flux readings and additional samples should be taken at regular intervals or when CO_2 sensors give indications of elevated CO_2 levels. The samples should be examined for their isotopic content of various molecules like CO_2, CH_4 and tracer molecules, if relevant.

Soil gas and water samples
Gas or water samples can also be taken from deeper locations like nearby water wells or (deeper) monitoring wells. Note that in the case where only the absolute concentration of CO_2 is measured it is very unlikely that changes below 1-2% can be identified as CO_2 leakage to the surface. Deviations in trends might be larger and make it impossible to detect an occasional seepage from the reservoir.

Isotope and tracer measurements
The addition of tracer molecules is a straightforward technique, requiring low amounts of tracers, at negligible cost. Tracer measurement can be performed at the *pptr* (parts per trillion) level.

Measurement frequency

The frequency of measurements varies among the type of data collected. For CO_2 concentration measurements, it is advisable to collect data on a continuous basis, as natural background levels are affected by weather and season. The baseline dataset should at least contain the seasonal variation in the area; data collection should start at least one year in advance of CO_2 injection. To rule out seepage, regular measurements of CO_2 isotopes and / or tracer molecules have to be carried out. The frequency of these measurements is higher at first (typically once a month), to establish a baseline, and lower once temporal variations are clear. After closure of the storage site, isotope and tracer analysis could be triggered by anomalous readings from the CO_2 concentration sensors.

The impact of these (near) surface measurements is negligible although when placing hundreds of buried CO_2 sensors and having to take and analyse numerous gas and/or water samples the costs might grow considerably.

9.5 Planning monitoring systems

A detailed study of the storage project is required to identify the storage aspects associated with the highest risks. These can be existing wells, well-related spill paths or sensitive areas at the surface. Monitoring should focus on these high-risk aspects. The choice of monitoring techniques follows from an analysis of expected leakage and the resolution and accuracy of available techniques. A study on the impact of leakage associated with the high-risk factors will have to determine which monitoring efforts are justified. This will also lead to different monitoring systems for similar storage projects in different areas in the Netherlands (e.g., densely populated or industrialised vs. rural areas).

Monitoring in different storage phases

A CO_2 storage project can be divided into different phases: preparation, operation, closure and post-closure. Monitoring efforts are required in each phase.

- Preparation phase. During this phase, which also includes the detailed site study mentioned above, a baseline is to be defined for each element of the monitoring system, to define the state of the system prior to injection of CO_2. The data are to be used to validate the physical models of the system, which are used to interpret the monitoring data during later phases of the project. While for some techniques defining a baseline means a single measurement (e.g., a baseline seismic survey), for other techniques defining a baseline implies running systems for some length of time to capture daily or seasonal variations in the background data (e.g., CO_2 soil concentrations).
- Operation phase. This is the phase with most intensive monitoring efforts, collecting data to prove safe and effective storage. Monitoring data are to be compared with predictions from the model(s) of the injection system, to identify deviations from expected behaviour. During the operational phase, as well as during the post-closure phase, intensified monitoring may be required when system deficiencies are detected or when the system behaves unexpectedly.
- Closure phase. At the end of injection, the injection system will be dismantled, along with part of the monitoring system (such as equipment in wells that are abandoned). Monitoring focus will change at this point, with emphasis on proving continued containment.

- Post-closure phase. Monitoring is continued, at a reduced level, until the system is shown to be in a stable, safe state. The definition of this state is site-dependent, as is the period of time needed by the system to reach this state. In pilot projects, it is advisable to retain accessibility to injectors and monitor wells (if any), to study reservoir behaviour after the injection phase. Periodically, reservoir pressure and temperature can be measured and gas samples can be taken. The gas samples can be analysed to study the mixing inside the reservoir (CO_2 mixing with residual natural gas; redistribution of water, natural gas and CO_2 in the reservoir). A stable state could be defined to exist when the reservoir state reaches equilibrium (within bounds). Once a stable state is reached, the injection site may be abandoned completely and monitoring may cease. At this moment, there is insufficient experience to define the minimum period during which a storage system is to be monitored after closure.

Reducing monitoring effort
It is emphasised that at this moment, ahead of any on-shore commercial CO_2 storage project, monitoring of such projects has a strong R&D component. There is very little experience which can be used to suggest a reasonable monitoring period. The key to developing effective monitoring strategies is to use the early projects to gain experience and to optimise methods and techniques for subsequent projects.

Site abandonment
It is foreseen that in future projects site abandonment may take place immediately after injection is ceased, closing and abandoning open wells, to minimise the risk of leakage along the wellbore. This will become possible once sufficient confidence is built up on abandonment methods and on reservoir behaviour after injection. It may take a number of injection projects, for different types of reservoir and cap rock, to reach such a state of confidence.

Pilot and demonstration projects
Monitoring systems in the first several CO_2 storage pilot and demonstration projects are expected to be more complex and to use more monitoring techniques than those in subsequent projects. Firstly, the applicability of monitoring techniques originally designed and developed for oil and gas production to CO_2 monitoring will become clear in the pilot storage projects. Examples of such techniques are well logging tools.

In addition, data will be collected to prove the efficacy of storage procedures. For example, the efficacy of well completion and well abandonment methods must be proven, to reduce the need for extensive well monitoring in future projects. Secondly, pilot projects should aim at using new, dedicated techniques for CO_2 monitoring, to optimise monitoring efforts, with the eventual aim of minimising monitoring efforts in future CO_2 storage projects. It is expected that with growing experience with CO_2 storage and with the development and use of dedicated monitoring systems, the monitoring of subsurface storage will approach an acceptable ‘minimum’ level.

9.6 Conclusions for a project-specific EIA

General issues for an EIA in Chapter 9

Generally in an EIA there is a chapter dedicated to monitoring and evaluation. In this chapter it is described how the expected impacts will me measured and checked if this is really the impact of the activities. After a certain period these findings are evaluated to determine if the activity can continue as planned; or maybe it will be decided that mitigating measures have to be taken.

Specific attention for CO_2 storage in Chapter 9

The monitoring of CO_2 storage is, almost by definition, site specific. Each depleted gas reservoir has its own geometry and properties, well distribution and well characteristics, which need to be assessed for storage hazards. Although for the majority of fields the reservoir itself and the cap rock can be considered safe, the wells in the field must be studied in detail. Rules and plans for storage and monitoring have to be defined for a site-specific EIA.

10 MONITORING (EMERGENCY) RESPONSE PLAN

The appropriate responses to monitoring data depend on the purpose of the monitoring in the first place. Definition of the responses to observations concerned with confirming the safe and satisfactory operation of the system must be part of the risk management plan for the specific storage project. In extreme cases these could be considered as emergency responses. Some other monitoring information, such as observations making up baseline surveys, demands no response.

The detailed types of responses which are available will always be project specific. There are nevertheless some commonly available types of response, including to the low-probability event of leakage. These are discussed below. It should be noted that some are clearly restricted by the phase of the project e.g. modification of the injection process itself can only occur during the injection period.

10.1 Possible responses

Wells

Wells are commonly used for both injection and for production. There is a wide range of procedures available in the oil and gas industry for improving their injection performance and for counteracting leakage along them. These techniques are also applicable to CO_2 storage.

Injection process

One response to excess pressure in the reservoir is to stop injection, and this is the only option if it is full. Reducing the injection rate may be appropriate if the pressure build up is local to the well. In that case sustaining a planned filling rate could involve the (construction and) use of additional wells or of wells with a more advantageous geometry.

Leakage treatment

If it is observed that CO_2 will have an adverse effect on a useful body of water, such as a drinking water aquifer, then the cheapest and most certain option may be to treat the water before it is used.

New data acquisition

If a leak is suspected, e.g. by inference using modelling studies (material balance etc), then new data acquisition may be planned in order to identify the leak with more confidence. Alternatively, if the model (re-)interpretations indicate the site's risk profile to evolve to unacceptable levels, then new data acquisition may be planned in order to reduce the risk profile through improved understanding of the reservoir.

10.2 Action to be taken based on the monitoring results

The results of monitoring can trigger actions, and these generally concern risk management or mitigation. For identified risks the actions to be taken in a specific case must be defined in the project's risk management plan.

Two examples are given below of the types of actions which could be taken if the monitoring shows that unexpected or unwanted processes are occurring:

1. Pressure reduction
2. Sealing the well zone

Pressure reduction
If there is leakage from the reservoir, which could result in an impact at or near the surface, then one option is that the pressure in the reservoir would be reduced. As discussed above, this may involve adjustment of the injection process, but in an extreme case some CO_2 might have to be released. If this became necessary, for example in the post-closure situation, it could even require construction of a new well and of surface facilities for handling and transport or for venting of the discharged CO_2.

Sealing the well zone
If a large flow is observed near the well then the surrounding area would be cleared and the pressure in the reservoir reduced. Options for reducing reservoir pressure have been discussed above. The options available for sealing the well zone depend on whether it is still in operation. In that case the option of working from inside the well is probably the better. Drilling to inject and cap rock around the outside of a closed well is an option in principle, but, as is generally the case, the costs and probability of success would have to be weighed against those for other options.

10.3 Critical values

It can be anticipated that the critical values of monitored parameters, which would lead to measures being taken, would be determined on the basis of the original modelling and planning, but that they might be modified on the basis of the observations made during operation. It is likely, for example, that the pressure within the reservoir would be limited, e.g. in order to avoid damaging the cap rock. The allowable injection rate, which would depend in part on this pressure limit, might well be adjusted on the basis of observations made during a pilot injection phase.

10.4 Plan for possible implementation of recovery measures

In the case that the monitoring results or other observations indicate a substantial negative impact from the storage system, and no other suitable remedial measures are available, then recovery of the injected gas could be required (LAP condition). It can reasonably be assumed that this will not be required once the authorities have allowed the facility to be closed, by issuing an abandonment permit. The decision to allow a storage facility to be closed will only be made once stable and safe conditions have been demonstrated to exist within the reservoir. It can therefore be assumed that the injection well will still be available for use in the recovery operation before abandonment.

During recovery two credible procedures are:

- Controlled release into the air.
- Removal through the original delivery pipelines.

Other implications of recovery of CO_2 depend on the context of the project. In the case of a pilot project this might be considered to be merely an unfortunate by-product of a large gain in useful experience. In the case that some financial advantage had accrued as a result of the saved emissions then these would be cancelled unless another suitable location for storage was available for immediate use.

10.5 Issues in Chapter 10 of a specific project EIA

General issues for an EIA in Chapter 10

As mentioned at the end of Chapter 9, monitoring and evaluation, are standard parts of an EIA. In addition a monitoring response plan gives information on how to react when monitoring shows that critical values are exceeded. In detail this is more an operational plan then part of an EIA. For an EIA it is important to make clear that action can be taken and to give an indication of the type of action available.

Specific attention to CO_2 storage in Chapter 10

Issues to be considered include the following:

- definition of critical values of observations in the context of a risk management plan;
- definition of the appropriate responses to observations approaching critical values;
- definition of responses for emergencies.

11 KNOWLEDGE GAPS

The identified knowledge gaps concern the planning, implementation and closure of an underground storage facility for CO_2 in the Netherlands. Knowledge gaps on implementation include lack of a process control filosophy and a process safeguarding philosophy (for injection, closure and post closure phase). These gaps may be technical, especially in a particular case, such as the details of existing penetrations into a prospective reservoir, but there are also more general gaps, particularly those surrounding the issues of ownership and liability. These are related to the long term uncertainty, the future conditions which may influence the filled CO_2 storage facility. In the following sections some of these project-independent gaps are discussed in more detail.

11.1 Gaps in information

It is not known at present how well a CO_2 storage system must perform, in the sense of the amount of leakage which is acceptable. This is potentially significant in the technical context of allowable impacts, but probably more so in connection with complying with the requirements of a CO_2 emissions control programme, and especially so if this involves financial incentives.

Data are lacking on the risk levels associated with subsurface storage of CO_2. There are very few cases in which performance aspects have been investigated and most results are based on model simulations of leakage scenarios for specific conditions (e.g. Van Eijs et al., 2005). Modelling results can be biased by limitations such as the model simplifications and by the uncertainty in the input parameters. There is only a limited amount of local geological, petrophysical and hydrodynamic data available for use in such modelling studies.

There is also very limited information available dealing with the quantification of the probabilities of scenarios involving CO_2 leakage and potential impacts.

The impact of the possible leakage of other gases from the reservoir has had only little attention in this study. It is possible that in case of leakage not only CO_2 will move from the reservoir into the biosphere, but other gases as well. Some of them could have more impact then CO_2.

11.2 Gaps in experience with impacts

Uplift of the ground
Injection of CO_2 might lead to uplift of the ground. It is expected that this will be less than the settlement caused by the gas production but there is still considerable uncertainty. After some reservoirs have been used and monitored, it will become clear if this takes place as expected.

Permanent storage
It is possible to calculate the expectations of CO_2 storage, but there remains uncertainty about how much CO_2 really stays in the reservoir. Sometimes a loss percentage of 1% over a period of 100 years is taken as an assumption. The loss itself might not cause much environmental impact, but it can be important for calculating the amount of stored CO_2, and payments for the storage.

Chemical reactions in reservoir
Although there is existing experience with pumping CO_2 underground it cannot be assumed that this is sufficient to provide a complete understanding of the potential long-term impacts resulting from eternal CO_2 storage systems. It is hoped at present that by using FEP's (an acronym for Feature, Event and Process) to cover all conceivable mechanisms, and by considering these in risk management plans, these unknowns can be satisfactorily contained. This is, nevertheless, still to be demonstrated in practice.

11.3 Gaps on future developments

The current gaps concerning the procedures and requirements for obtaining a permit for a CO_2 storage system can be understood in part as a consequence of the difficulty with allocating the responsibilities for the system, especially in the future. The operator may then no longer exist but it is generally assumed that there will be other bodies which are capable of assuming the long-term responsibility. It is however unclear how and under what conditions a transfer of responsibility will occur.

In the same context, the problem of giving proper consideration to other potential uses of the subsurface must be considered. The current principal potential conflict of interest may be considered to be between storing CH_4 - for energy security - and CO_2 - to reduce climate change. In the future there may be other potential uses which will be prevented by the presence of a reservoir filled with CO_2.

Future human activities are generally considered to be unpredictable, and especially so once any institutional control ceases to be effective. This means that it is not possible to exclude developments at the surface which increase the risk. It is also not possible to exclude future activities which damage the seals keeping the CO_2 within the reservoir. Approaches for accounting for these possibilities could be defined within regulations governing CO_2 storage systems, but such regulations do not yet exist.

11.4 Regulatory gaps

In order to calculate the risk profile of a specific site and monitor its evolution during the injection and post-injection phases, risk tolerance levels are required. Authorities have to state which exposure or impact norms apply, and how much 'Risk' (i.e. probability of exceeding this norm multiplied by the average impact of those scenarios that exceed the norm) can be tolerated. Moreover, authorities should give guidance on the volumes to which these norms pertain.

Without such norms and guidance, the site operator has to make his own assumptions. This will only invite arbitrariness and subjectivity, resulting in ineffective control. Therefore, if models are used to predict the risks, standards are a necessity, just like current (international) design standards for mining installations, rigs and process installations. (see also the appendix of Chapter 14).

11.5 Issues in chapter 11 of a project-specific project EIA

General issues for an EIA in chapter 11
The gaps in knowledge are important because they give insight in the available information at the time of the EIA. It also describes if the gaps are crucial in the way that impacts can be considerable different.

Specific attention to CO_2 storage in Chapter 11
The main gaps in knowledge are:

- There is much information from literature and relevant other projects, but specific information on CO_2 storage onshore in the Netherlands does not exist. As long as a first pilot project is not started, it will remain a gap. It could be considered whether to wait until neighbouring countries have started their own projects.
- An unpredicted impact could occur after a very long period of time, after hundreds or thousands of years. Relevant geological evidence can be obtained demonstrating that former reservoirs were stable for millions of years, but the storage of CO_2 is still a different situation.

Specific gaps could concern some aspects of the following, depending on the availability of information derived from the development and operation of the gas field:

- the reservoir - reaction of the cap rock to the injection of CO_2;
- the reservoir - reaction of the rocks to the injection of CO_2;
- the overburden strata - geometry and properties;
- the surrounding strata - geometry and properties;
- existing wells - geometry and condition;
- faults - geometry, permeability and susceptibility to modification by fluids rich in CO_2.

12 FOLLOW-UP

12.1 Overview of findings

This reports gives an overview of CO_2 storage in onshore gas reservoirs in The Netherlands, including findings from related (international) projects. The main conclusions are:

Technical
- The technical CO_2 storage potential is sufficient for tens to hundreds of years.
- There is an understanding of the site specific aspects of reservoirs in order to judge safety of long term CO_2 storage.
- Former gas reservoirs are considered to be potentially well-suited to long-term CO_2 storage.
- There is experience in the Netherlands with water injection and with gas injection.
- The design rules and methods applicable to long-term CO_2 storage in the Netherlands have not been defined.
- There is no onshore experience in the Netherlands with the injection of CO_2 for long-term storage.
- There is no experience in the world with injection of CO_2 at the rate which would be required to store all the emissions from a large power generating plant.

Risks
- In the Netherlands the probability of CO_2 leakage can be reduced by selection of the reservoir.
- Small risks can be reduced by ensuring wells are properly designed, constructed, and abandoned; and therefore by avoiding those reservoirs that have a large number of previously abandoned wells.
- The main risk is leakage associated with a well penetrating the reservoir.
- Site specific risk assessments are necessary to judge possible effects of long term storage of CO_2. (Ch. 7.3 gives significant leakage rates. However, situation is expected to be controlled within a few days. Therefore, total leakage/ emission is expected to be limited to couple of tonnes).

Overall, a low-risk CO_2 storage project can be implemented in the Netherlands.

Regulations
- For storage of CO_2 in the Netherlands it is possible to build upon existing legislation though amendments are necessary at some points.
- For the amendments account should be taken for international developments on legislation for CO_2 storage, as international policy makers might chose a different approach.
- Currently CO_2 is defined as waste in Dutch legislation. However in the waste legislation there are no conditions set yet for CO_2 storage. The waste definition implies that an EIA is obligatory.
- There are still issues to be settled in the Netherlands:
  - the future responsible authority for a newly established permit and related legal documents relevant to CO_2 storage are presently under debate;
  - the complementation and abandonment of a storage site is not yet well arranged;
  - it is unclear who will be responsible for the CO_2 in the post-closure condition;

- it is unclear when and based on which criteria responsibility will be transferred from operator to government;
- the waste legislation should be adjusted for CO_2 storage.

If CO_2 storage is recognised by the Dutch government as a serious CO_2 reduction option, the government (both national and regional) need to:

- prepare continuous and clear legislation;
- act and cooperate on making the necessary legal amendments;
- establish provisional legislation which will facilitate pilot projects.

Monitoring

- from related projects it is clear that there are many monitoring options which are effective in particular circumstances;
- modeling and monitoring is required to understand and safeguard leakage scenarios;
- learning from monitoring will make clear under which conditions long-term CO_2 storage can be relied upon.

Based on the findings above, we can conclude that if CO_2 storage is to be considered as a serious option for emissions reduction the next logical step is to start a pilot project. The pilot project should be part of four lines of activities which should be pursued if progress is to be made with CO_2 storage in the Netherlands in the near future.

- developing priorities and a list of suitable reservoirs;
- setting up procedures and rules for scheme design;
- defining the legal framework and responsibilities;
- starting a pilot project.

12.2 Establishing priorities

12.2.1 Priorities at provincial level

As it stands the provinces develop their own strategic plans. So far this is mainly for surface level activities but subsurface activities are also becoming important. Now that more gas reservoirs are reaching the end of their productive life the time has come for strategic choices. Which reservoirs can be used to store production water, or gas reserves, or CO_2?

To make a priority list it is possible to make a map showing high or low quality reservoirs for each type of use. To design the maps information from this report can be used, as mentioned in chapter 8. Once they have all the necessary information the decision has to be taken by the provinces.

Identifying which reservoirs are available for long term CO_2 storage would be one of the first steps in further exploring the feasibility and potential of onshore underground CO_2 storage.

12.2.2 Role of CO_2 storage at national level

The Dutch government identified CCS as one of the possible emission reduction options in the Netherlands. Recently published subsidy programs are expected to encourage the building-up of experience with CO_2 storage in the Netherlands. Based on these experiences the potential role of CCS as a serious reduction option can be judged. Meanwhile, it is important to reach agreement on amendments to current laws and regulations which will form the basis for future CCS projects.

From a financial point of view it seems clear that the first projects will be relatively expensive. Initially, at least, the authorities will have to find a way to make CO_2 storage feasible from the cost perspective. For a pilot project it is possible to bridge the gap with subsidy, but in the longer term either the emission rights of CO_2 under the European ETS (Emission Trade System) will have to become more expensive or technical developments have to reduce the costs of CCS, in order to make CCS an economically feasible option. Inclusion of CCS in the European Emission trading scheme might result in cost reductions.

12.3 Design basis

Starting even a pilot project is only possible if a technical basis exists in the Netherlands for the responsible authorities to issue the necessary permits. Consensus is necessary on the appropriate methods to be used in the course of developing and planning a storage scheme. Similarly for the standards which must be satisfied in order to achieve a satisfactory performance and an adequate level of safety, including in the long-term.

Because of the uncertainties inherent in all natural systems, and more particularly because of the objective of storing CO_2 securely for very long periods (i.e. eternity), it is very likely that this technical assessment basis will have to rely heavily on modelling of the reservoir system and on confirmation by monitoring that the design assumptions were reasonable.

Another anticipated feature is the requirement to develop an appropriate risk management procedure. Both the inherent natural uncertainties and the necessity to base decisions on monitoring of the actual behaviour mean that all eventualities must be considered in a framework which permits a flexible response which will ensure the long-term safety.

In this study we have described how the authorities can deal with risk and uncertainty. However, in the end, it is up to them to establish a maximum level of risk. Increasing demands of security will lead to an increase cost per tonne of CO_2. Since CO_2 storage at the moment is not cost effective, this may delay or obstruct serious development of CCS in the Netherlands. Here the Dutch EIA commission can play an important role.

For water injection projects a special methodology has been developed to give the authorities a clear insight into possible impacts, comparing possible impact in the biosphere with risks in the deep underground. The same principle applies here, but the authorities will have to choose between a possible local impact and a global one.

12.4 Legal framework and responsibilities

Long term responsibility for reservoirs
There is still discussion on some issues concerning the use and abandonment of reservoirs. It is not clear from the Dutch legislation who would own the CO_2 when it is stored underground. Furthermore, it is not stated explicitly in Dutch legislation which would be the responsible authority after transfer of liability some time after the abandonment of a storage site. It also is uncertain if and when liability would be transferred from an operator to the government and on the basis of which criteria. These issues need to be addressed, in order to facilitate pilot projects in the short term.

12.5 Starting a pilot project

In this study it has been mentioned that an important next step forward should be a pilot project. It is unlikely that more desk study will significantly increase knowledge and insight on the environmental aspects of CO_2 storage. Therefore starting a pilot and learning from doing seems a sensible thing to do. This is only possible if a pilot project can be developed with a low risk profile. From the information in this study it seems likely that suitable reservoirs are available.

In this study we did not look for a source of CO_2 or for transportation options. Therefore the findings will have to be considered together with information on Capture and Transportation facilities to select possible pilot locations.

The subsidy programs for CCS pilot projects announced by the Dutch government mid April 2007 will be a good way to gain experience with possible environmental aspects of CO_2 storage in the Netherlands.

12.6 The follow-up of the gaps

Operational aspects
The operational aspects of obtaining, monitoring and maintaining well integrity are very specific for oil field practices and limitations of operational aspects. A more detailed review on these issues could further increase the knowledge of the possibilities of CO_2 injection and storage.

Abandoned wells
One of the main concerns for CO_2 storage are wells penetrating potential reservoirs, and, more specifically, abandoned wells. Therefore it is important to ensure that complete information on abandoned wells becomes available, both the location and the details of abandonment. It is important that for each project this information is available, in order to make a risk assessment.

It could also be important to have a rough estimate on how many wells have been abandoned during a period before 1985, when regulations were less stringent with respect to abandonment requirements, making these specific wells less suitable for infinite storage of pressurised gas.

12.7 Enhanced Gas and Oil recovery

As mentioned in chapter 1 this study has focused on long term CO_2 storage, for the single purpose of CO_2 emission reduction. However CO_2 storage can also be used to enhance the recovery of oil and gas from a reservoir (EOR and EGR). Although this has not been part of the study, the results from the study can be used to address these issues.

Most issues that are relevant for permanent storage are also relevant for EOR and EGR. There will be a difference in the surface facilities, since there will be oil or gas production facilities on site and probably a system to reuse CO_2 from the production well. The monitoring system will be different since production of oil or gas and injection of CO_2 take place at the same time.

In the case of EOR and EGR it is important too that the maximum pressure will not be exceeded. In a CO_2 storage project the maximum pressure determines the amount of CO_2 that can be stored. In the case of an EOR or EGR the pressure is used to increase the production. Therefore a higher pressure will mean more CO_2 storage and more production. However if the pressure becomes too high, the risk of leakage will increase. Possibly the maximum pressure during production could be higher then after abandonment. This makes it possible to produce more gas or oil. In that case some CO_2 will have to be released during the abandonment phase.

Chapter 7 concludes that leakage near the well could occur and cause impact in the biosphere. Therefore special attention for the wells is required. For EOR and EGR there is an extra production well. It is important that during production and after abandonment this additional well will also be treated with the same care as the injection well.

12.8 Issues in chapter 12 of a specific project EIA

Chapter 12 is specific for the AMESCO study. In a project specific EIA there is no separate chapter referring to follow-up activities.

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14 APPENDIX OBSERVATIONS ON RISK QUANTIFICATION METHODOLOGY

14.1 Modelling the wells-reservoir-seal-overburden-shallow subsurface-biosphere system

To predict the possible environmental impact and the risks of CO_2 storage the total system of wells-reservoir-seal-overburden-shallow subsurface-biosphere is to be described. Ideally, a quantitative computer model is to be constructed that describes all pertinent physical flow phenomena (fluxes, chemistry, geomechanics) and HSE-impacts with adequate resolution in space and time and, since the majority of values for the subsurface parameters are poorly known, that does this probabilistically. *Continuous* model parameters that are poorly known should be given a range (i.e., a 'probability density function') and poorly known *discrete* model parameters ('scenarios', or 'features' / 'events') should be given a probability of occurrence. In practice, however, this is computationally too demanding and simplified approaches are required. The idealised, comprehensive approach described above is not yet mature. Coupled-physics models are still at the research stage, and high resolution models may be too demanding for current day computers, certainly if they are to be run probabilistically.

A pragmatic approach therefore is to limit the modelling study to the most sensitive (i.e. in terms of HSE-impact) scenarios (and/or stochastic realisations) of the model. To do so, however, one should have an *a priori* notion of these sensitivities, but how to estimate these without a fully comprehensive model is not evident. A recommended approach would be to use peer-reviewed databases of possible events (e.g. leakage flowpaths) and, during a peer-review / challenge process, to select only a few events (scenarios) for further quantitative modelling that are deemed to represent the highest sensitivity in terms of HSE-impact. Of course, such modelling is far from complete and will always be subjective to a significant degree, but given experience and fundamental understanding of the total system the biases in the forecasts can be reduced.

To predict the HSE-impact, the subsurface needs to be described first. Possible leakage pathways should be identified qualitatively and, if necessary, be modelled quantitatively. Subsequently, the physical processes related to CO_2 injection are simulated, the CO_2 fluxes (i.e. in case of leakage: migration to the surface) are predicted in time, and the exposure to CO_2 of the biosphere and shallow subsurface is translated into HSE-impact.

Quantifying the HSE impact

CO_2 fluxes thus reaching the biosphere and shallow subsurface can be translated into HSE-impact if HSE-impact models are coupled to the flux model. An important issue here is that the required model resolutions are compatible. This again will be a function of the HSE impact norms. The norms for the various quantitative indicators have to specified for the appropriate volumes. For example, if a MAC value (Maximum Allowable Concentration) is given as a norm, then this is meaningless without a specification of the volume considered. This volume should in principle govern the model's spatial resolution. Similarly, if a maximum exposure time is given, then this time should govern the model's temporal resolution.

Using probabilistic models, the HSE impacts can be quantified in terms of output pdf's (probability density functions) of the pertinent impact indicators. Given a norm (such as MAC) the cumulative probability of exceeding the norm can be calculated. To calculate the ‘risk’, this cumulative probability should be multiplied by the average value of those Monte Carlo samples that exceed the norm.

14.2 Acceptance norms

Whether or not accept a quantified risk value for a proposed alternative course of action depends on one’s ‘risk tolerance’. The quantified value for ‘risk’ should be compared to the applicable ‘risk tolerance’. If the ‘Risk’ < ‘Risk tolerance’, the proposed alternative is acceptable. See chart below.

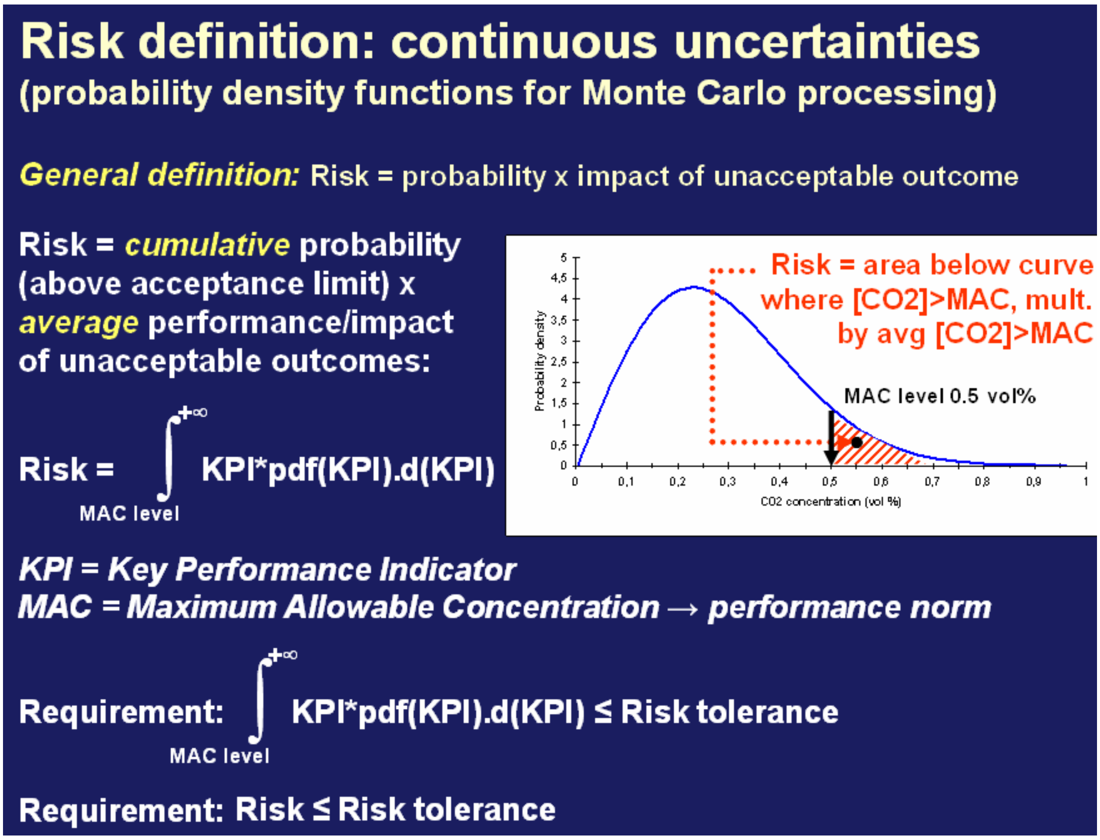

Figure15.1 – definition of ‘risk’ and ‘risk tolerance’ in case of Monte Carlo processing of subsurface and HSE-impact models

14.3 Pragmatic approaches

<u>Hazard prevention</u>

Risk assessment in the classic approach can be visualised by a bow-tie diagram (Figure 15.2). In the limited approach, the potential for CO_2 leakage can be regarded as a hazard, where a hazard is a situation that potentially leads to harmful effects. Risk assessment can then be geared to hazard prevention, without quantifying possible consequences, or HSE-impacts.

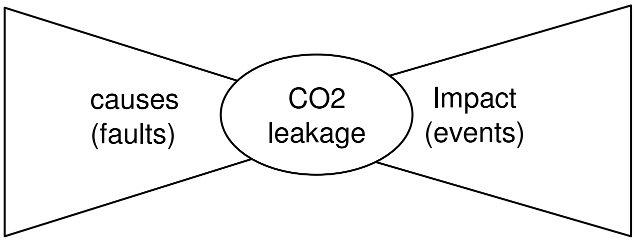

Figure 15.2 Classic risk assessment approach (bow-tie) showing at the left side the causes of leakage and at the right side the impacts.

<u>Exposure assessment</u>
A more elaborate approach is to quantify the impact of the leakage in terms of possible flux out of the reservoir through the overburden, and multiply this by the probability of that leakage event. Since this approach is limited to flux assessment, it is also called 'exposure assessment' rather than 'risk assessment'. The leakage risk can be defined as:

Leakage risk = probability of a flux out of the containment × CO_2 flux out of the containment

It should be noted that in this approach a CO_2 leakage scenario does not assess the HSE-effects at the (near-)surface. If it is likely that most of the escaped CO_2 will be buffered in the overburden due to dissolution of CO_2 in the pore water and/or secondary entrapment and/or mineralisation, this approach may be adequate.

<u>Risk assessment</u>
When the HSE-impact of the calculated CO_2 fluxes is quantified, and when acceptance norms are available, then the probability of exceeding these norms can be estimated. Reference is made to paragraphs 7.7.1-7.7.3. The method given here is the most elaborate.

<u>Limited sensitivity analysis (maximum impact starting from top-event)</u>
Whether opting for exposure assessment or for risk assessment, a minimum number of scenarios can be selected for pragmatic reasons: modelling all or many possible scenarios may be impractical. With such approach, one or several so-called 'top-events' are to be selected, i.e. scenarios that are deemed to represent extreme situations leading to extreme impacts. If such scenarios yield acceptable impacts, it may not be necessary to study additional scenarios. Of course, it should be made plausible that other parameter combinations that have not been studied are unlikely to result in worse impacts.

15 APPENDIX LEGISLATION

15.1 EU EIA Directive

The EU EIA Directive 97/11/EG requires that an environmental assessment be carried out in advance of those public and private projects '*which are likely to have significant effects on the environment*' (Art. 1). EIAs are to be undertaken at least at the project level. To the extent appropriate, Parties are also 'to endeavour to apply' EIA principles to policies, plans and programmes. The environmental impact assessment required may be integrated with the procedures for fulfilling requirements under the IPPC Directive (96/61/EC).

Prior, environmental assessments are required for projects listed in Annex I (21 categories) under Article 4(1) of 85/337/EEC, as amended, including a variety of industrial facilities, but not specifically storage of CO_2 in reservoirs. Projects listed in Annex II are evaluated by the Member States, who must decide whether a prior environmental assessment is required, either on a case-by-case basis or based on thresholds or criteria that the Member States themselves set establish (or both). These projects include a category of 'Other' projects. The category of 'other' includes '*installations for the disposal of wast*e' which could encompass CO_2 injection facilities or storage facilities. Annex II also includes '*any change or extension of projects* listed in Annex I or Annex II, already authorized or in the process of being executed, which may have a significant adverse effect on the environment.'

The applicability of the EIA Directive will depend upon whether EU Member States decide that a CCS project is considered 'likely to have significant effects on the environment by virtue of its nature, size or location' (Art. 2). In applying Annex II, different Member States may decide to employ different criteria in evaluating whether an environmental assessment is needed for geological storage. As mentioned earlier, the Dutch EIA-Decree is based on the EU directive 97/11/EG.

15.2 SEA Protocol and Directive

The 2003 SEA Protocol[95] to the Convention on Strategic Environmental Assessment in a Transboundary Context aims to provide for a high level of environmental protection, including health effects. Once it will be in force, the Protocol applies to the relevant provisions of the UNECE Conventions on Environmental Impact in a Transboundary Context and on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters (Art. 15).

Under the SEA Directive, each Member State is to ensure that an SEA is carried out for *plans and programmes* '*which are likely to have significant environmental, including health, effect.*'

The phrase 'e*nvironmental, including health, effect*' is defined as 'any effect on the environment, including human health, flora, fauna, biodiversity, soil, *climate, air*, water, landscape, *natural sites*, material assets, cultural heritage *and the interaction among these factors*.' CCS is likely to be considered to have such an effect, as CCS impacts climate, air, and the interaction among many of the listed factors.

[95] 2003 Protocol on Strategic Environmental Assessment.

‘*plans and programmes*’ means plans and programmes and any modifications to them that are (a) required by legislative, regulatory or administrative provisions; and (b) subject to preparation and/or adoption by an authority or prepared by an authority for adoption, through a formal procedure, by a parliament or a government’ (Art. 1). Plans and programmes in the areas of energy, industry, transport, waste management, or ones that may affect Habitats Directive sites, may be relevant to CCS activities. Plans and programmes to create a regulatory framework for CCS activities or creates regulatory incentives for CCS, or addresses accounting frameworks for CCS would seem to require an SEA, but only if these p*lans and programmes are likely to have significant effects on the environment.* The assessment is to be carried out *during preparation of the plan or programme and its adoption or submission to a legislative procedure*. A report must be prepared that identifies, describes and evaluates the likely significant effects. For plans and programmes subject to SEAs, an Environmental Report must be prepared that identifies, describes and evaluates the likely significant environmental, including health, effects of implementing the plan or programme and its reasonable alternatives.

Annex I contains 17 categories of projects. These are similar to those in the Espoo Appendix I (see above). A number of these are relevant to CCS. *Annex II* contains 90 categories of projects, a number of which may impact storage of CO_2. These include:

- deep drillings (in particular geothermal drilling, drilling for the storage of nuclear waste material, drilling for water supplies, with the exception of drillings for investigating the stability of the soil);
- waste disposal installations (including landfill), as far as not included in annex I.

15.3 Relevant legal documents

15.3.1 Mijnbouwwet (Mining Act)

Article 1i. Toepassing Mijnbouwwet
Artikel 1 In deze wet en de daarop berustende bepalingen wordt verstaan onder: i) Opslaan van stoffen: het brengen of houden van stoffen op een diepte van meer dan 100 meter beneden de oppervlakte van de aardbodem dan wel het terughalen van die stoffen anders dan het in de ondergrond brengen of houden of daaruit terughalen van stoffen gericht op het onttrekken van aardwarmte aan de ondergrond.

Artikel 3. Eigendom
1. Delfstoffen zijn eigendom van de staat.
2. De eigendom van delfstoffen die met gebruikmaking van een winningsvergunning worden gewonnen, gaat door het winnen daarvan over op de vergunninghouder. De eerste volzin is van overeenkomstige toepassing ten aanzien van delfstoffen die met gebruikmaking van een opsporingsvergunning in de vorm van monsters of formatiebeproevingen aan de ondergrond worden onttrokken.
3. De eigendom van stoffen die met gebruikmaking van een opslagvergunning worden teruggehaald, koMton door het terughalen daarvan te berusten bij degene die eigenaar was van de stoffen direct voorafgaande aan het in de ondergrond brengen daarvan, dan wel bij degene die ten tijde van het terughalen de rechtsopvolger is van die eigenaar.

4.	De staat wordt voor alle met de eigendom van delfstoffen verband houdende handelingen vertegenwoordigd door Onze Minister.

Artikel 7. Exclusiviteit algemeen	
1.	Een vergunning wordt niet verleend, voorzover deze bij het in werking treden zou gaan gelden voor een gebied waarvoor op dat tijdstip reeds een door een ander gehouden vergunning voor dezelfde delfstof geldt.
2.	Een vergunning wordt evenmin verleend, voorzover deze bij het in werking treden zou gaan gelden voor een voorkomen waarvoor op dat tijdstip reeds een door een ander gehouden opslagvergunning geldt.

Hoofdstuk 3. Vergunningen voor het opslaan van stiffen	
Artikel 25. Algemeen Vergunningen voor opslag	
1.	Het is verboden stoffen op te slaan zonder vergunning van Onze Minister.
2.	Het verbod geldt niet met betrekking tot bij algemene maatregel van bestuur omschreven categorieën van gevallen.

Artikel 26. Exclusiviteit gerelateerd aan opslagvergunning	
1.	Een opslagvergunning wordt niet verleend, voorzover deze bij het in werking treden zou gaan gelden voor een gebied waarvoor op dat tijdstip reeds een door een ander gehouden opslagvergunning geldt.
2.	Een opslagvergunning wordt evenmin verleend, voorzover deze bij het in werking treden zou gaan gelden voor een voorkomen waarvoor op dat tijdstip reeds een door een ander gehouden vergunning als bedoeld in artikel 6 geldt.

Artikel 27. Weigeren opslagvergunning		
1.	Onverminderd artikel 26 kan een opslagvergunning slechts worden geweigerd:	
	a.	op grond van de technische of financiële mogelijkheden van de aanvrager;
	b.	op grond van de manier waarop de aanvrager voornemens is de activiteiten, waarvoor de vergunning wordt aangevraagd, te verrichten;
	c.	op grond van het gebrek aan efficiëntie en verantwoordelijkheidszin waarvan de aanvrager blijk heeft gegeven bij activiteiten onder een eerdere vergunning op grond van deze wet;
	d.	in het belang van de veiligheid;
	e.	in het belang van de landsverdediging, of
	f.	in het belang van een planmatig beheer van voorkomens van delfstoffen of aardwarmte.
2.	Een vergunning kan op grond van de financiële mogelijkheden van de aanvrager worden geweigerd als onvoldoende verzekerd is dat de aanvrager zal voldoen aan hem op te leggen verplichtingen als bedoeld in de artikelen 46, 47 en 102.	
3.	Met het oog op de toepassing van het eerste en tweede lid kunnen bij ministeriële regeling nadere regels worden gesteld, die bij de beslissing op een aanvraag om een vergunning in acht worden genomen.	

Artikel 28. Overige bepalingen en beperkingen opslagvergunning	
In een opslagvergunning wordt bepaald voor welke stoffen, voor welk gebied en voor welk tijdvak zij geldt. Daarbij wordt bepaald dat:	
a.	de in de ondergrond gebrachte stoffen voor een in de vergunning geregeld tijdstip teruggehaald moeten worden, of
b.	de stoffen definitief in de ondergrond achtergelaten moeten worden.

Artikel 29
1. Een opslagvergunning kan voorts onder andere beperkingen dan die bedoeld in artikel 28 worden verleend. Aan een vergunning kunnen voorschriften worden verbonden.
2. De beperkingen en voorschriften, anders dan voorschriften op grond van artikel 98, kunnen slechts worden gerechtvaardigd door het belang van de veiligheid, de landsverdediging of een planmatig beheer van voorkomens van delfstoffen of aardwarmte.

Artikel 30
Onze Minister kan een opslagvergunning wijzigen of intrekken, indien dit wordt gerechtvaardigd op grond van de in artikel 29, tweede lid, bedoelde belangen.

Artikel 31
De houder van een opslagvergunning kan zijn vergunning slechts met schriftelijke toestemming van Onze Minister op een ander doen overgaan. De artikelen 20, tweede en derde lid, 26, tweede lid, en 27 zijn van overeenkomstige toepassing.

Artikel 32
Ten aanzien van een opslagvergunning zijn de artikelen 14, 17, 19, 21, met uitzondering van het vierde lid, en 22 van overeenkomstige toepassing.

Hoofdstuk 4. De zorg voor een goede uitvoering van activiteiten
§ 4.1 Algemene verplichtingen
Artikel 33
De houder van een vergunning als bedoeld in artikel 6 of 25, dan wel, ingeval de vergunning haar gelding heeft verloren, de laatste houder daarvan, neeMton alle maatregelen die redelijkerwijs van hem gevergd kunnen worden om te voorkomen dat als gevolg van de met gebruikmaking van de vergunning verrichte activiteiten:
a. nadelige gevolgen voor het milieu worden veroorzaakt;
b. schade door bodembeweging wordt veroorzaakt;
c. de veiligheid wordt geschaad, of
d. het belang van een planmatig beheer van voorkomens van delfstoffen of aardwarmte wordt geschaad.

De volgende artikelen gelden ook voor opslag, ondanks dat er winning staat.

Artikel 34
1. Het winnen van delfstoffen vanuit een voorkomen geschiedt overeenkomstig een winningsplan.
2. De houder van een winningsvergunning of de krachtens in artikel 22 bedoelde aangewezen persoon dient een winningsplan in bij Onze Minister.
3. Het winningsplan behoeft de instemming van Onze Minister.
4. Afdeling 3.4 van de Algemene wet bestuursrecht is van toepassing op de voorbereiding van het besluit omtrent instemming met een winningsplan, voorzover het winnen van delfstoffen niet geschiedt in het continentaal plat of onder de territoriale zee vanuit een voorkomen dat is gelegen aan de zeezijde van de in de bijlage bij deze wet vastgelegde lijn. Zienswijzen kunnen naar voren worden gebracht door een ieder. Afdeling 3.4 van de Algemene wet bestuursrecht is niet

	van toepassing indien het een besluit betreft inzake wijziging van een besluit omtrent instemming met een winningsplan.
5.	Het eerste lid is niet van toepassing op het winnen van delfstoffen in het kader van het verkrijgen van gegevens voor zuiver wetenschappelijk onderzoek of voor het door de centrale overheid te voeren beleid.

Artikel 35		
1.	Het winningsplan bevat voor elk voorkomen binnen het vergunningsgebied ten minste een beschrijving van:	
	a.	de verwachte hoeveelheid aanwezige delfstoffen en de ligging ervan;
	b.	het aanvangstijdstip en de duur van de winning;
	c.	de wijze van winning alsmede de daarmee verband houdende activiteiten;
	d.	de hoeveelheden jaarlijks te winnen delfstoffen;
	e.	de kosten op jaarbasis van het winnen van de delfstoffen;
	f.	de bodembeweging ten gevolge van de winning en de maatregelen ter voorkoming van schade door bodembeweging, voorzover het winnen van delfstoffen niet geschiedt in het continentaal plat of onder de territoriale zee vanuit een voorkomen dat is gelegen aan de zeezijde van de in de bijlage bij deze wet vastgelegde lijn, tenzij Onze Minister anders heeft bepaald.
2.	De Technische commissie bodembeweging brengt aan Onze Minister advies uit omtrent het eerste lid, onderdeel f.	
3.	Bij of krachtens algemene maatregel van bestuur kunnen nadere regels worden gesteld met betrekking tot het winningsplan.	

Artikel 36		
1.	1. Onze Minister kan zijn instemming met het opgestelde winningsplan slechts weigeren:	
	a.	in het belang van het planmatig beheer van voorkomens van delfstoffen;
	b.	in verband met het risico van schade ten gevolge van beweging van de aardbodem, voorzover het winnen van delfstoffen niet geschiedt in het continentaal plat of onder de territoriale zee vanuit een voorkomen dat is gelegen aan de zeezijde van de in de bijlage bij deze wet vastgelegde lijn, tenzij Onze Minister anders heeft bepaald.
2.	Onze Minister kan zijn instemming verlenen onder beperkingen of daaraan voorschriften verbinden, indien deze gerechtvaardigd worden door een grond als genoemd in het eerste lid.	
3.	Onze Minister kan zijn instemming intrekken of de beperkingen en voorschriften wijzigen, indien dat gerechtvaardigd wordt door de in het eerste lid genoemde gronden.	

Artikel 41. Bodembeweging	
1.	Met het oog op de kans op beweging van de aardbodem worden metingen verricht voor de aanvang van het winnen van delfstoffen, tijdens het winnen en tot dertig jaar na het beëindigen van het winnen. Bij of krachtens algemene maatregel van bestuur worden regels gesteld omtrent deze metingen en de rapportage over de uitkomsten daarvan.
2.	Dit artikel is van overeenkomstige toepassing op het winnen van aardwarmte en het opslaan van stoffen.

3.	Dit artikel geldt, tenzij in de desbetreffende vergunning anders is bepaald, niet met betrekking tot het winnen van delfstoffen of aardwarmte of het opslaan van stoffen in het continentaal plat en onder de territoriale zee, voorzover het winnen of het opslaan plaatsvindt vanuit of in een voorkomen dat gelegen is aan de zeezijde van de in de bijlage bij deze wet vastgelegde lijn.
4.	De verplichtingen van dit artikel rusten op de houder van de desbetreffende, in artikel 6 of 25 bedoelde vergunning, dan wel, indien de vergunning haar geldigheid heeft verloren, op de laatste houder van de vergunning. Indien de vergunning wordt gehouden door meer dan een natuurlijke persoon of rechtspersoon, rusten de verplichtingen van dit artikel op de in artikel 22 bedoelde aangewezen persoon, dan wel, indien de vergunning haar geldigheid heeft verloren, de laatstelijk op grond van dat artikel aangewezen persoon.

Artikel 38. Relatie met Wet Milieubeheer
Onze Minister houdt de beslissing op een aanvraag om een milieuvergunning als bedoeld in de Wet milieubeheer voor een mijnbouwwerk ten behoeve van het winnen uit een voorkomen dat is gelegen aan de landzijde van de in de bijlage bij deze wet vastgelegde lijn aan totdat hij heeft ingestemd met het winningsplan, bedoeld in artikel 34.

Artikel 127. Staatstoezicht
Het Staatstoezicht op de mijnen heeft tot taak het toezien op het verrichten van verkenningsonderzoeken, op het opsporen en het winnen van delfstoffen en aardwarmte en op het opslaan van stoffen.

15.3.2 Mijnbouwbesluit

§ 3.2. Het opslaan van stoffen

Artikel 26		
1.	Voor het opslaan van stoffen als bedoeld in artikel 39, onderdeel b, van de wet bevat een desbetreffend plan:	
	a.	een beschrijving van de hoeveelheid en de samenstelling van de stoffen die worden opgeslagen;
	b.	een opgaaf van de gegevens met betrekking tot de structuur van het voorkomen en de ligging van het voorkomen ten opzichte van andere aardlagen, met bijbehorende geologische, geofysische en petrofysische studies en de daarbij gehanteerde onzekerheidsanalyses;
	c.	een opgaaf van de stoffen die worden gebruikt bij het in de ondergrond brengen van de stoffen;
	d.	een inventarisatie van de risico's ten aanzien van de verspreiding van de stoffen die in de ondergrond worden opgeslagen, het optreden van chemische processen in de ondergrond en de aantasting van de in de ondergrond aanwezige reservoirs met delfstoffen of de samenstelling van deze delfstoffen;
	e.	een inventarisatie van maatregelen die worden getroffen om de risico's, bedoeld in onderdeel d, te voorkomen; Staatsblad 2002 604 8

	f.	een beschrijving van de wijze waarop het voorkomen na beëindiging van de opslag wordt achtergelaten, en
	g.	een risico-analyse omtrent bodembeweging en bodemtrillingen als gevolg van de opslag.
2.	Artikel 24, eerste lid, onderdelen d tot en met g, en onderdelen l, q, r en s, alsmede artikel 24, tweede lid, zijn van overeenkomstige toepassing, met dien verstande dat het eerste lid, onderdeel g, en de onderdelen q, r en s niet van toepassing zijn op voorkomens die gelegen zijn aan de zeezijde van de lijn die in de bijlage bij de wet is vastgelegd.	

Artikel 27	
In geval de opslag van stoffen van tijdelijke aard is, bevat het plan voor het opslaan van stoffen als bedoeld in artikel 26, tevens:	
a.	beschrijving van de wijze waarop de stoffen die zijn opgeslagen, worden teruggehaald en van de stoffen die daarbij gebruikt worden, en
b.	opgaaf van de samenstelling en hoeveelheden van de andere stoffen dan de opgeslagen stoffen die met het terughalen van de opgeslagen stoffen onvermijdelijk aan de bodem worden onttrokken.

HOOFDSTUK 4. HET METEN VAN BODEMBEWEGING	
§ 4.1. Metingen met het oog op bodembeweging	
Artikel 30	
1.	De uitvoerder verricht metingen naar bodembeweging ten gevolge van het winnen van delfstoffen of aardwarmte als bedoeld in artikel 41 van de wet. De metingen worden verricht overeenkomstig een meetplan.
2.	De uitvoerder dient het meetplan in bij Onze Minister voor ieder voorkomen waaruit wordt gewonnen.
3.	Het meetplan behoeft de instemming van Onze Minister alvorens met de winning wordt aangevangen.
4.	Onze Minister beslist over het meetplan binnen acht weken na indiening ervan. De instemming is van rechtswege gegeven, indien Onze Minister niet binnen de instemmingstermijn een beslissing heeft genomen. De instemming van rechtswege wordt voor de mogelijkheid van bezwaar en beroep gelijkgesteld met een besluit als bedoeld in artikel 1:3, eerste lid, van de Algemene wet bestuursrecht.
5.	Onze Minister kan de instemming onder beperkingen geven en aan zijn instemming voorschriften verbinden.
6.	Het meetplan beslaat de termijn van de winning en de daarop volgende dertig jaren. De uitvoerder actualiseert het meetplan gedurende de periode van winning en de daarop volgende vijf jaren jaarlijks en verstrekt daarvan afschrift aan Onze Minister. Onze Minister kan de uitvoerder een aanwijzing geven omtrent de tijdstippen waarop en de plaatsen waar gemeten wordt.
7.	Het meetplan bevat tenminste een beschrijving van: a. de tijdstippen waarop de metingen worden verricht; b. de plaatsen waar gemeten wordt, en c. de meetmethoden.
8.	Een van de tijdstippen, bedoeld in het zevende lid, onderdeel a, ligt voor de aanvang van de winning.
9.	Bij ministeriële regeling kunnen nadere regels worden gesteld omtrent het meetplan.

Artikel 31	
1.	De uitvoerder draagt ervoor zorg dat de metingen op een zorgvuldige en betrouwbare wijze plaatsvinden.
2.	De uitvoerder overlegt de resultaten van de eerste meting, bedoeld in artikel 30, achtste lid, uiterlijk twee weken voor de aanvang van de winning aan de inspecteur-generaal der mijnen.
3.	De uitvoerder overlegt de resultaten van de metingen twaalf weken na het verrichten van de metingen aan de inspecteur-generaal der mijnen.
4.	Bij ministeriële regeling kunnen nadere regels worden gesteld omtrent de inhoud van en de wijze van verstrekking van de meetresultaten.

Artikel 32
De artikelen 30 en 31 zijn van overeenkomstige toepassing op de opslag van stoffen.

Artikel 71
Een boorgat wordt niet eerder voor winning van delfstoffen of opslag van stoffen in gebruik genomen dan nadat het daartoe deugdelijk is ingericht en afgewerkt, alsmede ter afsluiting van deugdelijke beveiligingen is voorzien.

15.3.3 Besluit MER

Onderdeel C. Activiteiten, plannen en besluiten, ten aanzien waarvan het maken van een milieu-effectrapportage verplicht is
18.2 De oprichting van een inrichting bestemd voor de verbranding, de chemische behandeling, het storten of het in de diepe ondergrond brengen van gevaarlijke afvalstoffen. Het plan, bedoeld in de artikelen 2a, 4a, 7, 10, 11, eerste lid, en 36c van de Wet op de Ruimtelijke Ordening. De besluiten waarop afdeling 3.4 van de Algemene wet bestuursrecht en afdeling 13.2 van de wet van toepassing zijn.
18.5 De oprichting van een inrichting bestemd voor het storten of het in de diepe ondergrond brengen van niet-gevaarlijke afvalstoffen, niet zijnde baggerspecie. In gevallen waarin de activiteit betrekking heeft op een inrichting waarin 500.000 m^3 of meer niet-gevaarlijke afvalstoffen wordt gestort of opgeslagen. Het plan, bedoeld in de artikelen 2a, 4a, 7, 10, 11, eerste lid, en 36c van de Wet op de Ruimtelijke Ordening. De besluiten waarop afdeling 3.4 van de Algemene wet bestuursrecht en afdeling 13.2 van de wet van toepassing zijn.

Onderdeel D. Activiteiten en plannen alsmede besluiten, ten aanzien waarvan de procedure als bedoeld in de artikelen 7.8a tot en met 7.8e van de wet van toepassing is
17.2 Diepboringen dan wel een wijziging of uitbreiding daarvan, met uitzondering van diepboringen in het kader van:
a. het onderzoek naar de stabiliteit van de grond,
b. archeologisch onderzoek, of
c. de opsporing of w inning van aardolie, aardgas of zout.

Het plan, bedoeld in de artikelen 2a, 4a, 7, 10, 11, eerste lid, en 36c van de Wet op de Ruimtelijke Ordening. Het besluit, bedoeld in artikel 40, tweede lid, van de Mijnbouwwet of een ander besluit waarop afdeling 3.4 van de Algemene wet bestuursrecht en afdeling 13.2 van de wet van toepassing is, dan wel, bij het ontbreken daarvan, de vaststelling van het plan, bedoeld in artikel 11, eerste lid, van de Wet op de Ruimtelijke Ordening dan wel bij het ontbreken daarvan van het plan, bedoeld in artikel 10 van de Wet op de Ruimtelijke Ordening dat in de uitvoering van een diepboring dan wel de wijziging of uitbreiding daarvan voorziet.
18.3 De wijziging of uitbreiding van een inrichting bestemd voor het beheer van afvalstoffen, bedoeld in de categorieën 18.2, 18.3, 18.4 of 18.5 van onderdeel C van deze bijlage of de categorieën 18.1 of 18.2 van onderdeel D van deze bijlage. In gevallen waarin de activiteit betrekking heeft op:
a. Het storten of opslaan van baggerspecie van klasse 3 of 4 in een hoeveelheid van 250.000 m^3 of meer,
b. het storten of opslaan van andere afvalstoffen dan bedoeld onder 1°, in een hoeveelheid van 250.000 m^3 of meer,
c. het verwijderen van zuiveringsslib in een hoeveelheid van 5.000 ton droge stof per jaar of meer, Het plan, bedoeld in de artikelen 2a, 4a, 7, 10, 11, eerste lid, en 36c van de Wet op de Ruimtelijke Ordening. De besluiten waarop afdeling 3.4 van de Algemene wet bestuursrecht en afdeling 13.2 van de wet van toepassing zijn
25.3 De aanleg, wijziging of uitbreiding van een ondergrondse opslag van aardgas. In gevallen waarin ten behoeve van de opslag een ruimte wordt gecreëerd van 1 miljoen m3 of meer. Het plan, bedoeld in de artikelen 2a, 4a, 7, 10, 11, eerste lid, en 36c van de Wet op de Ruimtelijke Ordening. Het besluit, bedoeld in artikel 40, tweede lid, van de Mijnbouwwet of een ander besluit waarop afdeling 3.4 van de Algemene wet bestuursrecht en afdeling 13.2 van de wet van toepassing is

15.3.4 Wet Milieubeheer

Hoofdstuk 8: Inrichtingen
Titel 8.1 Vergunningen
Afdeling 8.1.1. Algemeen
Artikel 8.1
1. Het is verboden zonder daartoe verleende vergunning een inrichting:
a. op te richten;
b. te veranderen of de werking daarvan te veranderen;
c. in werking te hebben.
2. Het verbod geldt niet met betrekking tot inrichtingen, behorende tot een categorie die bij een algemene maatregel van bestuur krachtens artikel 8.40, eerste lid, is aangewezen, behoudens in gevallen waarin, krachtens de tweede volzin van dat lid, de bij die maatregel gestelde regels niet gelden voor een zodanige inrichting.
3. Het verbod bedoeld in het eerste lid, onder b, geldt niet met betrekking tot veranderingen van de inrichting of van de werking daarvan die in overeenstemming zijn met de voor de inrichting verleende vergunning en de daaraan verbonden beperkingen en voorschriften.
Artikel 8.2
1. Burgemeester en wethouders van de gemeente waarin de inrichting geheel of in hoofdzaak zal zijn of is gelegen, zijn bevoegd te beslissen op de aanvraag om een

	vergunning, behoudens in gevallen als bedoeld in het tweede, het derde en het vierde lid.
2.	Bij algemene maatregel van bestuur kan worden bepaald dat ten aanzien van daarbij aangewezen categorieën van inrichtingen gedeputeerde staten van de provincie waarin de inrichting geheel of in hoofdzaak zal zijn of is gelegen, of Onze Minister bevoegd zijn te beslissen op de aanvraag om een vergunning. Een zodanige maatregel wordt slechts vastgesteld met betrekking tot categorieën van inrichtingen ten aanzien waarvan dat geboden is gezien de aard en de omvang van de gevolgen die die inrichtingen voor het milieu kunnen veroorzaken, dan wel met het oog op de doelmatige bescherming van het milieu of met betrekking tot categorieën van gevallen waarin dat geboden is met het oog op het algemeen belang.
3.	In afwijking van het eerste en het tweede lid is Onze Minister van Economische Zaken bevoegd te beslissen op een aanvraag om een vergunning voor een inrichting die een krachtens artikel 1 van de Mijnbouwwet aangewezen mijnbouwwerk is, voorzover het niet betreft de ondergronds gelegen inrichting voor het opslaan van afvalstoffen die van buiten het betrokken mijnbouwwerk afkomstig zijn, dan wel gevaarlijke stoffen.
4.	In afwijking van het eerste en het tweede lid kan Onze Minister - indien dat geboden is in het belang van de veiligheid van de Staat - in overeenstemming met Onze betrokken Minister bepalen dat hij ten aanzien van een bij zijn besluit aangewezen inrichting bevoegd is te beslissen op de aanvraag om een vergunning.
Artikel 8.12b	
Aan de vergunning worden in ieder geval de voor de betrokken inrichting in aanmerking komende voorschriften verbonden met betrekking tot:	
a. een doelmatig gebruik van energie en grondstoffen; b. de bescherming van bodem en grondwater; c. het voorkomen van het ontstaan van afvalstoffen en afvalwater en, voor zover dat niet mogelijk is, het doelmatig beheer van afvalstoffen en van afvalwater; d. het beperken van de nadelige gevolgen voor het milieu van het verkeer van personen of goederen van en naar de inrichting; e. het voorkomen dan wel zo veel mogelijk beperken van door de inrichting veroorzaakte verontreinigingen over lange afstand of grensoverschrijdende verontreinigingen; f. het voorkomen dan wel zo veel mogelijk beperken van de nadelige gevolgen voor het milieu, die kunnen worden veroorzaakt door opstarten, lekken, storingen, korte stilleggingen, definitieve bedrijfsbeëindiging of andere bijzondere bedrijfsomstandigheden;	

g.
het voorkomen van ongevallen en het beperken van de gevolgen van ongevallen;

h.
het treffen van maatregelen om bij definitieve bedrijfsbeëindiging de nadelige gevolgen die de inrichting heeft veroorzaakt voor het terrein waarop zij was gevestigd, ongedaan te maken of te beperken voor zover dat nodig is om dat terrein weer geschikt te maken voor een volgende functie.

Titel 8.3 Regels met betrekking tot gesloten stortplaatsen		
Artikel 8.47		
1.	In deze titel en de daarop berustende bepalingen wordt verstaan onder:	
	a.	stortplaats: inrichting waar afvalstoffen worden gestort, dan wel het gedeelte van een inrichting, waar afvalstoffen worden gestort, indien in de inrichting niet uitsluitend afvalstoffen worden gestort;
	b.	gesloten stortplaats: stortplaats ten aanzien waarvan de in het derde lid bedoelde verklaring is afgegeven;
	c.	bedrijfsgebonden stortplaats: stortplaats waar uitsluitend afvalstoffen worden gestort, die afkomstig zijn van binnen de inrichting waartoe de stortplaats behoort.
2.	Onder stortplaats wordt mede verstaan een gesloten stortplaats. Tot de stortplaats wordt mede gerekend het gedeelte van de stortplaats waar het storten van afvalstoffen is beëindigd.	
3.	Het bevoegd gezag verklaart een stortplaats voor gesloten, indien:	
	a.	het storten van afvalstoffen is beëindigd,
	b.	voor zover een daartoe strekkend voorschrift voor de inrichting geldt, een bovenafdichting is aangebracht, en
	c.	een eindinspectie door het bevoegd gezag is uitgevoerd waaruit is gebleken dat aan alle voorschriften, verbonden aan de vergunning voor de stortplaats, is voldaan en dat ook geen andere maatregelen ingevolge de Wet bodembescherming getroffen dienen te worden door degene die de stortplaats drijft, in geval van verontreiniging of aantasting van de bodem onder de stortplaats.
Artikel 8.49		
1.	Met betrekking tot een gesloten stortplaats worden zodanige maatregelen getroffen dat wordt gewaarborgd dat die stortplaats geen nadelige gevolgen voor het milieu veroorzaakt, dan wel, voor zover dat redelijkerwijs niet kan worden gevergd, de grootst mogelijke bescherming wordt geboden tegen die nadelige gevolgen.	
2.	Tot de maatregelen, bedoeld in het eerste lid, worden in ieder geval gerekend:	
	a.	maatregelen strekkende tot het in stand houden en onderhouden, alsmede het herstellen, verbeteren of vervangen van voorzieningen ter bescherming van de bodem;
	b.	het regelmatig inspecteren van voorzieningen ter bescherming van de bodem, en
	c.	het regelmatig onderzoeken van de bodem onder de stortplaats.
3.	Degene die een stortplaats drijft stelt een nazorgplan op ter uitvoering van de maatregelen, bedoeld in het eerste en tweede lid. Het nazorgplan behoeft de instemming van gedeputeerde staten van de provincie waarin de stortplaats geheel of in hoofdzaak is gelegen. Gedeputeerde staten beslissen hierover binnen dertien weken na de indiening van het nazorgplan. De goedkeuring is van rechtswege	

	gegeven indien gedeputeerde staten niet binnen de instemmingstermijn van dertien weken een beslissing hebben genomen.
4.	Gedeputeerde staten kunnen degene die een stortplaats drijft bevelen het nazorgplan waarmee zij hebben ingestemd, aan te passen gezien de ontwikkelingen op het gebied van de technische mogelijkheden tot bescherming van het milieu en de ontwikkelingen met betrekking tot de kwaliteit van het milieu, dan wel in verband met een verandering van de stortplaats sedert de datum van instemming met het nazorgplan.
5.	Bij algemene maatregel van bestuur kunnen met betrekking tot de in het eerste en tweede lid bedoelde maatregelen alsmede met betrekking tot het in het derde lid bedoelde nazorgplan nadere regels worden gesteld.
Artikel 8.50	
1.	Belast met de maatregelen, bedoeld in artikel 8.49, zijn gedeputeerde staten van de provincie waarin de gesloten stortplaats geheel of in hoofdzaak is gelegen.
Titel 10.8 Verdere bepalingen	
Artikel 10.63	
Gedeputeerde staten kunnen, indien het belang van de bescherming van het milieu zich daartegen niet verzet, ontheffing verlenen van het in artikel 10.2, eerste lid, gestelde verbod om zich van afvalstoffen te ontdoen door deze buiten een inrichting te storten of anderszins op of in de bodem te brengen, voorzover het geen gevaarlijke afvalstoffen betreft, en, indien het belang van een doelmatig beheer van afvalstoffen zich daartegen niet verzet, ontheffing verlenen van de in de artikelen 10.37 en 10.54 gestelde verboden.	

15.3.5 LAP (wijziging)

Zowel nationaal als internationaal wordt in het kader van het klimaatbeleid de opslag van CO_2 in de (diepe) ondergrond genoemd als een optie om de uitstoot van CO_2 te beperken. De Nederlandse overheid staat positief tegenover een dergelijke opslag, in het bijzonder in lege gasvelden. Er is in Nederland één demonstratieproject offshore uitgevoerd, waarbij jaarlijks 20 kton CO_2 in een leeg gasveld is geïnjecteerd. De Nederlandse overheid wil meer ervaring opdoen met CO_2-opslag in ondergrondse reservoirs (ook andere reservoirs dan gasvelden) en daarvan leren wat in Nederland mogelijk is en onder welke voorwaarden. Daarom willen de ministeries van EZ en VROM diverse proefprojecten voor ondergrondse opslag van CO_2 financieel en inhoudelijk ondersteunen. Als CO_2 wordt opgeslagen in de diepe ondergrond en dan dus niet meer in de atmosfeer wordt geloosd, is sprake van het opbergen van afvalstoffen. Hierop is paragraaf 18.4 van het LAP van toepassing. Het in de (diepe) ondergrond opbergen van CO_2 is echter destijds niet meegenomen bij het opstellen van de huidige paragraaf 18.4 en de huidige tekst van de betreffende paragraaf kan dan ook niet worden toegepast voor het beoordelen van de opslag van CO_2.

Wijziging van het LAP
Gelet op het hiervoor staande wordt bij de wijziging van het LAP een passage toegevoegd aan paragraaf 18.4, die aangeeft dat de bestaande tekst van die paragraaf niet van toepassing is op het opbergen van CO_2 in de (diepe) ondergrond, dat wordt onderzocht aan welke voorwaarden de betreffende CO_2 opslag moet voldoen en dat daarna de voorwaarden mogelijk worden opgenomen in het LAP.

Participants workshop policies and permits for CO_2 injection

	Stuurgroep	
1	Arjan van Harten	Provincie Drente
2	Jan de Jong	Essent
3	Duco Drenth	SEQ
4	Berend Scheffers	Staatstoezicht op de Mijnen
	Extern	
1	Hans Knippels	DCMR
2	Joris Koornneef	Universiteit Utrecht
3	Anne-Claire Collee	VROM
4	Pieter-Geert van der Sleen	Provincie Groningen
5	Klaas Lemstra	NAM
6	Laura van Dijk	Provincie Drente
7	Janny Zantinge	Provincie Friesland
8	Hans Roest	Staatstoezicht op de Mijnen
9	Steven Pieters	Commissie MER
	Projectgroep	
1	Chris Hendriks	Ecofys
2	Saskia Hagedoorn	Ecofys
3	Marielle Vosbeek (aanwezig bij start workshop)	Ecofys

Appendix Figures

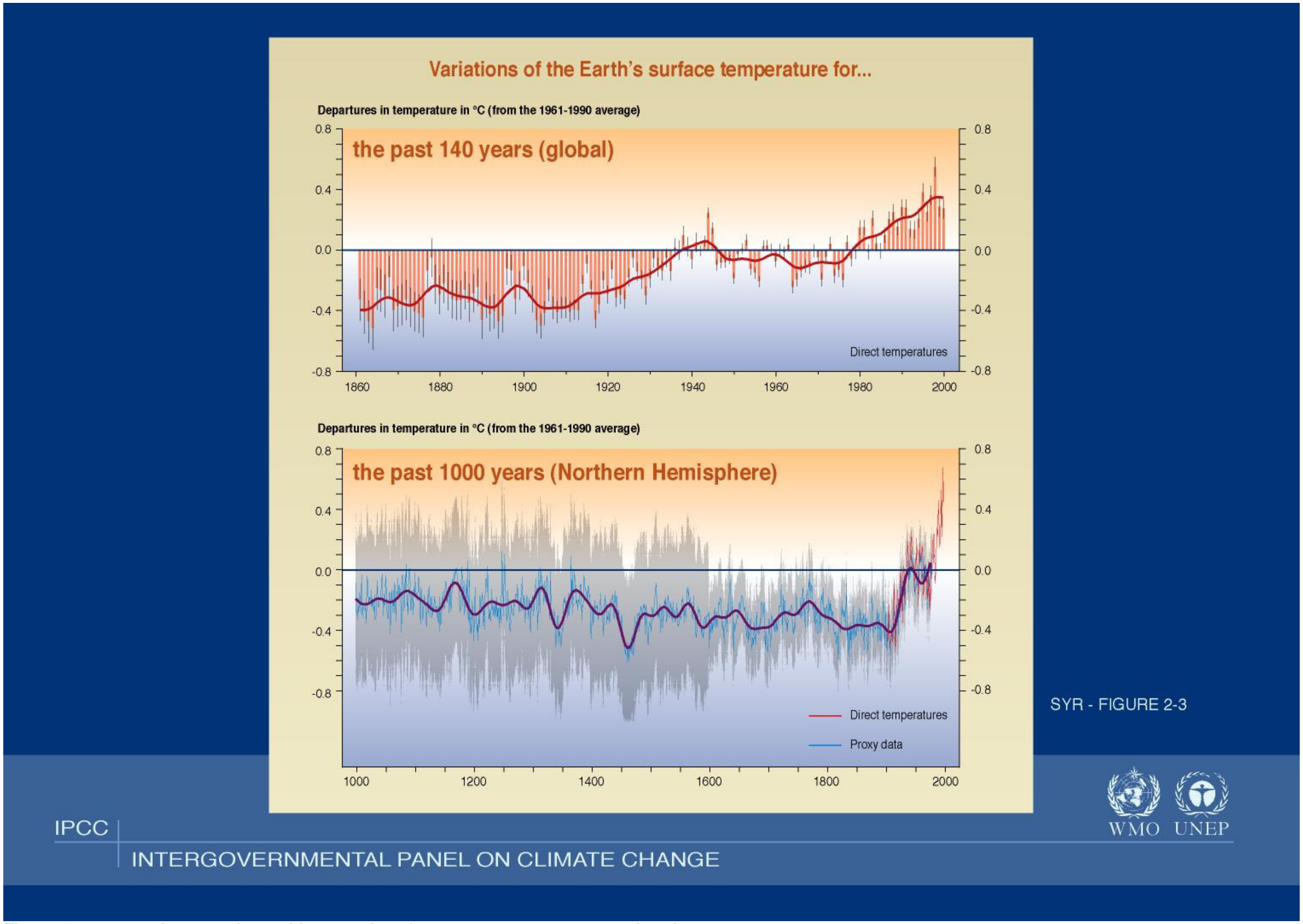

Figure 2.1 **Increase in earth's annual surface temperature, compared to the 1960 – 1990 average**

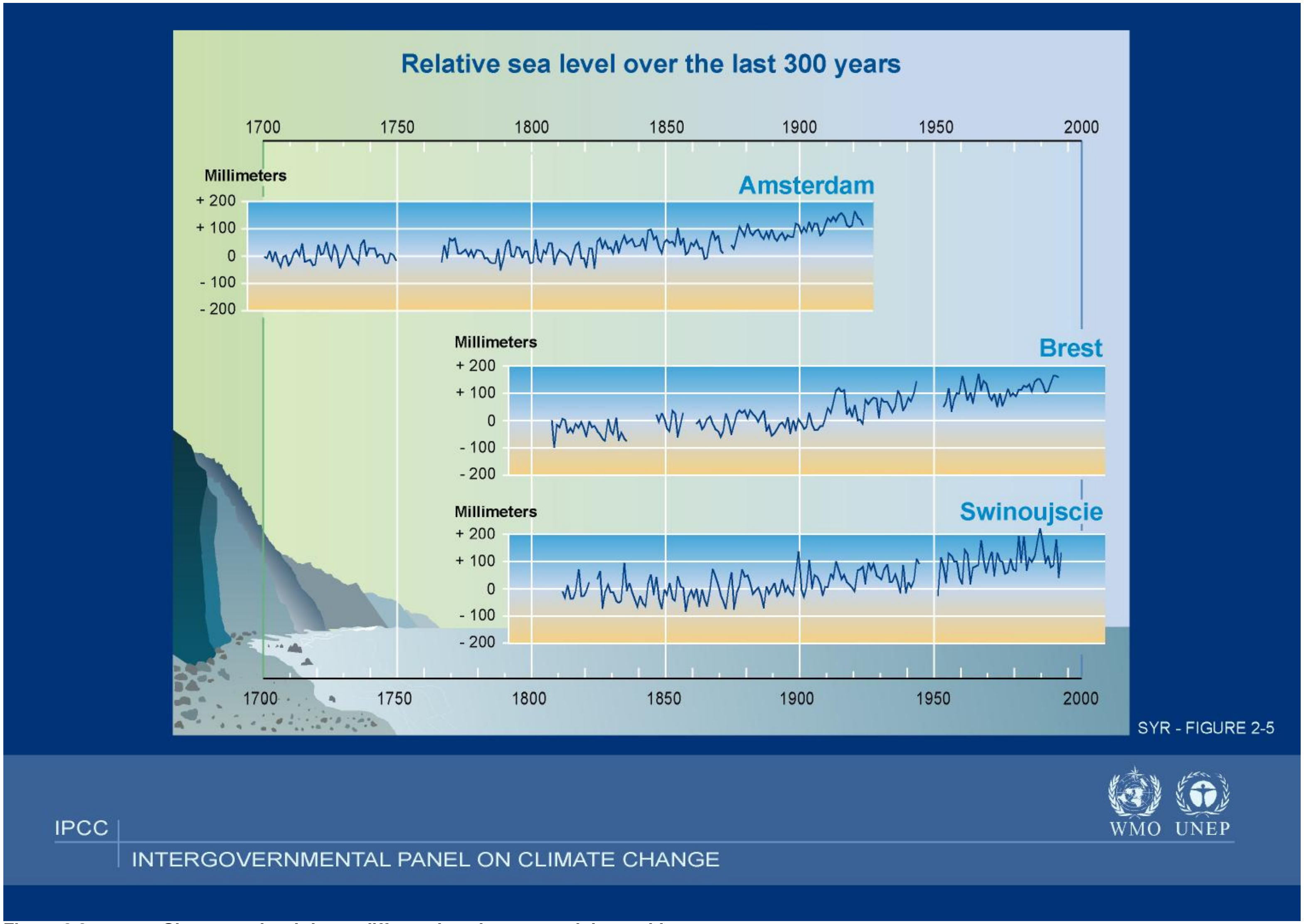

Figure 2.2 **Shows sea level rise at different locations around the world**

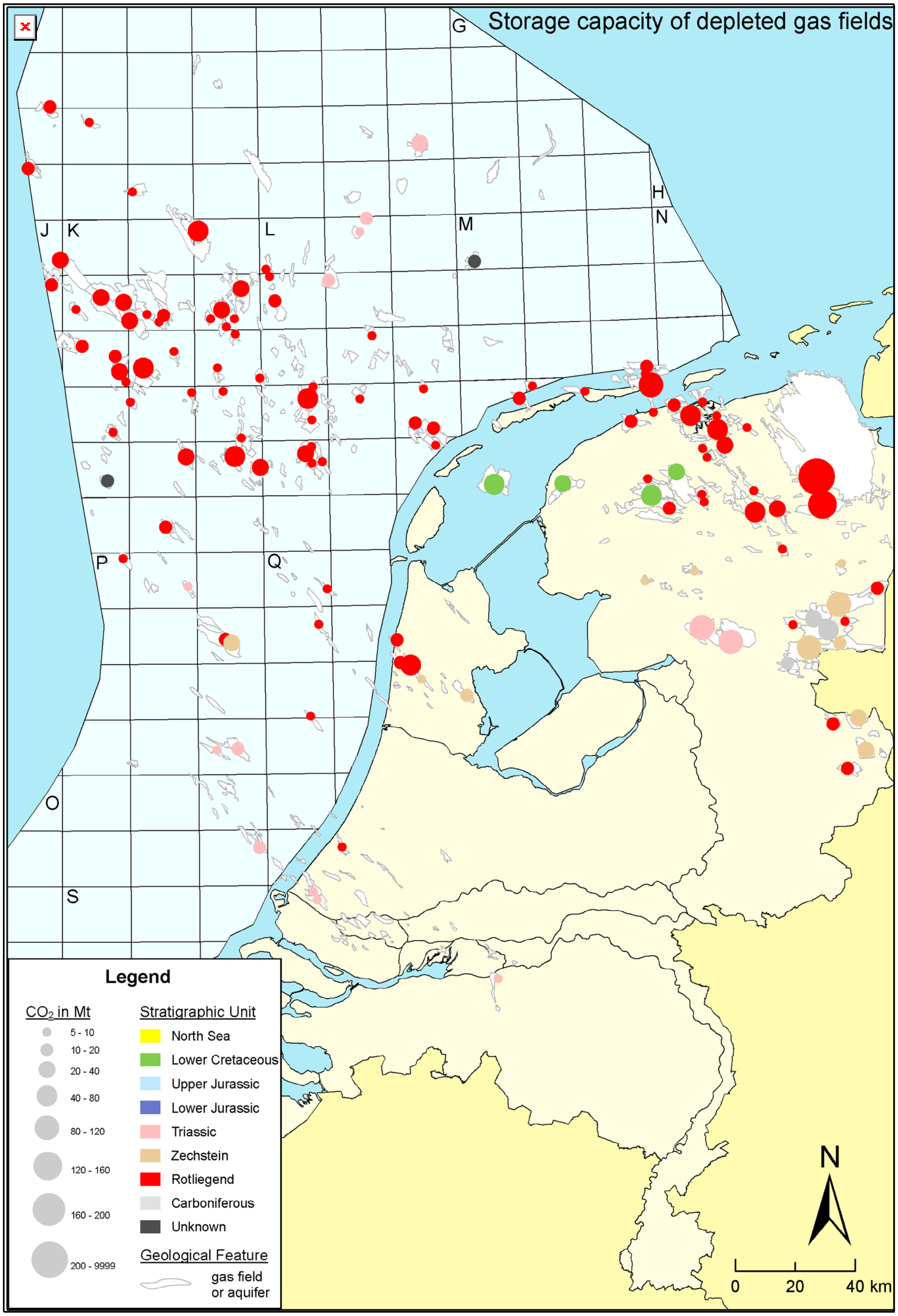

Figure 3.2 **Map of the gas fields in the Netherlands with the stratigraphical level of the reservoir and the storage capacity**

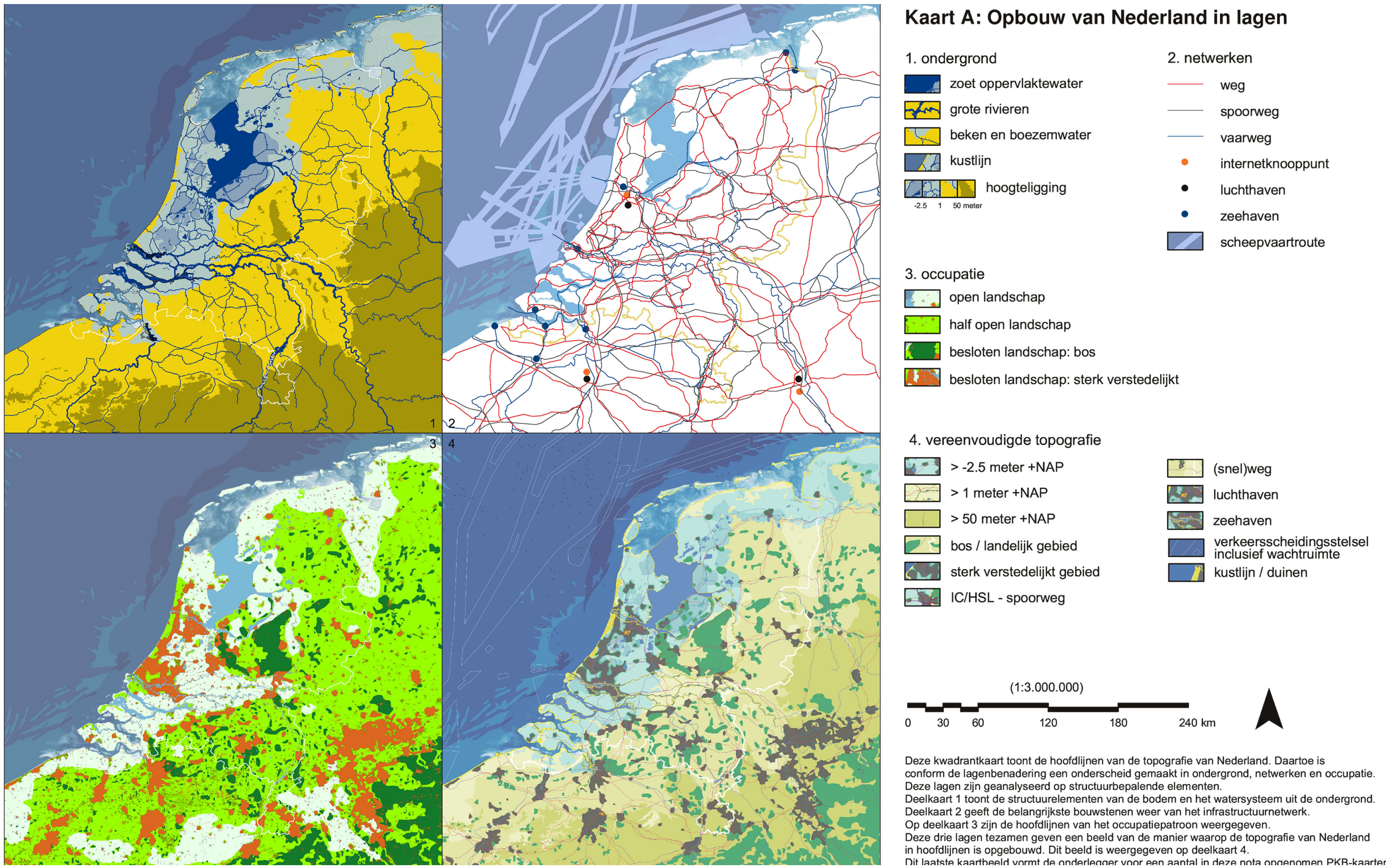

Figure 6.1 **Geographical information of the Netherlands**

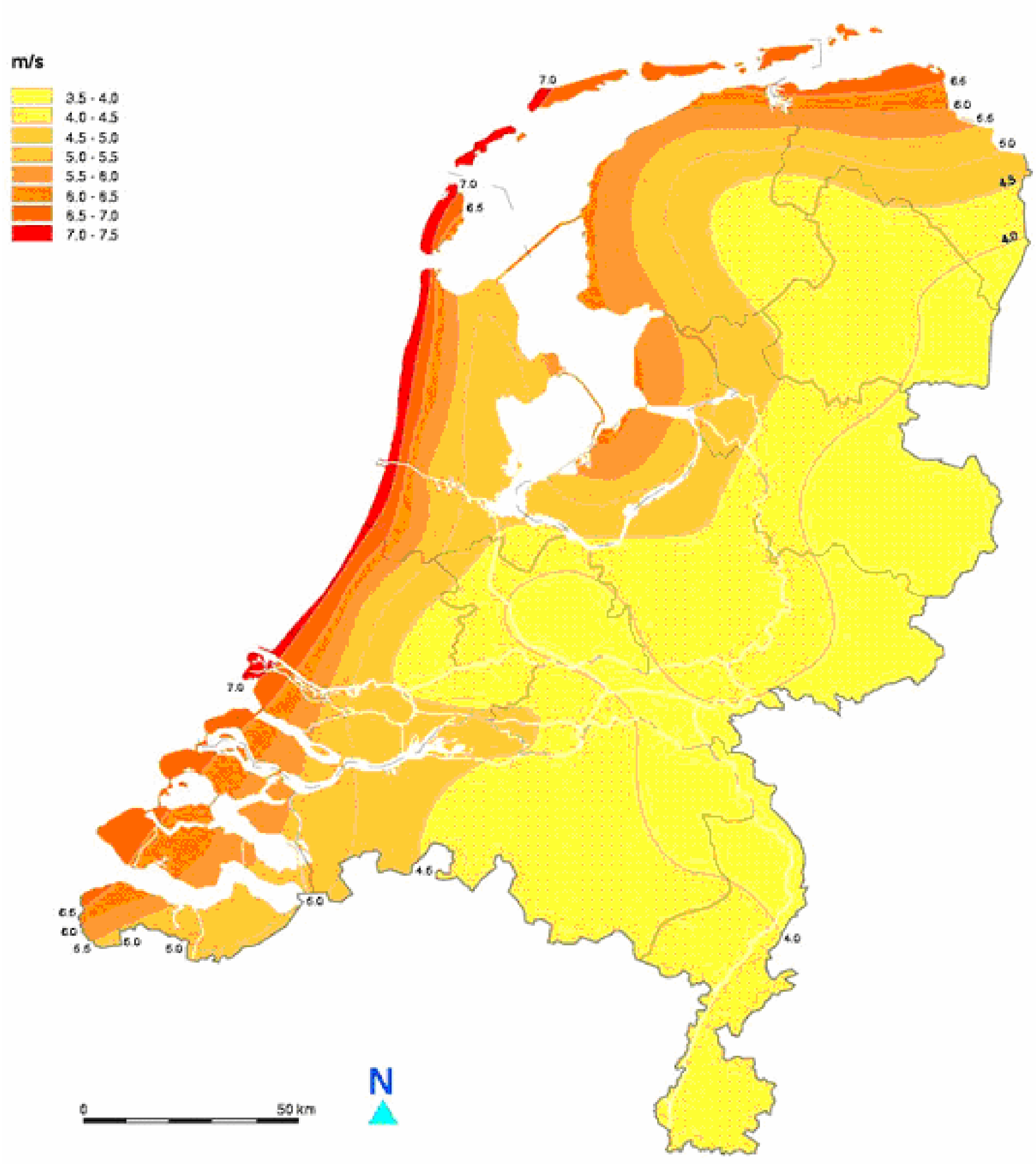

Figure 6.3 **Average windspeeds**

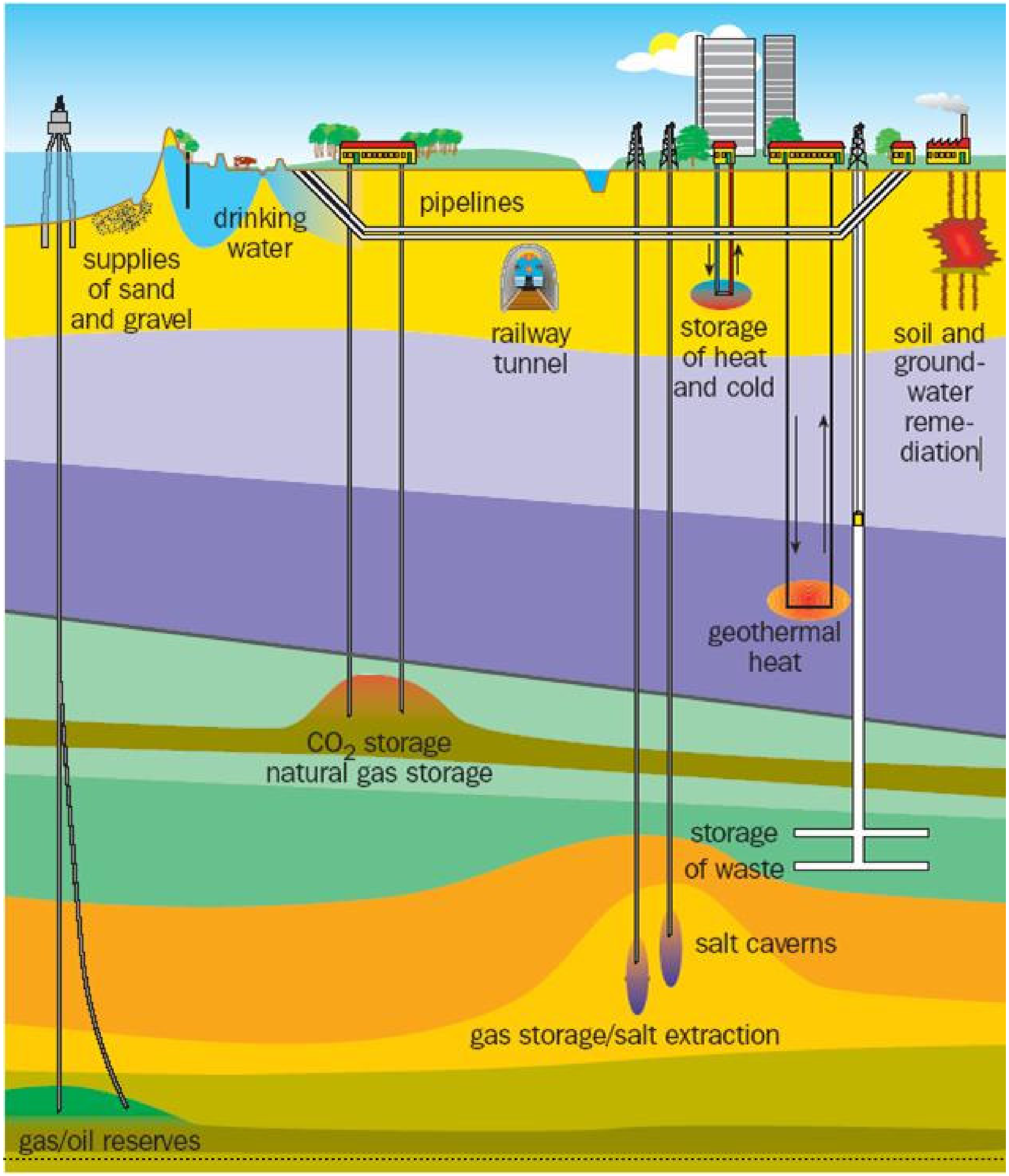

Figure 6.4 Examples of the use of the subsurface

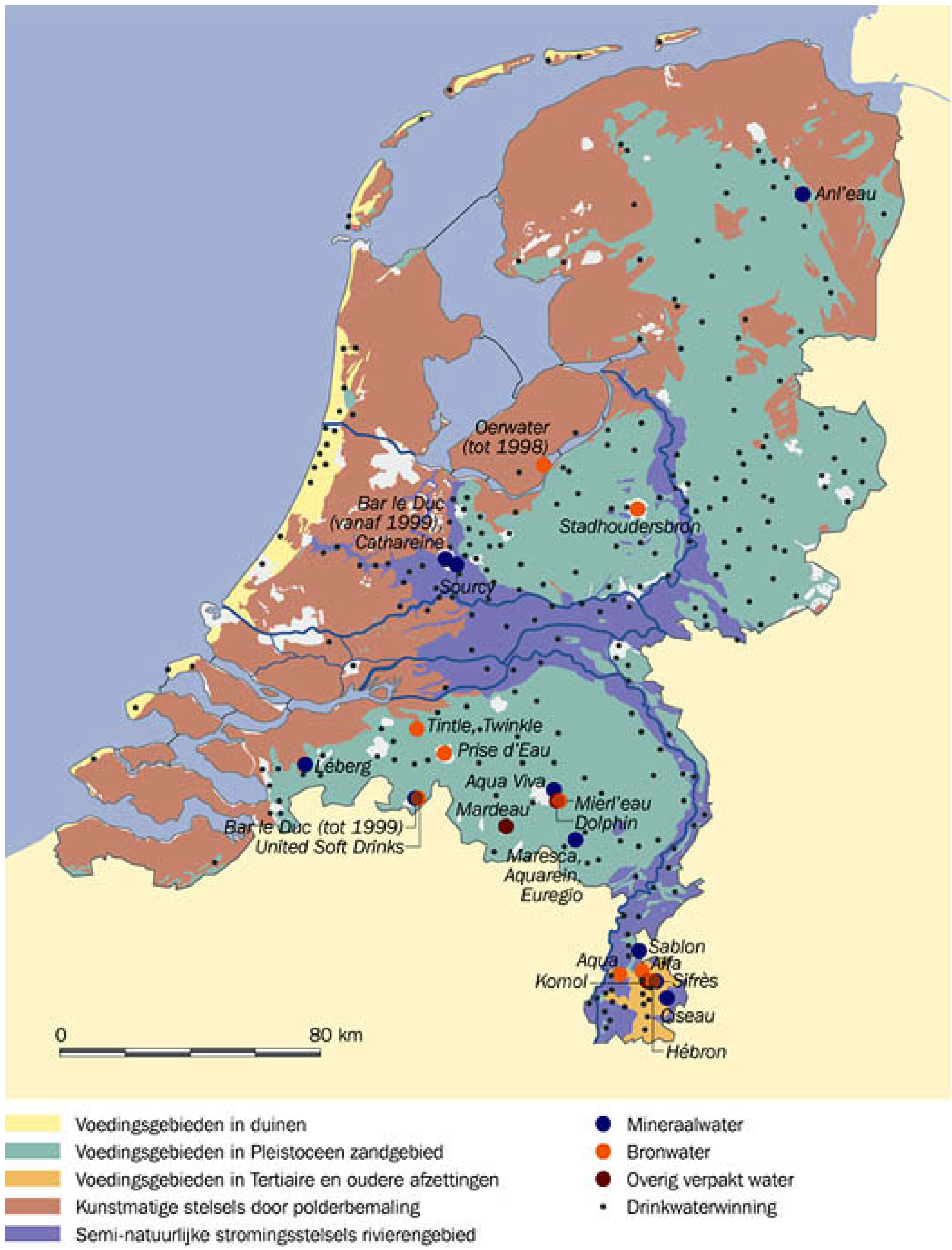

Figure 6.5 Production of drinking water from potable groundwater in the Netherlands

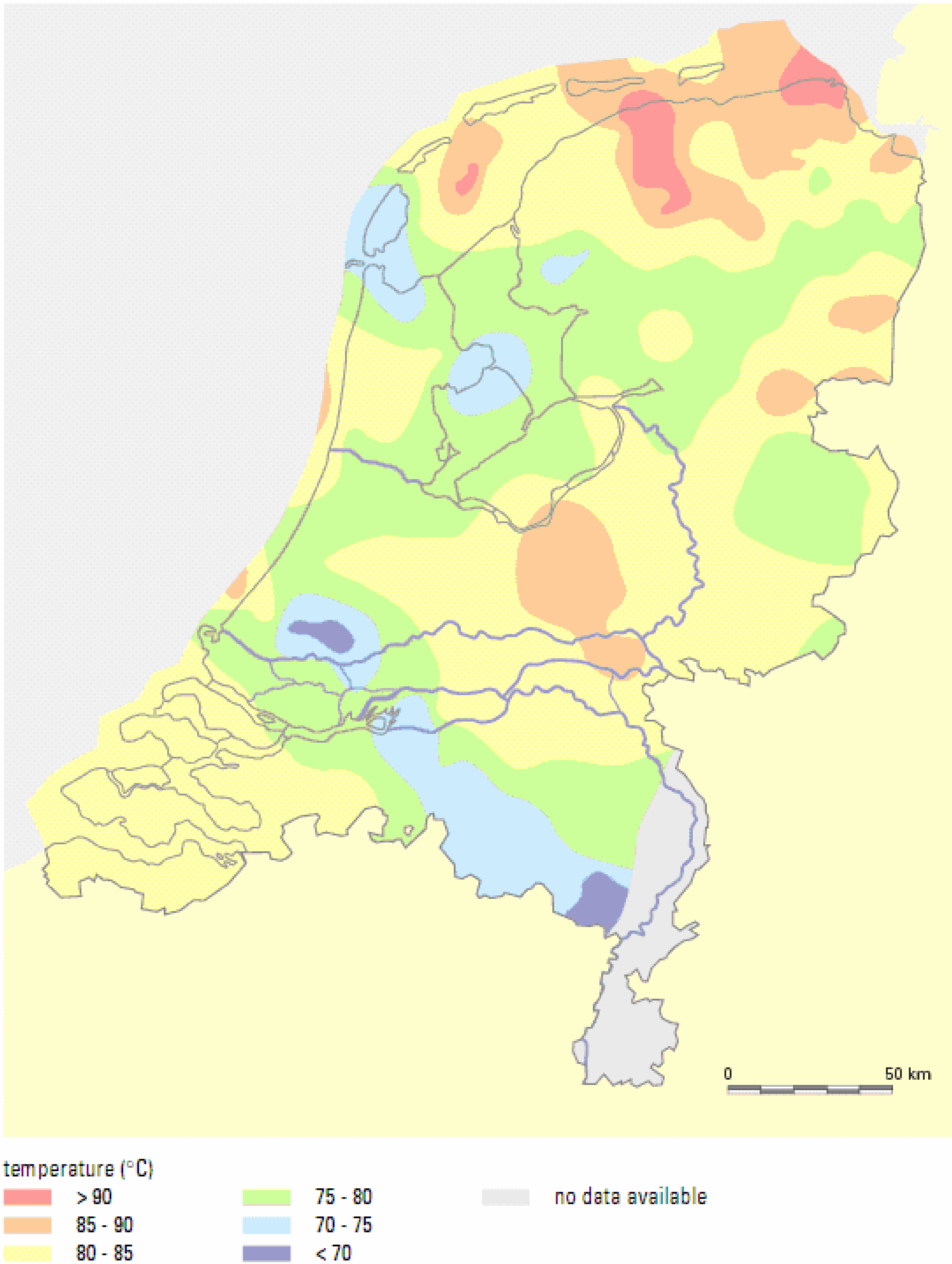

Figure 6.6 Temperature of aquifers in Dutch underground at 2.000 meters (DINO loket)

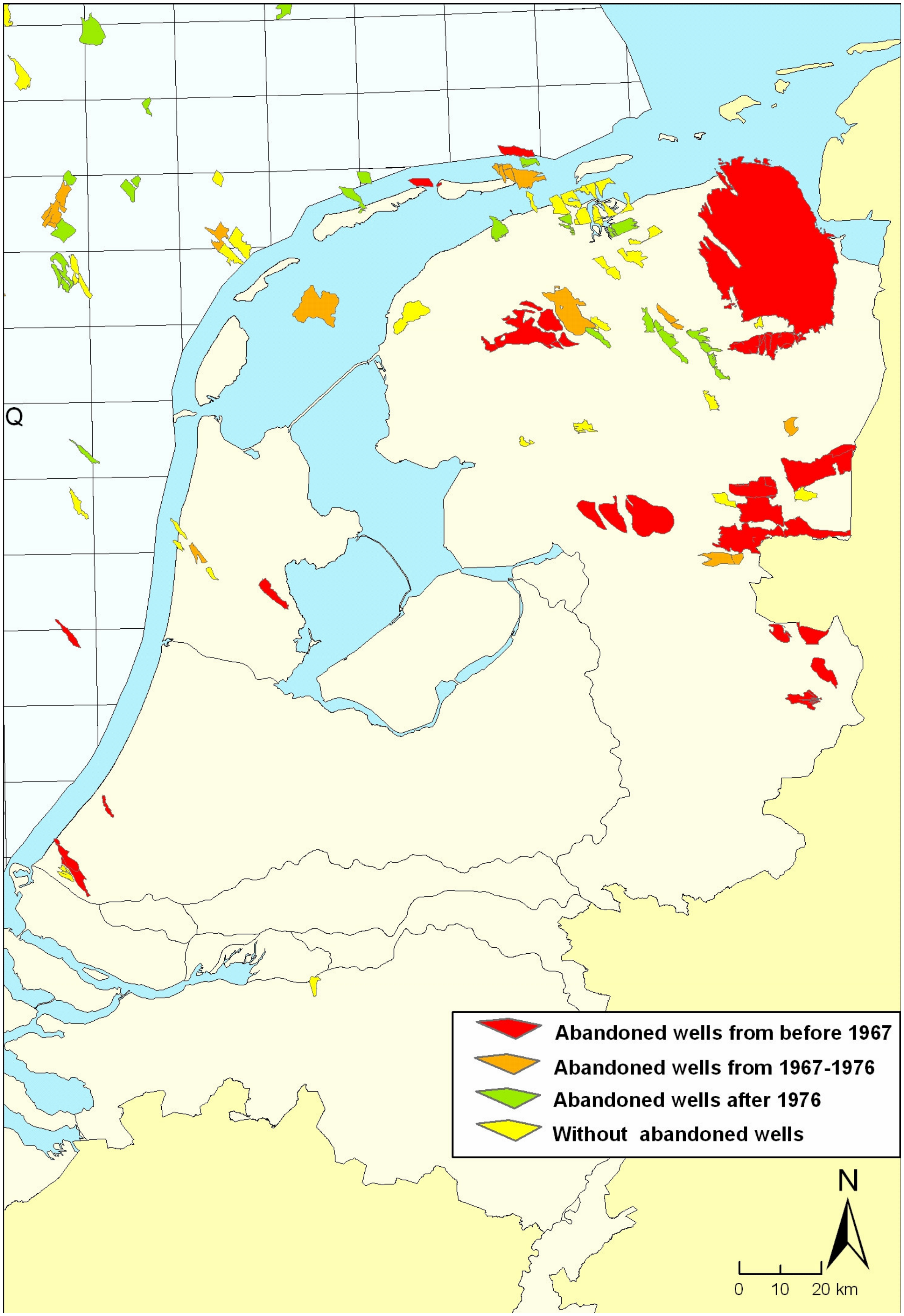

Figure 7.3 Presence of abandoned wells in Dutch gas fields showing the timing of abandonment relative to major revisions in the Dutch Mining Legislation in 1967 and 1976