"Support to the implementation of the CCS Directive"

Overview and analysis of issues concerning the implementation of the CCS directive in the Netherlands

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Executive Summary

In June 2009, the EU Directive on the Geological Storage of Carbon Dioxide entered into force. The European Member States are obliged to transpose the directive in their national legislations no later than 25 June 2011. The EU legislator has applied a regime of minimum harmonisation when drafting the CCS Directive, amongst others to achieve that an agreement could be reached on the CCS Directive by a majority of Member States. In other words; Member States have considerable discretionary powers while implementing the Directive. The CO_2 Storage Directive is mainly transposed into Dutch legislation by means of adaptation of the Dutch Mining Act. There are, however, still some issues in the implementation of this directive that need further clarification. The way these issues are addressed may impact the deployment of large-scale CO_2 capture and storage (CCS) in the Netherlands and Europe.

This report analyses several of these issues, and aims at providing possible pathways and recommendations on how to resolve them. The issues analysed in detail in this report include:

- Requirements regarding the composition of the CO_2 stream;
- Procedure and criteria for site selection;
- Liabilities with respect to health and property.

Issues addressed in less detail, but which will be researched in more detail in the coming years include:

- Transfer of responsibility;
- Financial Mechanism;
- Monitoring of the site;
- Type of infrastructure access arrangements;
- Supervisory structure.

Summary

The European Directive on the Geological Storage of Carbon Dioxide leaves considerable discretionary powers to the Member States while implementing the Directive.

In June 2009 the European Directive on the Geological Storage of Carbon Dioxide (Directive 2009/31/EC, hereafter CCS Directive)) entered into force. It obliges Member States to transpose the Directive in their national law no later than June 25, 2011. In the Netherlands the CCS Directive will be implemented by means of amending the Dutch Mining Act (Mijnbouwwet).

The EU legislator has applied a regime of minimum harmonisation when drafting the CCS Directive, amongst others to achieve that an agreement could be reached on the CCS Directive by a majority of Member States. Minimum harmonisation means that the Directive provides for a minimum set of rules and that Member States may decide to issue more stringent rules on national level. In other words; Member States have considerable discretionary powers while implementing the Directive. In addition, Member States may still issue additional rules governing CCS. This may pose two kinds of problems:

- First, the way in which Member States apply their discretionary powers may negatively impact the development of CCS in individual Member States.
- Second, it is possible that requirements in the Directive are implemented in a more rigorous manner in one Member State than in another Member State. This can lead to the situation that investors' propensity to invest in CCS is likely to differ substantially between Member States (there will be no level playing field).

Since storage costs will be passed through to power plants with CO_2 capture installations, (expected) electricity generation costs between Member States are affected differently and investments in new fossil fuelled generators might be cancelled. The level playing field between storage operators in different Member States is likely to be distorted, which may decrease overall social welfare in Europe.

There are still a number of issues regarding the implementation of the EU CCS Directive that need further clarification, and the way these issues are addressed may impact the deployment of large-scale CCS in the Netherlands and Europe.

This report analyses several of these issues, and aims at providing possible pathways and recommendations on how to resolve them. These recommendations concentrate on actions to be taken by governments. The issues can be classified into three categories:

- Issues for which the EU legislator has indicated that further EU guidelines will be presented (such as composition of the CO_2 stream, transfer of responsibility, financial mechanism, monitoring);
- Issues for which no such guidance is indicated and Member States have full discretionary powers (such as selection of storage sites, Third Party Access, supervisory structure); and
- Issues relevant for the development of CCS but not regulated in the Directive and thus totally governed by national law (such as long-term liability).

Three of these issues, one of each category, are researched in more detail in this report: the safe selection of storage sites, the composition of the CO_2 stream and long-term liability.

<u>ISSUE</u>: Lack of clear standards for safe site selection and the share of CO_2 that might be at risk to leak from a storage site.

The CCS Directive mentions that:

- The suitability of a geological formation for CO_2 storage has to be assessed through a process of characterization and assessment, and
- A storage site may only be selected if the likelihood of leakage is not significant, and risks for human health and environment are not significant.

It is not yet clear when there is a *significant* risk of leakage, and if this risk exists, whether environmental or health risks are *significant* as well. Furthermore, the Directive does not include clear standards for the share of CO_2 that might be at risk to leak from a storage site.

....Currently no quantitative standards can be set for safe site selection due to lack of data on probabilities for CO_2 leakage.

There is not yet enough information available about CO_2 leakage probabilities that could be used for setting quantitative standards on the maximum probabilistic level for leakage of CO_2 from storage sites. The procedure for characterisation and assessment of a storage site will lead to a substantial number of simulations. In those cases where leakage is shown to occur, further study will generally reveal its origin. It is therefore recommended to declare a storage site *unsafe* if:

- No clear-cut reason can be found for simulations of the storage site producing leakage;
- A clear-cut reason can be found, with essential parameters being highly uncertain.

If none of the simulations produces leakage the site might be deemed safe. This solution should preferably be implemented at the European scale since all countries face the same question.

....Complete and *permanent* containment of CO_2 can never be guaranteed.

The Storage Directive is about permanent storage of CO_2 in a geological storage container. The term “permanent” seems to impose a standard of rigor on characterisation and assessment that is not realistic in any scientific field. A way around this could be to pose a time horizon to qualify the word “permanent”. A recommendation that could be made operational in research is the definition of a time horizon before which no leakage should occur. This means that the modelling exercises must at least encompass this time horizon. The *definition* of the horizon is a political matter, somehow balancing health, safety and environmental (HSE) concerns and the desire to store CO_2

<u>ISSUE</u>: Unclear requirements regarding the composition of the CO_2 stream and the interpretation of the term “overwhelming CO_2“.

Regarding the composition of the CO_2 stream the CCS-Directive states: "A CO_2 stream shall consist overwhelmingly of carbon dioxide". In addition the CO_2 stream should not pose a risk on human health, the environment or affect the integrity of a CO_2 storage site or the transport infrastructure. To this end, no waste or other matter may be added for the purpose of disposing of that waste or other matter. However, a CO_2 stream may contain incidental associated substances from the source, capture or injection process and trace substances added to assist in monitoring and verifying CO_2 migration.

….Currently considered capture processes are well capable of meeting restriction regarding transport and storage systems, as well as health, safety & environment (HSE) considerations.

Our analysis shows that currently considered capture processes are well capable of meeting restrictions for preventing both effects on the integrity of infrastructure and significant risks to environment and human health.

....Regulation does not need to be more specific on the application of cleaning techniques as market parties have sufficient incentives to apply them.

At different stages in the process cleaning techniques will have to be applied. Main motivation for this additional purification will be the prevention of corrosion and two-phase flow formation. Since these concerns are of direct interest to the operators of the capture, compression and transport facilities, the requirements in the CCS Directive do not necessarily have to be made more specific in this respect.

....Acceptable bandwidth in the composition of the CO_2 stream will require specific attention from the licensing authorities.

One aspect that did not receive too much attention in the various discussions is the aspect of load variations. The CCS stream is the product from a cascade of installations that once in stationary operation on design load will certainly satisfy the specifications. However, with large-scale applications it is unavoidable that frequent load variations will occur: multiple start/stop operations and switches to different partial load levels. It cannot be avoided that during these load variations and transitions the specifications will vary over a given range. It is recommended that additional requirements on the allowable variations over time will be formulated for this issue. These requirements may result in an addition to the permit application with the licensing authority or form an element in the contract with the transport network operator.

ISSUE: Uncertainties with regard to the long-term liabilities.

Uncertainties with regard to the long-term liabilities might become an obstacle for the development of large-scale CCS. Different liability regimes apply to CCS, depending on the type of damage that might occur. The leakage of CO_2 from the CCS chain may cause physical damage to: 1) the global climate system, 2) the environment and ecosystems, 3) human health and materials. When looking at the long-term liability for possible damage caused by CCS, we see that there are three applicable regimes: climate liability, environmental liability and the existing national liability regimes for damage towards third parties.

Damage to:	Liabilities covered under	Liable person	Plaintiff
Climate	EU-ETS	Licensee (operator)	Competent Authority (Dutch emissions authority)
Health & Property (third parties)	Dutch Civil Code	Licensee (Operator)	Third parties that suffered the damage
Environment	ELD Directives as implemented in the Dutch environmental management act.	Licensee (operator)	Government/local authorities

….The national system handling liabilities towards third parties is not suitable for dealing with liability for the long-term storage of CO_2:

….(1) Currently there is an endless liability horizon for operators towards third parties.

The three regimes have different liability horizons. The liability horizons for climate liability and environmental liability are limited for companies, because with transfer of responsibility over the storage site the liabilities are also transferred to the competent authority. The liabilities towards third parties based on the national system, however, are not and are in principle endless. Although this is not unique for CCS, in case of a developing market (such as CCS). In case of a developing market (such as CCS), these long horizons might function as an obstacle for potential investors.

….(2) There is uncertainty with regard to which specific liabilities apply to CCS.

The national liability system distinguishes different grounds for liability, each of which has a specific liability horizon, specific damages that might be compensated and different possible defences for the liable party. Which of these liabilities will apply, will be determined by case law in court proceedings after damage has occurred and a court procedure has started. For operators, certainty in advance would be welcome.

….(3) The legal debate is very technical and current case law might follow different directions.

The legal debate regarding damage caused to third parties will be of a highly technical nature, whereby one might question the capability of judges to review these matters. Moreover the case law as developed by the courts does not necessarily follow the same direction, due to judicial freedom.

It is in the interest of operators and investors that they can predict the possible liabilities (and insurance or compensation costs) that might exist in order to assess the costs of an incident. The national liability regime might therefore function as an obstacle to the large-scale deployment of CCS.

….The long-term liabilities should be managed or be tailor-made for CCS. Options include:

….(1) Private insurance. Private insurance shifts the risk between parties in the market. There are two problems in using insurance. The first is that private markets are receptive to market failure, which might be solved by using the government as a risk bearer. Furthermore, CCS is hard to

insure, due to the long-term nature, the stage of development of the technology and possible gradual occurring damage.

….(2) Liability cap/exemption. In this case the operator is liable for the amount of the cap, but the damages above this amount is taken on by the government. This instrument is also used in the nuclear energy industry. It should be noted that although the liability cap provides for certainty and predictability for the industry, it might undermine the credibility of CCS in the eyes of the public.

….(3) Liability exemption. A variation on the liability cap is the liability exemption. This exempts a party from being liable for a given cause of action or injury. It could mean that the injured parties would be left without compensation, or that the government would take on the liability, thereby indemnifying the operator.

….(4) *Compensation fund.* The industry makes contributions to a fund that compensates possible damages. The types of damages (repairing leakage, injuries, financial loss) for which compensation is available are regulated and compensation can be required through different proceedings (court, prescribed situations).

For projects that have started, the current regime with all its uncertainties is applicable. For projects that are under development, it would be wise to change the long-term liability regime. One way to do so is to adopt a CCS specific liability article in the Dutch Civil Code that limits the liabilities of operators to a certain timeline. However, in that situation, the uncertainties of the judicial regime remain. In designing an instrument to solve the uncertainties created by the current regime, the following considerations should be taken into account:

- *What objective is pursued?* Deterrence, risk spreading, lowering or stimulating activities or guaranteeing compensation? And in line with that: who should pay for the damages? Polluters, society?
- *Who do we want to make the decision on compensation?* Judges, experts, legislator?
- *How quickly should the instrument adapt itself to change?*

Furthermore, the instrument that will be developed cannot be seen separately from the discussion on the financial security to be provided by operators and the financial contribution needed for the transfer of responsibility to the competent authority. The same types of instruments that may be used to manage long-term liability might also be used for the financial security and compensation, although the scope of the latter arrangements is different.

In addition to the issues researched in the report, we note that there are still several other uncertainties. A short description and first recommendation are provided on these other issues including (if applicable) the main questions for further research.

ISSUE: Lack of clear criteria for transfer of responsibility

The Directive requires that a *minimum period* has elapsed before the responsibility for the storage site can be shifted from the operator to the competent authority. In principle the length of the required minimum period is 20 years, but national competent authorities are allowed to reduce the period before transfer of responsibility can take place. This is the case, when the authority is convinced that the stored CO_2 will be *completely and permanently contained* before the end of a shorter period.

....Rigorous screening of a storage site is key in the decision on the transfer of responsibility, as 20 years of monitoring will probably not provide much more information on the chances of leakage

The assessment phase of a storage site should be very rigorous. This step will provide authorities with most of the information needed to decide on the safety of a storage site and on the chances that CO_2 will or will not leak. Based on this information authorities should expect an eventual successful transfer of responsibility. Twenty monitoring years are useful to the extent that they provide an indication of whether the situation is under control just after injection has ceased, and no major incidents did occur during injection or closure. However, it will not likely provide much more insight on the chances of leakage for the next period, which chances are some orders of magnitude larger. All in all, the monitoring period is not superfluous for the assessment taking place before the transfer of responsibility.

....However, it is advised to standardize the period until transfer of responsibility can take place to either prevent a "race to the bottom" or a "race to the top".

The current policy creates the chance that when one Member State let short-term (industry) interests prevail to long-term climate and security interests and consequently shortens the minimum period, other Member States will follow because of level playing field considerations. Ultimately, this may induce 'a race to the bottom' to the detriment of health and environmental interests. The other way around, safety concerns etc. may lead to a race to the top with very long periods before liability can be shifted (if national liability laws are very strict, for instance Germany considers 30 years), which increases cost uncertainty for storage site operators dramatically. Both arguments suggest that the transfer of responsibility should be fully fixed by legislation. On the other hand, one may say that such a practise does not take into account differences between storage sites, which drive the need for variable periods before responsibility is transferred from storage operators to the competent authority. However, climate and safety risk differences between storage sites are expected to be limited since storage operators have to prove permanent and complete containment of CO_2 in the storage facility already before obtaining a storage permit. Hence, it is advised to standardize the length of the transfer of responsibility period.

ISSUE: Uncertainty on the type of financial security and on the amount of financial contribution is an obstacle for the industry to invest in CCS.

In order to attract CCS industry some Member States might take on more of the possible costs and risks, whereas in other Member States the thresholds might be formulated more rigorously when they do not want to stimulate CCS. The level playing field might be at risk in formulation the elements of the financial mechanism. The EU commission has issued guidelines on the financial security and financial contribution. The document defines different categories of costs and determines whether or not these costs should be included in either the financial security or the financial contribution. Further research is needed on the type and amount of financial security and financial contribution in relation to the existing long-term liabilities for CCS. The central questions in the discussion are:

- To which degree should financial certainty be proven in advance?
- Should the industry be financially responsible for the larger and more unknown events that might occur?
- Which type of security is reasonable?

ISSUE: Third party access (TPA) to CO_2 infrastructure

The CCS Directive provides that third parties should be provided access to transport networks and storage sites in a transparent and non-discriminatory manner. This implies that third parties should have at least the possibility to negotiate access to the CO_2 infrastructure. However, it may be that the market structure for large scale CCS requires a more regulated form of TPA in the medium or long term. More research is needed on the suitability of the different possible access regimes.

ISSUE: A suitable and effective supervisory structure still has to be designed

The CCS Directive states that 'in cases of transboundary transport of CO_2, transboundary storage sites or transboundary storage complexes, the competent authorities of the Member States concerned shall jointly meet the requirements of this Directive and of other relevant Community legislation'. It seems likely that the division of responsibilities between Member States will sometimes evolve in cross-border disputes. Whether consultation between Member States is enough for solving possible cross-border disputes regarding CO_2 transport remains to be seen. Relevant questions are:

- Which type of supervisory organisation is best suitable for CCS permitting and safety
- Should there be some kind of structure which enables international cooperation between these supervisors'

ISSUE: Accuracy of monitoring technologies is not laid down in the CCS Directive but seems to have been solved with the publication of the MRG under the ETS Directive.

The Directive describes the assessment that should take place to guarantee complete and permanent containment of CO_2 in storage facilities, but does not prescribe any particular monitoring technology. The recent CCS monitoring and reporting guidelines for the Emission Trading System provide more direction on the way monitoring and reporting of emissions of greenhouse gas in the CCS chain should be carried out. As leakage is included as one of the potential sources of CO_2-emissions, this guideline does also include emission quantification rules for leakage from storage sites. Leakage of a storage complex has to be quantified with a maximum overall uncertainty of ± 7.5%. If the uncertainty is above ± 7.5%, the 'excess' uncertainty with respect to ± 7.5% requirement has to be added to the reported greenhouse gasses. This method seems fair for storage operators, as it helps to keep monitoring costs to an acceptable level for emissions that will probably not occur. And from the government and society side it keeps the uncertainty of the emission in line with uncertainty generally required in the MRG for emission accounting under ETS. Furthermore, the EC guidelines narrow the scope for unfair competition for location of CO_2 storage across the EU. Stricter requirements do not seem necessary as a higher accuracy in emission estimates will imply higher costs. Therefore, this issue has been resolved.

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1 Introduction

1.1 Background and objectives

In June 2009 the European Directive on the Geological Storage of Carbon Dioxide (Directive 2009/31/EC, hereafter CCS Directive)) entered into force. It obliges Member States to transpose the Directive in their national law no later than June 25, 2011. In the Netherlands the CCS Directive will be implemented by means of amending the Dutch Mining Act (Mijnbouwwet).

The EU legislator has applied a regime of minimum harmonisation when drafting the CCS Directive, amongst others to achieve that an agreement could be reached on the CCS Directive by a majority of Member States. Minimum harmonisation means that the Directive provides for a minimum set of rules and that Member States may decide to issue more stringent rules on national level. In other words; Member States have considerable discretionary powers while implementing the Directive. In addition, Member States may still issue additional rules governing CCS. This may pose two kinds of problems:

- First, the way in which Member States apply their discretionary powers may negatively impact the development of CCS in individual Member States.
- Second, it is possible that requirements in the Directive are implemented in a more rigorous manner in one Member State than in another Member State. This can lead to the situation that investors' propensity to invest in CCS is likely to differ substantially between Member States (there will be no level playing field).

This report analyses these issues, and provides possible pathways and recommendations on how to resolve them. In our recommendations we concentrate on actions to be taken by governments.

1.2 Research approach

The purpose of this first report is to analyse the Directive and to identify the issues which may lead to uncertainties and hamper the development of CCS. In order to find these issues, we analysed the EU Directive on the Geological Storage of Carbon Dioxide, in order to determine what is regulated by which level of government (EU or Member State). This report also presents a general overview of the regulatory framework surrounding the CCS Directive, as well as the national legal framework that will be used to implement the Directive (according to the proposal published by the Ministry of Economic Affairs). The result of this analysis is a long-list of issues that need further clarification. These issues can be categorised into three categories:

- Issues for which the EU legislator has indicated that further EU guidelines will be presented (such as composition of the CO_2 stream, transfer of responsibility, financial mechanism);
- Issues for which no such guidance is indicated and Member States have full discretionary powers (such as selection of storage sites, Third Party Access); and
- Issues relevant for the development of CCS but not regulated in the Directive and thus totally governed by national law (such as long-term liability, supervisory structure).

The long-list of issues was discussed with policy makers, consultants and stakeholders in order to prioritise the issues for further research. During these discussions the project team selected the three issues with the highest priority to be researched in this report, being: 1) criteria/standards for safe site selection, 2) requirements on the composition of the CO_2 stream, and 3) management of long-term liabilities related to possible damage caused by CCS.

The other issues are put on our research agenda for further research. Information for the analysis in this report was mainly gathered through desk research, complemented with input from expert i and a brainstorm session with policy makers at the Ministry of Economic Affairs.

1.3 Reading guide

The report is structured in the following way:

- Chapter 2 provides an overview of the existing EU and national legal framework. It provides an overview on the unresolved issues we have identified and recommendation on how these can be researched and resolved (author: Van der Welle, ECN).

The other chapters are more detailed and technical and provide a comprehensive overview on the following three issues:

- Chapter 3 provides an overview on issues relating to safe site selection (authors: Nepveu/Van der Kuip, TNO)
- Chapter 4 deals with issues relating to the composition of the CO_2 stream (authors: De Wolff/Blank, KEMA).
- Chapter 5 provides an overview of the risks in the CCS chain, and discusses the long-term liability related to possible damage caused by CCS (authors: Harmelink/Lako ECN and Haan-Kamminga/Roggenkamp, RuG).

1.4 References

EC (2009) Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006

Dutch Lower House of Parliament (Tweede Kamer), 2010, 32 343, proposal for implementation of the CCS Directive.

2 Existing legal framework

Abstract

This chapter discusses the current international and national legal framework relating to the geological storage of CO_2. Starting point for the international legal framework is the EU Directive on global storage of CO_2. Cause and scope of the Directive and the link with other EU Directives are discussed. Subsequently, an overview is provided on the transposition of the EU Directive into Dutch legislation. The final paragraph provides an analysis of issues which (at first sight) seem not yet sufficiently addressed on both European and national level, and identify the issues that will be further explored in the next chapters of the report.

The selected issues can be categorised in:

- *Issues for which the EU legislator has indicated that further EU guidelines will be presented (such as composition of the CO_2 stream, transfer of responsibility, financial mechanism, monitoring);*
- *Issues for which no such guidance is indicated and Member States have full discretionary powers (such as selection of storage sites, Third Party Access, supervisory structure); and*
- *Issues relevant for the development of CCS but not regulated in the Directive and thus totally governed by national law (such as long-term liability).*

2.1 Introduction

This chapter provides an overview of the CCS Directive and the legislative framework used to implement the CCS Directive in national law. The relevant international and European legislation is summarised in the appendices (CCS Directive, OSPAR, London Convention). As the main focus of this report is to identify issues related to the implementation of the CCS Directive in national law, starting point for our research is the EU Directive on global storage of CO_2. The second paragraph provides an overview of the main issues covered in this Directive, the link with other EU Directives and the relevant national legislation used to implement the Directive. Based on an article–by-article analysis of the Directive (see appendix), issues were identified which do need further clarification. In the third paragraph these selected issues are discussed. The final paragraph concludes with an overview of the most urgent issues to be studied in more detail in years to come.

2.2 Directive for the Geological Storage of CO_2

2.2.1 Establishment of the CCS Directive

On 10 January 2007, the European Commission adopted a Communication on "Sustainable Power Generation from Fossil Fuels: aiming for near-zero emissions from coal after 2020". The Communication outlined the Commission's intention to bring forward an enabling legal and policy framework for carbon capture and geological storage. Following this communication, on 23 January 2008 the European Commission issued a draft storage Directive. The Commission proposal intended to enable CCS by providing a framework to manage environmental risks and remove barriers in existing legislation. On June 25, 2009 the Directive entered into force as Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009. Countries are obliged to transpose the Directive in their national legislation no later than 25 June 2011. This paragraph first describes the European legal framework and then describes the national legal framework in which the CCS Directive will be implemented.

2.2.2 Scope of the CCS Directive

The CO_2 Storage Directive mainly regulates the use of the subsoil for the purpose of injecting and permanently storing CO_2. Issues relating to capture and transport are either regulated by other EU Directives/regulations or regulated at the Member State level. The CCS Directive uses the principle of minimum harmonisation. This means that the Directive prescribes the minimum requirements and that Member States are able to issue more strict rules for their country. The legal framework covering the CCS chain is illustrated in Figure 1.

Figure 1: Overview of relevant EU legislation in the CCS Chain

CCS CHAIN		
Capture	Transport	Storage
Relevant EU legislation		
Storage Directive ETS Directive Environmental Liability Directive Environmental Impact Assessment (EIA) Directive Waste Directive		
IPCC Directive Large Combustion Plan Directive		Water framework Directive

Several other EU Directives are amended in order to complement or support the CCS Directive and provide for a coherent legal framework. The CCS Directive amends the following EU Directives:

- Council Directive of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment (*EIA Directive*). Following the amendment of Directive 85/337/EEC, capture, transport and storage of carbon dioxide is often subject to an environmental impact assessment (EIA), to be carried out in the capture permit process.[1] For remaining categories of installations for capture and transport of CO_2 streams, Member States are allowed to decide whether the project shall be made subject to such an assessment (EC, 1985)[2].

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[1] Annex I of Directive 85/337/EEC states that an EIA is compulsory for installations for the capture of CO_2 streams from installations defined in this Directive, or with total yearly CO_2 capture of 1,5 megaton's or more. Pipelines with a diameter of more than 800 mm and a length of more than 40 km. Storage sites pursuant to Directive 2009/31/EC.

[2] Annex II of Directive 85/337/EEC states that an EIA is voluntary for installations for the capture of CO_2 streams for the purposes of geological storage pursuant to Directive 2009/31/EC from installations not covered by Annex I to this Directive. Pipelines for the transport of CO_2 streams for the purposes of geological storage (projects not included in Annex I).

- Directive 2000/60/EC of 23 October 2000 establishing a framework for Community action in the field of water policy (*Water framework Directive*). The Directive is amended to allow for injection of CO_2 for the purposes of geological storage into saline aquifers, under a number of strict requirements to protect groundwater against pollution and deterioration amongst others, EC (2000).
- Directive 2001/80/EC of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants (*LCP-Directive*). The Directive will be amended to oblige new combustion plants with a rated electrical output of 300 MW or more to be capture ready. In this way, the EC aims to ensure that new investments in fossil fuel power generation are able to facilitate substantial reductions in emissions if suitable CO_2 storage sites are available and CO_2 capture and transport are technically and economically feasible, EC (2001).
- Directive 2004/35/EC of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage (*Environmental liability Directive*). The amendment foresees inclusion of the operation of storage sites in the list of occupational activities i.e. any activity carried out in the course of an economic activity, of the Directive. Consequently, environmental liability with regard to the prevention and remedying of environmental damage due to failure of permanent containment of CO_2, also applies to storage site operation activities, EC (2004)[3].
- Directive 2006/12/EC on Waste (*Waste Directive*)[4]. According to the amendment, carbon dioxide captured, transported and stored should not be considered as waste, EC (2006a).
- Regulation (EC) No 1013/2006 of 14 June 2006 on *shipments of waste*. The amendment excludes the shipment of CO_2 for the purposes of geological storage from coverage by the regulation. Hence, the shipment of CO_2 does not require fulfilment of obligations related to shipment of waste (EC, 2006b).
- Directive 2008/1/EC of 15 January 2008 concerning integrated pollution prevention and control (*IPPC Directive*). To ensure that best available techniques to improve the composition of the CO_2 stream are established and applied, certain industrial installations for capture of CO_2 streams for geological storage are included in the list of installations covered by Annex I of this Directive (EC, 2008).
- Finally, activities in the CCS chain are covered in greenhouse gas emission allowance trading schemes (*Emission Allowance Trading Directive*). Therefore the amount of CO_2 stored can be deducted from the CO_2 emissions of the installation where the CO_2 has been captured. Under the condition that the price of CO_2 allowances is sufficiently high, actors in the CO_2 chain receive a financial incentive for capture, transport and storage of CO_2. This issue does not originate from the CO_2 storage Directive but is mandated by Directive 2003/87/EC about the greenhouse gas emissions trading allowances scheme (EC, 2003), lastly changed by Directive 2009/29/EC (EC, 2009a).

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[3] Liability for climate damage as a result of leakages is covered by the inclusion of storage sites in Directive 2003/87/EC.

[4] Directive 2006/12/EC is repealed by Directive 2008/98/EC with effect by 12 December 2010.

2.2.3 Implementation of the Storage Directive in the Netherlands

Figure 2 summarizes the relevant national legislation related to the CO_2 Storage Directive for the whole CCS chain.

Figure 2: Overview of relevant national legislation in the Netherlands

CCS CHAIN		
Capture	Transport	Storage
Relevant national legislation		
Mining Act (Mijnbouwwet) Environmental Management Act (Wet milieubeheer) Decision on Environmental Impact Assessments (Besluit milieueffectrapportage 1994) Decision on Emission Allowance Trading (Besluit handel in emissierechten)		
Decision on emission limits for large combustion plants (Besluit emissie-eisen grote stookinstallaties milieubeheer (BEES-A)) / MR omgevingsrecht)	Mining Act (Mijnbouwwet)	Water decision (Waterbesluit)

The CO_2 Storage Directive will be implemented in Dutch legislation through an amendment of the Mining Act. Moreover, some amendments will be made in the Environmental Management Act and decisions and regulations based on this act, as well as one change in a decision based on the Water Act. A Bill presenting the proposed implementation of the CCS Directive was presented to the Parliament in March 2010.[5] The relevant legislative instruments are described below.

- Following the amendment of Directive 85/337/EEC, an installation for the capture, transport and storage of carbon dioxide is either mandatory or voluntarily subject to an environmental impact assessment before a carbon capture permit can be obtained. This amendment will be implemented in Dutch legislation through extension of the Annex of the Decison on Environmental Impact Assessments 1994. The Annex will be extended with categories related to pipelines for CO_2 transport, CO_2 storage and installations for the capture of CO_2 streams.

- Injection of CO_2 in saline aquifers is allowed due to the amendment of Directive 2000/60/EC. This change has been implemented through the Water decision, which entered into force by 1 March 2010.

- As a result of the amendment of the large combustion plant Directive (Directive 2001/80/EC), new combustion plants with a rated electrical output of 300 MW or more are obliged to be capture ready. Implementation of this adjustment is announced to take place in the Decision on emission limits for large combustion plants (BEES-A) or through the Ministerial Regulation Environmental Law (‘omgevingsrecht’).

- The operation of storage sites is added to the list of economic activities subject to environmental liability in Directive 2004/35/EC. New Dutch legislation to implement this change is not required since Article 17.7 of the Environmental Management Act automatically

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[5] Kamerstukken 2009-2010, 32 343, nr. 3.

takes into account changes in the list of occupational activities in the Directive; it refers to the list of the latter.

- According to the amendment of Directive 2006/12/EC on waste, carbon dioxide captured, transported and stored should not be considered as waste. This adjustment will be implemented together with the implementation of Directive 2008/98/EC, repealing Directive 2006/12/EC, with effect by 12 December 2010.
- The amendment of Regulation (EC) No 1013/2006 on shipments of waste excludes the shipment of CO_2 for the purposes of geological storage from the scope of the Regulation. This Regulation applies directly and therefore does not require adjustments to the Environmental Management Act.
- The extension of the list of industrial installations of Directive 2008/1/EC (IPPC Directive) with installations for capturing CO_2 streams does not require adjustments of the Environmental Management Act. The Act already refers to Annex I of the Directive and therefore automatically covers installations for CO_2 capture.
- Inclusion of capture, transport and storage of CO_2 under the greenhouse gas emission allowance trading schemes (EU ETS, based on Directive 2009/29/EC) is in principle already covered under the current Environmental Management Act. Capture and storage are both a constitution that contains a CO_2 storage installation. Transport of CO_2 is not performed within such an constitution, therefore the application of Title 16.2 of the Act has been expanded[6] Subsequently, activities related to capture, transport and storage will be assigned as CO_2 activities under the (future) Decision on Emission Allowance Trading. Consequently, all CCS activities for the complete value chain (capture, transport and storage) are subject to the duties of greenhouse gas emission allowance trading; licensing, monitoring, reporting and surrendering (allowances) duties. Furthermore, measures are taken to preclude double counting of CO_2 emission allowances.[7]
- Injection of CO_2 in saline aquifers is allowed due to the amendment of Directive 2000/60/EC. This change has been implemented through the Water decision, which entered into force by 1 March 2010. Moreover, as there are no plans yet to use saline aquifers for storage of CO_2, this is not yet relevant for the Netherlands.

2.3 Selected issues under the CCS Directive

2.3.1 Introduction

As the CCS Directive is based on the principles of minimum harmonisation, it is inevitable that there will be issues which give Member States the powers to go beyond the minimum requirements set by the Directive. Consequently, there may be different legal requirements in individual national laws. Based on an article by article analysis of the Directive, we tried to identify the issues that need further clarification and elaboration. As the development of large-scale CCS

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[6] The application is limited to CO_2 transports from capture installations to storage facilities, as other transports are assumed to be ultimately emitted in the atmosphere (Kamerstukken 2009-2010, 32 197, nr. 6).

[7] Kamerstukken 2009-2010, 32 197, nr. 3.

requires a stable legal framework, we discussed the issues identified with an expert panel, in order to determine which of these issues might become an obstacle in the development of large-scale CCS in the Netherlands. Such an obstacle might be a distortion of level playing field between potential investors in different countries as they experience different transport and storage costs. Since transport and storage costs will be passed through to power plants with CO_2 capture installations, this affects electricity generation costs between Member States differently, and therefore may impede the full realisation of a truly internal electricity market. Other unresolved issues can be linked to the lack of clear requirements and standards, leading to risks and uncertainty which do not motivate investors to invest in CCS. Based on the discussions with the expert panel we found three categories of uncertainties for policymakers and potential investors.

A first category of uncertainties can be derived from the text of the CCS Directive itself and the choice for minimum harmonisation. In a few articles the European legislator explicitly retains the possibility to formulate more specific rules and guidelines. These articles are:

- Article 12 on the composition of the CO_2 stream;
- Article 18 on the transfer of responsibility;
- Article 20 on the financial mechanism.

Furthermore, a guideline for the ETS directive has been issued which indirectly provides more detailed rules for

- Article 13 on monitoring.

A second category of issues is also derived from the minimum harmonisation strategy that is used in the Directive, and provides for discretionary space for Member States (either explicit or by using vague formulations). These issues are found in:

- Article 4 on the selection of storage sites;
- Article 21 on Third Party Access;
- The regulatory and supervisory structure that is chosen as competent authority (articles 23, 24)

A final category of issues are the items that are not covered by the Directive and thus governed by national law. These issues may also be an obstacle in the development of CCS.

- Issues related to long-term liability (consideration 34).

All issues are elaborated upon in more detail in this paragraph, ordered by category. For each of the issues we describe shortly which questions might rise and possibly in which direction solutions might be sought.

2.3.2 Issues for which further EU guidelines will be presented

2.3.2.1 Requirements regarding the composition of the CO_2 stream

The first article in which the EU legislator announces the possibility of introducing further guidelines is article 12. Article 12 (1) of the Directive states that 'A CO_2 stream shall consist overwhelmingly of carbon dioxide'. Discussion has emerged on the specification of the CO_2 stream, mainly focussing on the purity of the CO_2 stream and the presence of substances as H_2S or SO_2. According to the continuation of Article 12, 'a CO_2 stream may contain incidental associated substances …, [but] concentrations of all incidental and added substances shall be below levels that would:

- adversely affect the integrity of the storage site or the relevant transport infrastructure;
- pose a significant risk to the environment or human health; or
- breach the requirements of applicable Community legislation.'

The concentration levels of substances are not further defined; however the Directive remarks that 'the composition of the CO_2 stream is the result of the processes at the capture installations. Following inclusion of capture installations in Directive 85/337/EEC, an environmental impact assessment has to be carried out in the capture permit process'. Furthermore, best available techniques to improve the composition of the CO_2 stream have to be applied according to Directive 2008/1/EC. Therefore, negative environmental impacts of the composition of the CO_2 stream are already partly prevented by existing legislation[8].

In addition, the operator of the storage site has to meet certain requirements for the composition of the CO_2 stream and the CO_2 stream acceptance procedures in order to obtain a storage permit (Article 9). To this end, he has the duty to both analyse the composition of the CO_2 stream including a risk assessment and to keep a register of the quantities and properties of the CO_2 streams delivered, including the composition of those streams (Article 12 (3)). According to chapter 4, currently considered capture processes are well capable of meeting restrictions for preventing both effects on the integrity of infrastructure and significant risks to environment and human health. Requirements in the CCS Directive on the application of process cleaning techniques do not necessarily have to be made more specific as market parties want to prevent corrosion and two-phase flow formation and hence have incentives to apply those techniques. The Commission issued also a technical guidance documents in June 2010, in which several techniques are discussed.

2.3.2.2 Transfer of responsibility

As part of the post-closure procedure, Article 18 of the Directive requires that a minimum period has elapsed before the responsibility for the storage site can be shifted from the operator to the competent authority. In principle the length of the required minimum period is 20 years, but national competent authorities are allowed to reduce the period before transfer of responsibility can take place. This is the case, when the authority is convinced that the stored CO_2 will be completely and permanently contained before the end of a shorter period.

This policy has a number of disadvantages. First of all, it creates the risk that when one Member State prevails short-term (industry) interests to long-term climate and security interests and consequently shortens the minimum period, other Member States will follow because of level playing field considerations. Ultimately, this may induce 'a race to the bottom' to the detriment of health and environmental interests. The other way around, safety concerns etc. may lead to a

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[8] See point 27 of the preambles of the Directive.

race to the top with very long periods before responsibility can be shifted (for instance, Germany considers 30 years), which increases cost uncertainty for storage site operators dramatically. Both arguments suggest that the transfer of responsibility should be fully fixed by legislation. On the other hand, one may say that such a practise does not take into account differences between storage sites, which drive the need for variable periods before responsibility is transferred from storage operators to the competent authority. However, climate and safety risk differences between storage sites are expected to be limited since storage operators have to prove permanent and complete containment of CO_2 in the storage facility already before obtaining a storage permit. Hence, it is advised to standardize the length of the transfer of responsibility period.

Article 18 (2) of the Directive states explicitly that the Commission may adopt guidelines on the assessment of technical criteria relevant to the determination of the minimum periods. Preferably, the Commission should keep a close eye on the different national prerequisites concerning the transfer of responsibility in the short term. In that way, more coordination between Member States is achieved and measures that distort the internal market can be prevented. In June 2010 the Commission has issued a draft guidance document in which possible criteria are listed. The document has raised a lot of discussion on the criteria to be used. Question for further research are the influence of the criteria for the transfer of responsibility on the development of CCS for specific Member States and in the EU as a whole.

2.3.2.3 Financial Mechanism

Article 20 (2) of Directive 2009/31/EC states that “Member States shall ensure that the operator, on the basis of arrangements to be decided by the Member States, makes a financial contribution available to the competent authority before the transfer of responsibility pursuant to Article 18 has taken place”. This needs to be further elaborated for the Netherlands in the Dutch Mining Act or a separate regulation. A difficult point will be to make a good estimate of the monitoring costs; these are (currently still) surrounded by large uncertainties. In June 2010 the Commission issued a guidance document on the financial security and the financial contribution. This document raised a lot of discussion between the industry and legislators, as it defines which risks are to be financed by the industry itself and are the responsibility of governments.

The document defines different categories of costs and determines whether or not these costs should be included in either the financial security or the financial contribution. The central questions in the discussions are:

- To which degree should financial certainty be proven in advance?
- Which party (industry or competent authority) should be financially responsible for the larger and more unknown events that might occur?
- Which type of security is reasonable?

In order to attract CCS industry, some Member States might limit the requirements and concomitant costs and risks, whereas in other Member States the thresholds might be formulated more rigorously, which influences the level playing field for CCS. Whether or not the level playing field will actually be influenced is a question for further research.

2.3.2.4 Monitoring of the site

The subject of monitoring is treated in Article 13 (2) of the Directive. The operator is obliged to issue a monitoring plan according to the requirements laid down in Annex II. The Directive does not prescribe any particular monitoring technology. Because the monitoring method applied influences the storage costs of the operator, this might cause unfair competition for location of CO_2 storage across EU Member States if monitoring is given different interpretations by several Member States. However, the recent CCS monitoring and reporting guidelines for the Emission Trading System provide more direction on the way monitoring and reporting of emissions of greenhouse gas in the CCS chain should be carried out (EC, 2009). As leakage is included as one of the potential sources of CO_2 emissions, this guideline also includes emission quantification rules for leakage from storage sites (implemented as Annex XVIII of EC, 2007). Leakage of a storage complex has to be quantified with a maximum total uncertainty of ±7.5%. If the uncertainty is above ±7.5%, the 'excess' uncertainty with respect to ±7.5% requirement has to be added to the reported greenhouse gasses. This method seems fair, as it helps to keep operators' monitoring costs to an acceptable level for emissions that will probably not occur. And from government and society perspective it keeps the uncertainty of the emission in line with uncertainty generally required in the MRG for emission accounting under ETS. Furthermore, the EC guidelines narrow the scope for unfair competition for location of CO_2 storage across the EU.

At the same time, these uncertainty limits may pose some problems for specific storage sites where 'standard' monitoring technologies cannot be applied. As a result, operators of these sites either have to report substantial CO_2 leakage or demonstrate lower levels of 'leakage' through application of better monitoring technologies which may come at considerable costs. However, this is not unfavourable for European citizens, as monitoring results may lead to selection of the most safe storage sites, with lowest doubts about safety. All in all, stricter requirements seem not necessary as a higher accuracy in emission estimates will imply higher costs (Wartmann et al., 2009). A deeper analysis of the emission quantification uncertainty is provided in the Deliverable 4.1.03 of WP4.1 in CATO-2 "Analysis of the uncertainty requirements of the Monitoring and Reporting Guidelines for CCS under the EU-Emission Trading System".

2.3.3 Issues for which no EU guidelines will be presented

2.3.3.1 Procedure and criteria for site selection

This topic relates to the technical selection of safe sites as well as spatial planning policies that govern the economic viability of CCS.

Concerning the technical selection of safe sites, Article 4 (4) of the Directive states that 'A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exists'. It is not yet clear when there is a *significant* risk of leakage, and if this risk exist, whether environmental or health risks are *significant* as well. This is the case since current monitoring techniques do not allow for precise quantification of leakage risks.

Article 4 (3) of the Directive sets out the procedure to assess the suitability of a geological formation for use as a storage site and refers to criteria specified in Annex I. Out of the characterisation of the storage dynamic behaviour a number of technical risks have to be derived. Furthermore, a risk assessment with hazard characterisation, exposure assessment, effects assessment and risk characterisation is prescribed. However, the Directive does not include clear standards for the share of CO_2 that might be at risk to leak from a storage site, offering Member States some discretionary powers in their assessments of storage site selection. Therefore, some utilities are afraid of a too strict interpretation of the Directive by some Member States making CO_2 storage too costly (see for instance Radgen *et al.*, 2009).

In order to take away these concerns, different possibilities to make criteria for safe site selection more explicit should be considered. One possibility would be to mention a certain, maximum probabilistic level of leakage in European legislation (either by Directive or Regulation). Hence, leakage risks and associated environmental and health risks should not exceed a certain standard risk level with a certain chance, given the monitoring techniques available. A low standard risk level would imply a strict assessment regime which comes at higher costs, while a high standard risk level would mean a more loose assessment regime with lower associated costs. However, for leakage there is not yet enough information available about CO_2 leakage probabilities. Furthermore, statistical material from related industries such as the hydrocarbon business which could possibly be used for setting a maximum probabilistic level for leakage of CO_2 storage, is not available. In chapter 3 it is therefore recommended to declare a storage site *unsafe* if:

- No clear-cut reason can be found for simulations of the storage site producing leakage;
- A clear-cut reason can be found, with essential parameters being highly uncertain.

If none of the simulations produces leakage the site might be deemed safe. This solution should preferably be implemented at the European scale since all countries face the same question.

The other dimension of site selection relates to spatial planning regarding CCS. There are currently no spatial policies in place, but plans are being prepared by the relevant ministries. Related to this is the issues of availability of gas fields where the extraction of gas has been finalized, and which can be re-used. These locations for CO_2 storage purposes should preferably not be cut off, but the closure requirement often make reuse impossible. In order to solve this, the rules for removal of extraction equipment after the extraction of gas has ended should be adjusted (EBN/Gasunie, 2010). These issues need to be resolved in order to develop large-scale CCS.

2.3.3.2 Type of infrastructure access arrangements

The number of CO2 storage facilities available in a specific Member State may be quite limited due to geological conditions. Besides, the number of storage sites to be developed as well as CO2 transport pipelines connecting CO2 emitters to storage may be limited due to the high capital intensity of building new storage facilities and pipelines, implying substantial economies of scale. The latter impedes duplication of CO2 infrastructure by investments of new users. Access to CO2 infrastructure may become a condition for the building of major point emitters like power plants. Hence, potential electricity generators should be able to obtain access to existing pipeline and storage facilities. Article 21 (2) states that 'The access … shall be provided in a transparent and non-discriminatory manner determined by the Member State'. This implies that third parties should have at least the possibility to negotiate access to the CO2 infrastructure. However, Member States have the discretion to choose their own regime of third party access (TPA) to the CO2 infrastructure. They may go beyond purely negotiated access. In case of negotiated access, potential users have to negotiate on the conditions for connection and use-of-system services. In case of regulated access, a regulator is allowed to set conditions for connection and use-of-system services, tariff structures and tariff levels. Generally, in case of negotiated access, stakeholders negotiate the conditions of access themselves, and have recourse to an ex-post competent authority, while in case of regulated TPA the regulator is mainly involved ex-ante.

There are different approaches with respect to the developments on TPA.

- It can be argued that a system with negotiated access is favourable for the development of CO2 infrastructures (Roggenkamp, 2009). This is based on the analogy with the access regime applied to upstream oil/gas pipelines, i.e. the regime governing those pipelines connected to the storage reservoirs. The analogy seems reasonable since the potential users of storage locations are mainly point emitters, of which we have approximately twelve in the Netherlands [see report task force CCS], which creates a rather small market. The negotiated access regime is deemed to offer investors more certainty of fast cost recovery compared to a system of regulated access. Besides, if partners cooperate well, a negotiated access regime may imply lower administrative costs.
- At the same time, it can also be argued that a system with regulated access is favourable for the development of CO2 infrastructures in the medium or long term. The EU Directive leaves room for countries to introduce divergent national policies to establish network access. Experiences in the electricity sector learn that divergent national policies can be a barrier to the development of a sustainable and harmonized (internal) market since non-harmonised network access policies tend to distort the level playing field between electricity generators. Likewise, with the uptake of CCS a lack of harmonized rules for CO2 infrastructure charging may imply distortion of competition between CO2 emitting industries. Furthermore, it may impede the utilisation of the most cost-efficient storage sites and network infrastructure across Europe. This may favour the development of more harmonised regulation regarding TPA.

In the Netherlands, based on the Directive a negotiated TPA has been implemented in Article 32 of the Bill.[9] In this proposal, Dutch policy makers do not pay attention to the issue of TPA other than stating that potential users and owners of transport and storage facilities have a common interest in sharing these facilities. Potential users are often competitors in electricity generation. It is possible that vertically integrated companies develop, thereby increasing the number of markets in which they compete and hence their incentive to restrict third-party access to a favourable storage/transport facility (i.e. vertical foreclosure). Although there are legal thresholds to encounter this (competition law, recourse to the competent authority), one should realise that CCS is a developing market and such complications may develop. Therefore, policy makers should analyse the development of the market and third-party access practices, and adjust Dutch legislation if appropriate. Such adjustments may be either implemented by Royal Decree (AMvB)[10] or another legal instrument.

Further research on TPA is needed in order to weigh all arguments for and against more specific regulation on the access arrangements, related to the development of a potential market for CCS.

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[9] Kamerstukken 2009-2010, 32 343, nr. 2.

[10] Kamerstukken 2009-2010, 32 343, nr. 6, p. 11.

2.3.3.3 Supervisory structure

The Directive requires the Member States to appoint a competent authority that should supervise the permitting and safety regime for CCS. The Directive furthermore requires a dispute handling system related to the TPA. Member State thus have to develop a regulatory and supervisory structure for CCS. Existing structures might be used, or new structures might be developed. According to the Directive, the competent authorities are obliged to cooperate in cases of transboundary transport and storage; Article 24 states that ‘in cases of transboundary transport of CO_2, transboundary storage sites or transboundary storage complexes, the competent authorities of the Member States concerned shall jointly meet the requirements of this Directive and of other relevant Community legislation’. It seems likely that discussions about responsibilities between Member States will sometimes evolve in cross-border disputes. Hence, Article 22 (2) states that ‘… Where, in cross-border disputes, more than one Member State covers the transport network or storage site concerned, the Member States concerned shall consult with a view to ensuring that this Directive is applied consistently.’ Relevant questions for further research are the design of the supervisory structure and the capability of this authority to cooperate internationally. This issue is also of specific interest to the Commission as the review procedure contains the following statement: ‘The Commission shall assess in particular … experience with … the provisions on transboundary cooperation pursuant to Article 24, …’ (Article 38(2)).

2.3.4 Issue totally governed by national law

2.3.4.1 Liabilities with respect to health and property

The leakage of gaseous CO_2 from the CCS chain may cause physical damage to: 1) the global climate system, 2) the environment and ecosystems, 3) to human health and property. When looking at the long-term liability for possible damage caused by CCS, we see that there are three applicable regimes: climate liability, environmental liability and the existing national liability regimes for damage towards third parties. The liabilities towards third parties are to be dealt with on the national level (consideration 34 in preamble Directive 2009/31/EC). The most general basis for liability with respect to health and property is Article 6:162 of the Dutch Civil code. This is a form of fault-based liability. An act is unlawful if it violates statutory law, unwritten rules or law or infringes a right of another. When the operator has failed to comply with the conditions of the different permits that are required, this causes his actions to be unlawful. Besides the fault-based liability system, Dutch legislation also knows more strict liabilities: the risk based liabilities. The question is which of these liabilities might apply to CCS. There is a specific risk-related liability for mining activities (resulting in blow-outs or soil movement), but the section on blow-out specifically refers to blow-outs of minerals, which CO_2 is not.

It might be questioned whether or not the national system handling liabilities towards third parties is suitable for dealing with liability for the long-term storage of CO_2. Elements that might prove to be a roadblock for investors in CCS might be the liability horizon, the type of liabilities that apply and the uncertainty that is a result of leaving decisions on liability up to the judicial system. Furthermore, based on Chapter 9 of the Mining Act, affected parties may appeal to the Guarantee Fund for Mining Damage (‘Waarborgfonds Mijnbouwschade’) if the damage is caused by an insolvent operator. The Ministry of Justice currently prepares a legislative proposal to cover this gap, by adding a legal provision to the Dutch Civil Code. This provision will indicate who is liable, which damage will be covered, under which circumstances there is no liability assumed and which related periods of prescription will hold.[11] But it can be questioned whether or not all uncertainties for operators and investors are dealt with by just adding a specific liability. Other methods of managing the long-term liabilities and related uncertainties should be explored too. See also chapter 5.

2.4 Research agenda

It can be concluded that there are many issues that need further research and further clarification to ensure a sound and effective regulation regarding CCS. In the coming years of the CATO-2 research programme, these issues will be further investigated. As not all issues can be researched at once, the project group and the expert panel have selected issues to be researched right away and issues that are placed in the agenda for the following years.

Issues that were selected to research right away are the procedures for safe selection of storage sites, composition of the CO_2 stream and liability, as they provide insight for operators in the possible costs they face. These were the issues the stakeholders prioritised as well. In chapter 3 the procedures for safe site selection are addressed. In chapter 4 the composition of the CO_2 stream and in chapter 5 the issues related to long-term liability. Issues related to the government and supervisory structure, monitoring and TPA are postponed to next year, and the issues on which guidelines were expected (and published during our research year) were also postponed. For these issues, more specific research questions will be formulated and incorporated in the research agenda of this work package.

During our research the Dutch government published its proposal for implementation of the CCS Directive. The government chose to implement the text literally and did not add or elaborate any of the issues that are not already elaborated in the existing legal framework, although concerning liabilities with respect to health and property new legislation was announced.

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[11] Kamerstukken 2009-2010, 32 343, nr. 6, p. 12, 13, 15.

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3 Safe site selection

Abstract

The legal basis for Safe Site Selection is the so-called Storage Directive (EC 23/4/2009) with its annex I. This Directive must be implemented into the various national legal systems of EC countries. Safe site selection is detailed in Chapter 2 of the Storage Directive. Two points are essential:

- *The suitability of a geological formation for CO_2 storage has to be assessed through a process of characterisation and assessment, and*
- *A storage site may only be selected if the likelihood of leakage is not significant, and risks for human health and environment are not significant.*

It is not yet clear when there is a significant risk of leakage, and if this risk exists, whether environmental or health risks are significant as well. Furthermore, the Directive does not include clear standards for the share of CO_2 that might be at risk to leak from a storage site.

There is not yet enough information available about CO_2 leakage probabilities that could be used for setting quantitative standards on the maximum probabilistic level for leakage of CO_2 from storage site. The procedure for characterisation and assessment of a storage site will lead to a substantial number of simulations. In those cases where leakage is shown to occur further study will generally reveal its origin. It is therefore recommended to declare a storage site unsafe if:

- *No clear-cut reason can be found for simulations of the storage site producing leakage;*
- *A clear-cut reason can be found, with essential parameters being highly uncertain.*

If none of the simulations produces leakage the site might be deemed safe. This solution should preferably be implemented at European scale since all countries face the same question.

In this Chapter the conditions mentioned in Annex 1 of the Storage Directive are detailed. The level of description offered here is such that the demands are clear to technical professionals in this line of business. These professionals generally have a background common to these working in the hydrocarbon producing business.

3.1 Introduction

The formal basis for safe site selection is given within the “Directive 2009/31/EC of the European Parliament and of the Council of 23/4/2009”, hereafter to be called Directive. The field of legislation for CO_2 storage has quite some history, as the London Convention (1972) and Protocol (1996), and the OSPAR convention show (see Appendix 2 and 3 for more information.). Indeed it is not surprising that, within the Directive, there is mention of the OSPAR Convention of 2007 [Directive statement (14)].

Chapter 2 of the Directive deals with “Selection of storage sites and exploration permits”. Three articles from this chapter are of paramount importance for our present task.

- Article 4 sub 2. stipulates that "Member States which intend to allow geological storage of CO_2 in their territory shall undertake an assessment of the storage capacity available in parts or in the whole of their territory…".
- Article 4 sub 3. stipulates that "The suitability of a geological formation for use as storage site shall be determined through a characterisation and assessment of the potential storage complex pursuant to criteria specified in Annex I ", where this Annex is part of the Directive.
- Article 4 sub 4. states that "A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risk exists."

Member States which intend to allow CO_2 storage in their territory have to take the effort to determine which "physical" room there is in their territory for this storage. In this exercise some ideas will necessarily emerge on what sites offer themselves on the basis of capacity considerations alone. This activity necessarily involves an identification of geological layers and structures with sufficient porosity and permeability to make CO_2 storage feasible.

On the basis of the foregoing a distinction is made between pre-selection and selection, as given in Table 1. ***Pre*-selection intends to identify sites with sufficient storage potential, given operational costs, the possibilities to monitor operations, accessibility and HSE (Health, Safety, Environment) issues.** Here we deal largely with *expectations*. Sites that emerge from this phase should be those candidates that are truly *promising*. That is, when the issues just mentioned do not bar the sites right away, there should be high hopes that further inquiry will show the candidate-site to meet the requirements of article 4 sub 4. in an economically sound way.

In the next Chapters we will concentrate on the site-investigation process, i.e. the second phase mentioned in Table 1. Once the sign has been given to go for a full investigation, together with the application for an exploration permit, the necessary actions can be described in a more uniform way than in a pre-selection phase.

Table 1: Relevant phases of CO_2 selection

No.	CO_2 storage phase	Objective
1.	Screening (pre-selection of storage sites)	Identify candidate storage sites based on available data, storage volume, economic, logistic, health, safety and environmental considerations.
2.	Site investigation (selection)	Assess storage potential and determine chemical, mechanical and physical properties of the reservoir and overlying formations to ensure safe and effective CO_2 storage.

3.1.1 The methodological basis of site selection

From a careful perusal of the stipulations in the Directive one must conclude that a successful storage site – and only those that are selected - must

- have the potential to store CO_2 indefinitely
- put no significant risk to health, safety and environment.

The first bullet is effectively the result of Directive Chapter 4, Article 18 where the transfer of responsibility to the competent authorities is treated in the post-closure phase. It is stated that such a transfer can only take place when, inter alia, "all available evidence indicates that the stored CO_2 will be completely and permanently contained."

In the pre-selection phase more "mundane" issues have been tackled already. Legal and physical accessibility in connection with adequate monitoring potential is an issue that we henceforth consider cleared.

In order to meet the objectives of the site selection phases different research activities need to be conducted. In the pre-selection phase assets are researched based on available knowledge. In the site selection phase, however, the knowledge basis is described in general terms in the Directive, notably in Annex 1. The three steps that are to be taken for a proper site characterisation and assessment are described in the next section.

3.2 Site Characterisation and Assessment

Quite some work has been done over the years by TNO and others to produce a coherent picture on site characterisation and assessment in several projects (see for a recent overview book report TNO-034-UT-2009-02240/A: **CCS** CO_2 Capture and Storage, December 2009). In the present description we loosely follow the Association ASPEN report (2009) where TNO had the lead on this topic.

Let us repeat the three steps required by the Storage Directive:

- Data collection
- Building the three-dimensional static geological earth model
- Characterisation of the storage dynamic behaviour, sensitivity characterisation, risk assessment.

In this chapter a number of activities that have to be carried out is listed. Many of these activities are firmly rooted in the hydrocarbon business, but the emphasis is now shifted. Risk assessment and the steps that follow are relatively new, although these subjects in themselves have made significant strides since the 1960's or so. In any case, knowledge obtained in the exploration and production business is essential in what follows.

The procedure starts with data collection. These data are used to build static models and later perform dynamic simulations. Based upon these simulations the storage site can be characterised and a quantitative risk assessment can be carried out. *However, we do not deal with a linear process. The steps are strongly intertwined, and several re-iterations may be needed between the steps.*

3.2.1 Data collection

The first step is to compile and evaluate available data. When the intended formation is a depleted hydrocarbon reservoir a host of data will be available. The table below gives a fair indication.

Table 2: Type of data that need to be collected and their use.

Data type	Use
2D/3D seismic surveys	Mapping of a possible containment structure; insights into extension of caprock and structure of overburden
Borehole data	General idea of stratigraphy and rock properties; evaluation of well integrity.
Wireline logs	Characterisation of sedimentological development of the storage compartment, overburden and caprock.
Data from core sample analysis	First-order assessment of flow characteristics (e.g. clay breaks)

A second step is to collect and process site data. The collection of additional data is aimed at a more detailed determination of the storage capacity, the containment concept, and the risk assessment. One should realise that existing data collection by the industry is focussed on the reservoir and not so much on the overburden. Proper risk assessment, though, requires sufficient data on *the storage complex, caprock, overburden, shallow subsurface and surface data in the vicinity of the site*. (Formally one may derive this from the Storage Directive (see Annex 2); scientifically it is obvious).

For the construction of a 3D static earth model the data should cover: geology and geophysics, hydrogeology, reservoir engineering, geochemistry, geomechanics, seismicity and man-made or natural leakage pathways.

3.2.1.1 Geology and Geophysics

Here one should think of:

- Seismic surveys to map out the large geological structures. For a proper assessment 3D seismics is required to characterize container, possible compartimentalisation, and caprock and overburden. Also a first characterisation of faults and fault structures in the overburden is targeted.
- Wireline logs to estimate the geometrical extent and geometrical properties of the storage container (e.g. GR logs, sonic logs, density logs). Besides we want to assess the internal structure and assess continuous reservoir properties (porosity, permeability, shale content) with sonic logs, neutron logs and density logs. Specialized logs may shed light on diagenetics and composition. Obviously the wireline logs must be run in several wells spaced across the structure.
- Core and rock samples. They enable lithology determination and various rock properties.

3.2.1.2 Reservoir engineering and petrophysics

These disciplines are used in estimating reservoir pore volume, petrophysical analysis of porosity and permeability, pressure data and well-test analysis. They allow to quantify porosity and permeability on microscopic and macroscopic scales, and aid in assessing compartimentalisation. We mention in particular:

- Petrophysical analysis of wireline logs to assess pore volume.

- Pressure measurements from well tests, RFT data to assess large-scale heterogeneities in the storage container. These data add to an understanding of compartimentalisation, along-hole permeability variation and the sealing nature of faults and fractures.
- In depleted hydrocarbon fields production data inform about large-scale permeability, preferred flow paths and compartimentalisation.
- Fluid sample measurements are needed to establish PVT conditions in the container and they give information on composition, viscosity and density. For saline aquifers brine composition and density are thus determined.

3.2.1.3 Geochemistry

Geochemistry is important for the mineralogical characterisation of the storage container and overburden. Compositional data are important to assess the likelihood of chemical reactions with the injected CO_2. One should mention as fruitful data:

- Chemical composition by x-ray diffraction of rock samples. Clay-fraction XRD is performed to establish the clay minerals within the pores.
- Thin section analysis helps to give poro-perm information. This analysis also helps establishing surface characteristics of specific components. This gives clues with respect to reactivity with formation water. It is input to geochemical modelling.

3.2.1.4 Geomechanics

For a geomechanical characterisation of the storage container, caprock, overburden and *underburden* one needs information on

- Layer thickness and structuration of the four zones, extension and orientation of faults within these layers. These data come from seismic interpretations.
- Mechanical parameters derived from laboratory testing.
- In-situ stress data. These data may be known from nearby wells.
- Pore pressure data are important for fault reactivation analysis. If not available assumptions can be based upon hydrostatic pressure gradients.

3.2.1.5 Seismicity

In order to assess possible injection-induced seismicity one will consult seismic hazard maps and seismic intensity maps. In case of planned injection into former hydrocarbon fields records of induced seismicity can be used to estimate the effect of increased pore pressures. In case of aquifer storage one will have to rely on geomechanical modelling, based on the input as indicated above.

3.2.1.6 Hydrogeology

Analysis in this case encompasses:

- Availability of groundwater compartments intended for consumption, and
- Possible influence by caprock and overburden on the storage container.

In order to monitor changes in groundwater chemistry during the injection process and in later stages local baseline conditions must be established. Porewater samples should be available or collected for the storage compartment, caprock and overburden. Sample collection from caprock and low-permeability rocks is difficult, and characteristic values are best extracted from rock samples or reconstructed from residual sault analysis. Temperature, conductivity, pH, alkalinity should be measured in situ.

3.2.1.7 Natural and man-made pathways

As CO_2 may escape via natural migration pathways, such as outcropping permeable formations, and non-sealing faults, and also via boreholes one must:

- Detect natural pathways. This is particularly important in the case of aquifer storage. Usual 2D/3D seismics gives clues, but phenomena like mud volcanoes, fluid/gas seeps, microseismicity and shallow-gas pockets are relevant hints as well.
- For boreholes in the storage area all aspects of well configuration need to be inventoried, including casing/cement, perforations, plug locations etc. to judge the sealing quality of the wells.

3.2.1.8 Earth Surface

The surface area in the immediate vicinity of the storage site as well as the surrounding region needs to be inventoried in terms of hazards, economic or technical conflicts and logistics. The following issues are to be taken into account:

- In case of onshore or near-shore storage CO_2 leakage may affect the population. Thus population data must be inventoried as regards density, spread, clustering.
- Any locations of social or economic activity (major infrastructural elements, hydrocarbon production, groundwater production, geothermal energy production, etc.) need to be inventoried so as to prevent conflicting situations.
- The potential CO_2 mass for injection and its composition must be estimated, as well as expected fluctuations in supply. Availability and capacity of any adequate transport networks must be assessed.

3.2.2 Building the three-dimensional static geological earth model

For the analysis of injectivity, storage capacity and containment of a depleted hydrocarbon field or aquifer an accurate, static, computer-based earth model is needed. Such models are generally built using a range of software applications, The workflow, however, is rather standardized and well-known in the hydrocarbon industry.

A static earth model gives quantified 3D information on the geological structure and its properties and it serves as the input for a study of the dynamic behaviour during CO_2 injection, and in the post-closure phase. Earth models for CO_2 injection have specific requirements on account of their ultimate purpose, and differ in some respects from hydrocarbon models as used in the relevant industry. These differences relate to:

- Conventional hydrocarbon earth models focus on the reservoir, generally. The CO_2 storage earth models are developed for the purpose of risk assessment, and therefore the focus is on caprock and overburden which they want to detail more.
- For an accurate geomechanical analysis for these models they should extend beyond the areal extent of the storage container and include an underburden down to 1.5 - 2 times the depth of the storage compartment.
- Earth models for CO_2 storage focus on container and the entire overburden. These models are laterally extensive, and are defined to known flow/no-flow boundaries, such as faults, outcrops, unconformities. Such a model may comprise two or more nested models which characterise the storage complex plus overburden plus underburden on a low resolution regional scale, and the storage container and overburden on a high resolution local scale. A regional model is of particular importance where (flow) boundary conditions for the local model have to be determined.

3.2.2.1 Workflow

Here a number of general steps are defined.

- *Mapping the overall structure and layering of the study area.* This done is through (loading of) seismic interpretation of a number of key horizons.
- *Refinement of the layering in the storage compartment.* This is based on geological (sedimentological) correlation of wireline logs.
- *Mapping of faults from seismic data and building a fault model*. This will commonly involve simplification or generalisation of fault planes.
- *Gridding the 3D space* to allow population of the volume with geological, chemical and physical properties.
- Assigning sedimentological (facies, grain size) and petrographical information (rock components, porosity, cements) to wells in the storage container, caprock and overburden. Extending this information in the uncored parts of the model.
- *Population of the model space with physical properties*. This will be based on plug measurements (poro-perm data), wireline logs (neutron-density, sonic, density), reservoir engineering data (pressures)
- Exporting (parts of) the model for follow-up modelling steps.

We now detail these steps.

3.2.2.1.1 Structure mapping

The input comes from interpreted seismic surfaces, and fault planes and from wells:

- Effective mapping of the storage structure requires high-quality 3D-seismic. For regional mapping 2D-seimic may be adequate. In case of storage in traps or structural closures the mapping should be extended well below the primary storage container because water containing dissolved CO_2 may migrate downward.

- Seismic-scale faults must be mapped accurately in the entire storage complex. This is of paramount importance for the identification of migration routes, leakage pathways and the determination of the connectivity of the compartments in the storage complex.
- Robust evaluation of the overburden and identification of possible leakage pathways is a key part for the later risk assessment. Consequently, large effort should go into mapping overburden and fault systems. Any signs of hydrocarbon presence or migration through the overburden must be captured as a token of long-term fluid migration.

3.2.2.1.2 Well correlation

Wireline logs from wells in the storage compartment should be correlated to refine layering of the units.

- For accurate mapping of thickness variations of the storage container correlations should be based on the various logs. In addition these logs should be used for the determination of layering and compartimentalisation in the container, i.e. to define layers with different flow properties. With insufficient well-control stratigraphy and velocity control from nearby wells, model updating is essential upon injection or appraisal drilling.
- In depleted hydrocarbon reservoirs the storage capacity, injectivity and containment are commonly well-known. In the case of aquifer storage frequent updating after appraisal drilling, and possible later injection drilling is important.
- Sub-seismic faults may be inferred when well correlation shows that stratigraphic sections are missing or doubled (Normal and reverse faults, respectively).

3.2.2.1.3 Gridding the 3D model

After structure, layering and faults have been mapped a 3D is to be defined for the purpose of property modelling. Each cell is endowed with a specific value of the various geological, physical and chemical parameters, as it is the smallest unit for the subsequent computations. The number of grid cells has a big influence on computation time. Hence the grid cells should be chosen such that required detail can be captured, while computation times are limited. This can be achieved by

- Choosing a small grid-cell (areal) size (e.g. 50m x 50 m) for the storage container area while choosing a substantially larger size (say, up to 1 km x 1 km) for the surrounding area.
- Choosing a small value for the gridcell height within the container (e.g. 5-10 m) to honour heterogeneity, and to define thick layers in underburden and overburden. Here thickness could be based on layer thickness, depending on lithologic heterogeneity (e.g. 100m). More detail would be advised for the caprock.
- Obviously, a priori knowledge of the time requirements of computational schemes used in the later dynamic simulations is helpful in order to determine if and where to “economize” in the gridding.

3.2.2.1.4 Sedimentology, petrophysics, porosity/permeability

These data are important for the characterisation of heterogeneities within the storage container, caprock and seal. Seal properties require full attention. But it is also important to identify sealing properties in the overburden (layers) so as to identify potential leakage pathways.

- A sedimentological model is built, based on integration of cored sections, and wireline log data. Well correlation adds to an understanding of the regional distribution. Statistical mapping tools (e.g. kriging) allow the model to be populated with lithological data. The detail is related to the gridding.
- Where cored sections are available results from petrographical studies give information on chemical rock composition, cement chemistry and crystal shape and size. These data too have to be extrapolated in 3D. Statistical tools based on the facies model will have to be applied.
- The distribution of cements affects the porosity and the permeability of the storage compartment, but is not usually among the properties with which the model is populated. This is done indirectly by attributing poro/perm values to the facies model. For areas, strongly affected by diagenesis the results of the sedimentary-petrographical studies should be incorporated when assigning reservoir properties to the facies model.
- Diagenesis and compaction are highly dependent on burial depth (and history?). Hence, when large, dipping aquifers are modelled this depth dependency should be taken into account. Compaction is especially important in quartz-poor and fine-grained lithologies, and is dependent on depth. However, quartz cementation may have formed a solid granular framework in which case reservoir properties are less depth-dependent.
- Clay cements like illite, kaolinite show a strong depth dependence. They do not significantly affect porosity, but may well cause a drastic permeability reduction, when precipitated in pore necks. This may require corrections, dependent on the way permeability has been derived.
- When petrographical data are not available conservative porosity-permeability can be assumed. Updating here is essential whenever rock samples become available during exploration drilling.

3.2.2.1.5 Updating / exporting the earth model

The earth model should be *updated regularly*. An initial model (or a number of scenarios) are built during a reconnaissance phase, when limited data (even only regional) are available. Such a model is based on many assumptions. During exploration / appraisal drilling more hard information becomes available. Model or scenario updating is then of paramount importance.

The static earth model is the basis for dynamic reservoir studies (geomechanics / reservoir engineering / geochemical modelling). This imposes requirements on the static model. This also requires upscaling.

- Specialist studies may require additional input (e.g. rock stiffness and strength in geomechanical studies). Such data can be collected separately, be loaded to the earth model when needed, and then exported to specialist software tools. There remain still some “nasty” issues.
- Unfortunately, follow-up modelling is often carried out in software incompatible with the output of geological modelling packages. For example, in geomechanical studies triangular grids are often used, as these are more compatible with the mathematics used in the simulations. Data must then often be imported manually.

- The amount of detail is often too much to handle in dynamic simulations (e.g. flow characteristics determined by reservoir engineering). Upscaling must take place, that is clusters of cells must be merged into larger-scale cells. Modelling packages feature tools for realistic property-averaging. However, here is still room for discussion.

After the 3D static earth model has been constructed and made fit for exporting flow-up modelling can be done, geomechanics and geochemistry come into focus.

3.2.2.1.6 Geomechanics

It is important to assess the sealing properties of faults, as this may lead to compartmentalisation (of the storage compartment) and/ or leakage through the seal. Compartmentalisation is a key property within the earth model. It leads to rapid pressure increase during CO_2 injection, and may indicate the need of many wells for a successful storage operation. Three methods can be used to assess the sealing capacity: *Finite element modelling, Mohr circle analysis, and estimation of clay-smeer potential.* The following aspects are particularly important:

- Accurate mapping of fault networks, especially small localized areas of intense faulting. This will require high-quality 3D seismics. Identification of fracture networks requires cored sections and borehole image logs. Fracture networks are often associated with faults. Hence, studying the relation between faults and fractures may help to predict fracture networks and their orientation in undrilled areas.
- For use in geomechanical studies the earth model must be more extensive than in hydrocarbon reservoir studies. It should include reservoir layers, caprock, overburden, underburden, sideburdens, faults with estimated inclination and aerial extent. For accurate modelling the lateral extensions may require extension up to tens of kilometres beyond the edges of the storage compartment. The underburden should be included to typically twice the depth of this compartment.
- All differentiated layers should be characterised in terms of material properties (elasticity modulus etc.). These can be derived from laboratory tests and well logs. If no site-specific data are available these values can initially be based upon general conservative values or a range of possible values, based on analogue studies. As before, updating is required as soon as information by explorational / appraisal drilling is available.

3.2.2.1.7 Geochemistry

Geochemical analysis of lithologies and pore fluids in the storage container, caprock and overburden is needed to assess the likelihood of CO_2 precipitation after injection. It is also important for assessment of CO_2 controlled mineral dissolution and the creation of leakage pathways.

- If the mineral compositions of storage compartment, caprock or overburden do contain a large proportion of CO_2 reactive minerals 2D/3D reactive transport modelling may be needed. Potential dissolution of grains / intergranular networks, or the precipitation of authigenic minerals may affect porosity, and especially permeability. Since both lithological composition and diagenetic character may show lateral variation on a kilometre-scale the assignment of these properties should be studied at the appropriate resolution. Input from cored sections is essential.

- The reactivity of CO_2 depends on porewater chemistry. The earth model should be populated with porewater properties based on well measurements. Since lateral variations are not here expected on scales of a few kilometres this can be done with a rather low lateral resolution. However, in the vicinity of salt domes or large faults water chemistry may change. A smaller modelling scale may then be appropriate.
- The nature of fracture or fault-filling minerals must be assessed, since CO_2 induced dissolution may reduce the sealing capacity of faults that cut the reservoir or overburden. Likewise, the carbonate content of sealing formations should be studied and incorporated in the modelling, in particular if these formations are fractured or faulted.

3.2.3 Characterisation of the storage dynamic behaviour

A suitable modelling and simulation suite needs to be able to predict all important aspects regarding:

- Determining injectivity, storage capacity and technical feasibility under constraints of reaching threshold parameters of maximum allowable reservoir pressure, arrival at spill point or other limitations.
- Evaluating containment on the short term, i.e. during operations and until the transfer of responsibility to the competent authorities.
- Evaluating containment in the long-term, including fate and transport of CO_2 in the storage compartment. Step 2 could also be used for long-term simulations involving interactions with the aqueous phase. In case processes like long-term dissolution, fate and transport in the aqueous phase and mineralization are considered to be important, dedicated specialized models should be used.
- Providing input for the risk assessment, e.g. seal and fault integrity.
- The increase of pore pressures as function of time and location.
- Displacement of formation fluids such as brine in an aquifer, of natural gas in a depleted gas field, or of crude oil in oil reservoirs.

Some general considerations are important ab initio:

- Depending on the storage compartment and its specific complications a choice can be made between tools ranging from simple analytical tank models (which is unlikely though) to fully compositional reservoir simulators like Eclipse, STOMP, TOUGH II etc.
- In some cases thermal simulation is also required.
- Coupled modelling is required for describing (strongly) mutually dependent processes which control the behaviour of the injection stream in the reservoir.
- Whenever substantial assumptions are required, conservative values should be used. In case important input parameters or boundary conditions are uncertain, multiple simulations may be required.

3.2.3.1 Development of assumptions

Characterisation of dynamic behaviour and the following risk assessment depend on assumptions. Feasibility studies of the nature described here are fraught with uncertainties, and making assumptions should not be done too lightly: *In general, if assumptions have an impact on risk, it is important to use those assumptions that actually favour the occurrence of undesirable events and processes*.

- When more information becomes available and is included in the modelling process the predictions on safety should become more reliable. This often occurs with predictions concerning the mechanical integrity of the seal, which tend to improve after the actual minimum in-situ stress of the formation has been determined, e.g. after an extended leak-off test.
- In connection with the above a loop structure for the workflow becomes inevitable. Following the loop is necessary whenever new information alters one or more assumptions in a radical way. Expert judgement is of the highest importance in order to keep the amount of work manageable.

3.2.4 Sensitivity characterisation

Sensitivity studies involve modelling / simulating a scenario several times changing certain parameters within a natural range. The spread within the group of outcomes can predict whether or not a parameter or related process is important for the risk assessment of a proposed CO_2 storage site. This kind of study is clearly mandatory if parameters or processes are uncertain, or little-known. In cases where uncertain parameters or processes are dominant two lines of inquiry can be pursued:

- Deterministic modelling / simulating by applying the most unfavourable assumptions as described before.
- Probabilistic modelling of risks. It is possible to combine all important processes into a complete set of dimensionless parameters, drawing upon Buckingham's PI-theorem. "Completeness" is not meant to be an absolutum; it refers to the description and parameterisation one has chosen. Buckingham's theorem informs us how many independent sets of dimensionless parameters can be defined. This is important, as it can be used to determine the number of models / simulations that has to be made to arrive at a comprehensive picture.

3.2.5 Risk assessment

3.2.5.1 Risk assessment basis

In order to perform a successful risk assessment several aspects have to be defined.

- Purpose, e.g. assessment of hazards or impacts (on human safety, groundwater, marine life, vegetation, etc.)
- Principle of the CO_2 containment, e.g. structural, residual gas, dissolution, mineralogical trapping, etc.

- Geographical and geological setting of the storage complex, with a view on possible failure mechanisms.
- The assessment basis has to be defined very early in the process of site characterisation and assessment. It may need re-evaluation after each major step in the process. The reason is that new information may have an impact on (details of) the workflow.

3.2.5.2 Risk identification and qualitative evaluation.

This is crucial in risk assessment. Again, risk identification and qualitative evaluation should be done *very early* in the process, preferably even before the data collection has taken place. It may even be the focus of the process. The main risk categories are:

- CO_2 leakage via seal, wells and faults, or internally via the spill point. This may have impact on humans, animals, fresh groundwater quality.
- Brine displacement. This may have impact on quality degradation of fresh groundwater.
- Ground movement, either seismic or a-seismic. This may lead to infrastructural damage and damage to buildings.

The following sources should be used, whenever available:

- Existing databases with risk factors (e.g. so-called FEP databases containing Features, Events and Processes)
- Expert elicitation via workshop or via the worldwide web.
- Supporting screening and ranking tools.

The selection of experts should be such that all involved disciplines are well-covered. Expert judgement is used in identifying which risks and technical issues are relevant, and which are of lesser importance. The relevant risks and issues are then investigated in more detail.

3.2.5.3 Developing scenarios.

The identified and screened risks should be clustered in one or more scenarios. They describe possible ways of CO_2 leakage to the biosphere, displaced brines or ground movement. The most critical scenarios should be identified for further, quantitative evaluation. It is essential that HSE experts are involved right from the start, when risk identification takes place. [technical addendum: for answering some quantitative questions, useful for policy makers, a description of the system in terms of “states” might be more appropriate, leading to these answers by means of Markov Chain analysis of the system so constructed (Nepveu et al., 2009)].

Table 3: Overview of steps in scenario development

Type of scenario	Use
Reference scenario	Describes status of full containment of CO_2 in the target reservoir
Deviation scenario	Describes possible failure mode of contained CO_2 : • Leakage along well • Leakage along fault • Leakage across seal • Lateral flow/spilling • Brine displacement • Induced seismicity • Uplift or subsidence

3.2.5.4 Hazard characterisation

Fault integrity can be evaluated by:

- Finite Element analysis,
- the analysis of fault stability by investigating its stress development during and after injection and;
- Shale Gouge Ratio.

The most comprehensive method is the first one. The analysis involves the stress field, the geology of the seal and its surroundings. It is common practice to select a 2D slice with the highest likelihood of fault failure.

Seal integrity can be compromised when:

- Chemical reactivity of the seals leads to increased porosity and permeability.
- Induced fracturing leads to short-circuiting of the seal
- Increased pore pressure (due to injection) leads to differential uplift of various sections of the seal.
- Spontaneous fracturing may occur due to increasing Bottom Hole pressures during injection. This can be investigated with fracture generation software.
- The lower interfacial tension of CO_2 with respect to CH_4 leads to exceeding the seal entry pressure and subsequent leakage.

The entry pressure of the seal can be measured, or estimated from the initial pressures of a gas reservoir or estimated based on data from comparable seals. In many cases the actual entry pressure of the seals far exceeds the capillary pressures at the top of the gas reservoir under initial conditions.

Geochemical evolution is an issue, as the injection of CO_2 into a storage compartment leads to initial acidification of the compartment through interaction and dissolution of carbon dioxide with the ambient water or brine. This may trigger mineralogical reactions.

The steps in a geochemical analysis are:

- Modelling of short-term reactions of the water / rock system. This modelling is constrained by laboratory experiments (types of reactions, kinetic parameters)
- Long-term predictive modelling requiring expertise to select relevant reactions, chemical data and the appropriate modelling concept.
- Sensitivity analysis for various scenarios.

A full geochemical model is far from trivial as the overall kinetics is a function of pH, temperature, actual presence or absence of certain minerals, injection rate. The large-scale fluid motions are of a diffusion-type and a final equilibrium situation may well take thousands of years to establish.

Ground movement can be assessed by using modelling tools for calculation of subsidence or uplift. [At TNO one uses “AEsubs” developed in-house (Fokker and Orlic, 2006)].

Induced seismicity as a result of CO_2 injection can be expected in areas which have shown seismicity upon hydrocarbon extraction. For areas without such a history the stability of faults can be investigated as indicated above.

Well integrity can be assessed by the following:

- Evaluation of the performance of already existing wells “with a history” (e.g. used for hydrocarbon extraction). The abandoned wells represent a special case, especially when they are not accessible for remediation efforts. If and when the risk of leakage cannot be ruled out this type of wells can become a show-stopper!
- Evaluation of the quality of the well completion before and during injection by well testing and well logging. The safety performance record of existing wells, built up over many decades, often provides the required information to evaluate the expected performance for CO_2 injection.
- Evaluation of integrity of injection, monitoring and other already existing wells on the long-term by assessing the chemical and mechanical degradation of cement plugs and any remaining parts of the casing.

3.2.5.5 Risk assessment post-closure

The intention of the risk assessment is to assess risks in the drilling phase, but also in the much longer post-closure phase of the prospective storage site. In principle the assessment should shed light on both phases.

A *new* situation will emerge when the post-closure phase has arrived: the injection phase has gone by and one may concentrate on long-term risks. The regular 3D-earth model updating and the updating of the dynamical modelling during the site operational phase -intended by the Directive- will have led to a fuller understanding of container, caprock, overburden and underburden and the relevant physico-chemical processes. Now, in the post-closure phase further observation through monitoring and modelling should convincingly show that the containment is permanent (But see Chapter 3, Issue 5). Monitoring is the most important source o direct information in this phase.

Updating models is required if a “significant irregularity” occurs, i.e. some phenomenon that is not expected from previous modelling and potentially with an impact on risk. This, however, is a story that rightfully belongs under the heading "Monitoring and mitigation plans". Elsewhere is dealt with these.

3.2.6 Exposure assessment

In assessing potential CO_2 exposure to man and environment several modelling domains are relevant:

- Migration outside of the storage compartment is modelled with specific software
- Modelling of hypothetical migration and secondary trapping in the overburden can be performed with an exploration model using simplifying assumptions, such as the exclusion of CO_2 dissolution. This gives an actual overestimation of the negative results for humans and environment.
- In situations where timescales of order $10^{2\text{-}3}$ concerning the migration in the overburden are deemed relevant (upon the foregoing step, for instance) a full model needs to be used.
- Migration to and accumulation of CO_2 in the shallow subsurface will lead to dissolution of carbon dioxide and to pH-lowering. This may lead to mobilization of heavy metals. This can be simulated with reactive transport models. This concerns a further detailing of the computation sequence under a.
- Once in the open atmosphere dispersion mechanisms due to turbulence are usually very strong and any CO_2 plume is readily dispersed. The onset of turbulence can be triggered by buoyancy or other mechanisms. This leads us to expect that a sudden, violent emission of CO_2 (blowout) would lead to air movement, increased turbulence and atmospheric dispersion. A small rate of emission will usually readily dispersed as well. Leakage of CO_2 leads to significant exposure, however, when it is concentrated in confined spaces without efficient ventilation. Basements form the prime example.
- Gas vents in the water column tend to form bubbles, which are visible upon arrival at the sea surface where dispersion in the atmosphere takes place. During ascending the bubbles may dissolve in the ambient water.

3.2.7 Effect assessment

Potential effects that need to be evaluated are:

- Human health and safety
- Ground water quality
- Surface water quality
- Biodiversity
- Quality of marine environment
- Damage to the built environment and infrastructure
- Climate change.

Performance criteria need to be developed on a site-specific basis, which determine the maximum allowable CO_2 concentration, pH change, etc. It seems sensible that CO_2 storage activities are subject to already existing norms of individual and group risks in other industrial activities, for CO_2 concentrations in closed spaces, ground water quality norms, and other environmental norms.

3.2.8 Remarks on Aquifers.

Empty hydrocarbon fields will have been studied actively and with great care by the producing companies, but the same is not true for aquifers. Hydrocarbon companies might have "stumbled on them" in the course of the hydrocarbon exploration process, unintentionally. The data so obtained are a genuine source of knowledge, and in all likelihood they form the bulk of hard data one possesses.

Aquifers are identified certainly down to the Carboniferous (see TNO report 034-UT-2010-00474/A by van Wees et al.). For an identified aquifer to survive the pre-selection phase one would like to identify a trap mechanism. Concrete ideas may be underpinned by existing well information, seismics, and by regional information. In the selection phase data collection is a particularly heavy burden in the case of aquifers, since very little is generally available as regards "hard" information. Seismic studies are of paramount importance, as they may reveal information that will guide later well planning for explorative (and later injection) purposes. For many aquifers seismic results may already be available, but if these date back to the 1970's (roughly) and before, the data quality or the data processing will likely not be up to present-day standards. Seismic lines should then be re-shot or at least re-processed.

Aquifer seal integrity is a particularly sensitive subject.

- First of all, the starting pressures for any possible CO_2 injections into the aquifer are the original ones and not the significantly reduced pressures in "empty" hydrocarbon reservoirs. This makes integrity issues even more urgent than in emptied hydrocarbon reservoirs; aquifer seals seem to be put to an even harsher test on injection.
- Secondly, the information that a seal above a gas reservoir proved its integrity by the very fact that the reservoir has existed for many millions of years is not available for aquifers. Hence it is important to take seal samples and test them in the lab on CO_2 entry pressures and apply yield tests to these samples. The question how many wells must be drilled to acquire trustworthy results on overall seal integrity will largely depend on geological background knowledge as regards estimated correlation lengths. This will also hold when establishing porosities and permeability.

All together, then, the amount of data collection and modelling will be appreciable as one starts from a far poorer knowledge position. This raises the question whether there are any particular consequences for subsequent risk assessment. For the work flow one should not expect any fundamental changes. On the other hand it may well be necessary to work with several viable subsurface models. So it is safe to assume that the modelling part of the assessment will likely deal with uncertainties on a more basic, conceptual level (e.g. What exactly is the trap mechanism? What physico-chemical processes offer themselves in this respect, consistent with the data?). As a sweeping statement: in hydrocarbon fields the man-made well is an obviously weak spot, and in aquifers the seal and possibly undiscovered faults (?) are added as "negative bonuses".

3.3 Synthesis

Site characterisation and assessment are crucial activities underpinning the qualification of a site for safe storage of CO_2. The steps are:

1. Compile and evaluate available data. All accessible site data relevant for the prospective CO_2 containment and any irregularity both on the short and the long-term are to be gathered.

2. Define the assessment basis. Here one defines the containment concept, the targets of the risk assessment, and the geographical and geological context. This step is crucial, because it induces focus into the subsequent activities.

3. Risk identification and evaluation. The potential risks are identified with step 2 as the natural starting point.

4. Collect and process site data. The site characterisation programme is to be defined on the basis of the outcomes of steps 1-3. By the execution of these steps gaps in the data are more easily identified. The work is focussed on the risk assessment. All modelling and simulation is in fact geared to its successful and reliable execution.

5. Building the 3D static earth model. Based upon the previous steps the model is itself the basic input to subsequent modelling steps.

6. CO_2 dynamic modelling. Here one simulates the dynamic behaviour in all physico-chemical aspects as far as dictated by steps 2 and 3. Focus is on migration and potential leakage.

7. Quantitative risk assessment. Here quantitative simulation of the risks identified in step 3 is the ultimate goal. Exposure assessment and effect assessment have to be scrutinized in quantitative terms.

Two points are worth mentioning in particular:

- Re-iterations may occur as the execution of each of the steps 4 - 7 may cast doubts on the validity / completeness of a previous execution of steps 2 and 3. It is also possible that later findings suggest that these earlier steps have to be re-done, and focussed / augmented in their scope.
- Annex I to the Directive mentions (Text right below *Step 2*): "a three-dimensional static geological model, or a set of such models…". Indeed, there are situations where available data leave room for significantly different structural or "populative" interpretations. In such a case the geological "skeleton" or its determining properties are among the uncertainties. In such a case it may then be necessary to develop *several* models. Until later data acquisition eventually gives a verdict -and allows discarding some structural possibilities- one has to scrutinize initially a *set* of models.

Issue 1: What is "Capacity"?

The EC Directive mentions the concept of "capacity" as if that concept were crystal clear by itself. However, capacity could be understood as the amount of CO_2 that fits in the total volume of all voids in a formation. But capacity might also mean the total amount of CO_2 that can be stored *in actual fact*. The first definition is basically geometrical in nature, the second requires a physical and engineering understanding of the storage process. Practically relevant here is the pressure allowed in the storage reservoir. Determination according to the second definition requires the application of reservoir engineering techniques. **In the pre-selection phase, when one should use only data already available, one can only use the geometric meaning. Modelling in his first phase is not feasible**.

Issue 2: What is "significant"?

In article 4 sub4. there is the expression "no significant risk of leakage." In the same article there is the expression "no significant environmental or health risk". We already discussed the two meanings of the word "risk." Here we concentrate on a different issue: what exactly is "significant"?

In the first of the above expressions we deal with a probability of occurrence. "Significant" would have to be defined in terms of a "critical" probability. In the second expression one would have to deal with "critical" risk levels such as the expected number of fatal accidents per year. **It is sensible to match such numbers to those employed for licensing purposes for chemical plants**.

However, there is a problem as regards the probability of occurrence of leakage. In the hydrocarbon industry one knows the event of a "blow out". Upon production gas squirts from a well in an uncontrolled manner. Some statistics as to its occurrence ought to be available, although this is not exactly material that is widely advertised by the business. In the injection phase of CO_2 storage such an operational mishap might occur.

For *leakage*, a long-term process, there is no equivalent in the hydrocarbon business. That is, one certainly does not have comparative statistical material available. How can we proceed?

The characterisation and assessment practice as described in this chapter will lead to a substantial number of simulations. In those cases where leakage is shown to occur further study will generally reveal its physico-chemical origin.

It looks like a sound advice to declare a storage site unsafe if:

- no clear-cut reason can be found for simulations producing leakage, or
- a clear-cut reason can be found, with essential parameters being highly uncertain.

If none of the simulations produces leakage the site might be deemed safe.

Note that in formulating this recipe we have avoided the definition of probabilities. Especially if these probabilities are small (1 in 100,000 for instance) it would require at least some 100.000 simulations to substantiate this probability. This amount of work is likely to be prohibitive.

Issue 3: Pre-selection and selection.

The EU Directive does not make a formal distinction between a pre-selection (screening) phase and a selection phase. If we like to do exploration during any of these phases we would have to apply for an exploration permit, according to article 5 sub 1. This will mean in practice that a *pre-*selection will be done on *available* data, as detailed in Table 2. For depleted oil- and gas fields generally a wealth of data is available. For instance, the Dutch Mining Law requires operators of such fields to hand over certain data to the competent authority. This automatically means that not-so-well-studied sites have more difficulty to pass the hurdle of pre-selection.

Indeed, if a pre-selection is to be made **from a set** of possible candidates the depleted gas fields will prima facie look most attractive. Oil fields would likely come second and saline aquifers next. Obviously this ordering should only be handled as a "rule of thumb".

Issue 4: Selecting saline aquifers?

This issue is a concrete detailing of the previous one, leading to a rather substantial bias. One might -and would certainly like to- consider saline aquifers for CO_2 storage. However, as we discussed in 3.2.8, since they do not contain hydrocarbons they will hardly have been studied – certainly not by commercial parties. The available data will generally be relatively scarce. This will likely result in very few aquifers to come out the pre-selection with high expectations for a successful further scrutiny. Indeed, when confronted with scarce data, one might not like to embark on a "risky" selection study in view of the financial consequences.

Issue 5: How permanent is "permanent"?

The Storage Directive is about permanent storage of CO_2 in a geological storage container The word "permanent" seems to impose a standard of rigor on characterisation and assessment that is not realistic in any scientific field. Indeed, if the word "permanent" is used in its literal meaning no one site could ever be selected. Since this is clearly not the intention of the Directive sensible choices must be made here.

In order to operationalize this word one may revert to probabilistic statements. This, however, leads to the same sort of problems encountered in issue 3. Alternatively, one may pose a time horizon to qualify the word "permanent". Two considerations can be helpful:

1. In general, increasingly restrictive demands increase the scientific burden of proof and hence the required activity, hence cost.
2. The costs should be balanced to the risk and the fact that storage avoids CO_2 emissions to the atmosphere. In other words, it is necessary to limit risks, but one should not lose sight of the positive achievements by storing CO_2

A recommendation that could be made operational in research is the definition of a time horizon before which no leakage should occur.

Issue 6: Independent experts.

In the risk identification and evaluation phase one needs domain experts who possess site-specific knowledge. However, it is sensible also to invite experts who have no direct ties to the site or the operator who oversees the activities. Likewise one may invite representatives of NGOs to take part in this activity. This mode of behaviour should enhance public trust in the findings and the chosen direction of later developments.

Issue 7: Implementation.

Here we note a few points.

- In the Annex I to the Storage Directive three basic steps are mentioned that have to be taken in the characterisation and assessment of the potential storage site. In each of the steps details are mentioned as to the quantities to be determined, and activities to be undertaken. The question then is which research activities can and should be enforced by Law and how this should be done. A law is not a handbook on research after all. The professionals responsible for the technical work know best what to do. Some details may be laid down, however. In the Dutch legislative system, for instance, it would be possible to address specific technical points as "*Algemene Maatregel van Bestuur*". It seems that some legal body consisting of technical professionals should oversee and judge the characterisation and assessment activities as clarified in such an AMvB.

- There is still another angle to be considered. When confronted with excessive mandatory research activities with an uncertain final outcome site operators might decide not to embark on them. This might quench the CCS activities. The Law is obviously not meant to have this effect. But still, if site operators are not willing to embark on the activities, who else would? Obviously, the implementations in different EU Member States should not diverge too much, as the economic "playing field" with respect to, for instance, emission rights should be level. Maybe the EU itself may play a supervising or orchestrating role here.

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4 Composition of the CO_2 stream

Abstract

Regarding the composition of the CO_2 stream the CCS-Directive states: "A CO_2 stream shall consist overwhelmingly of carbon dioxide.". In addition the CO_2 stream should not pose a risk on human health, the environment or on the integrity of any element in the CCS chain.

When health considerations and transport restrictions are compared with the likely compositions of the product streams of the various capture techniques currently considered the conclusion is that the requirements from the CCS-Directive can be satisfied....

One new aspect that deserves more attention however, is the aspect of varying specifications during load variations and start-up procedures. This issue may result in an additional requirement in the permit application with the licensing authority or form an element in the contract with the transport network operator. Furthermore, our analyses indicate that at different stages in the capture process purification techniques will have to be applied. The main motivation for this additional purification will be the prevention of corrosion and two-phase flow formation.

It can be concluded that the requirements as formulated in the CCS Directive provide good opportunity to design and operate a well balanced capture process. No further specification is needed because the market holds sufficient incentives to solve this issue.

4.1 Introduction

The requirements for the CO_2 stream composition, or more accurate, the current lack of a comprehensive set of requirements for the CO_2 stream composition already was the subject of many recent discussions (See for instance Aspelund and Jordal 2007, Bachu 2008, Bachu and Bennion 2009, Pipitone and Bolland 2009, Thitakamol, Veawab and Aroonwilas 2007, De Visser et al. 2007, De Visser et al. 2008, Zakkour and Haines 2007). In spite of these discussions there is little clarity yet. This chapter makes an effort to provide an overview of the subject and concrete guidance. After an initial discussion of the detailed formulation of the requirements in the CCS-Directive the possible compositions from the various capture technologies are compared with estimates for the allowable concentrations from health, safety & environmental considerations for the transport network and storage site. With the results from this comparison the requirements as formulated in the Directive are assessed.

4.2 Requirements from the CCS Directive

Starting point for the discussion is Article 12 from the CCS-Directive which states the famous line: "A CO_2 stream shall consist overwhelmingly of carbon dioxide.". The same article gives some further specification in the following sentences; " To this end, no waste or other matter may be added for the purpose of disposing of that waste or other matter. However, a CO_2 stream may contain incidental associated substances from the source, capture or injection process and trace substances added to assist in monitoring and verifying CO_2 migration. Concentrations of all incidental and added substances shall be below levels that:

- adversely affect the integrity of the storage site or the relevant transport infrastructure;
- pose a significant risk to the environment or human health; or

- breach the requirements of applicable Community legislation."

In the second paragraph of the same article the Commission announces its intention to provide guidelines "to help to identify the conditions applicable on a case by case basis for respecting the" three criteria given above. In the third paragraph the Directive becomes more specific where it indicates that for acceptance of a CO_2 stream it is required to carry out: "an analysis of the composition, including corrosive substances, of the streams". Furthermore a risk assessment has to demonstrate that "the contamination levels are in line with the conditions referred to in paragraph 1;"

The objectives of this section of the CCS Directive are clear, but the absence of strict specifications leaves room for divergent individual interpretations and possible differences of opinion about for example the specific numbers for the maximum concentration of oxygen and water content in the CO_2 stream. Clearly the CCS Directive does not leave an opening to add any hazardous chemical waste to the CO_2 stream and dispose these in the storage site, even if all risks could be excluded. This exclusion is well-imaginable and provides the clarity that is being sought after. A further positive consequence of the current requirements is that the formulation provides room to make a well-balanced decision about the removal of a component present in the stream. If it can be demonstrated that the available concentrations do not impose any risks on any part in the system, they do not necessarily have to be removed. For some components separation could be impractically expensive, especially to remove the last ppm's from the stream.

For clarity and uniform definitions the following CCS chain is sketched. Starting point is the source of the CO_2, which in most cases will be a power production unit, but different industrial sources are well imaginable. The feedstock for the combustion or conversion process taking place in the CO_2 source can be coal, oil, gas, biomass or any mixture of these fuels. Another possibility is that the CO_2 is separated as by-product in the natural gas or mineral oil production. The CO_2 containing stream from the source will in general pass through some capture unit since its concentration is too low to be considered as overwhelmingly CO_2. The CO_2 enriched stream leaving the capture unit will be compressed to high pressures because it is highly likely the CO_2 stream will most likely be transported in dense state. Before, or as part of, the compression stages the CO_2 stream can be further purified. After compression the CO_2 stream is transferred to the transport infrastructure and the composition of this transferred stream is the subject of this discussion. In the transport infrastructure the CO_2 stream is possibly mixed with CO_2 streams from other sources and transported to the storage site injection point. Many different combinations of source types, capture processes, compression units, transport modalities and storage locations are possible but this general picture will stand.

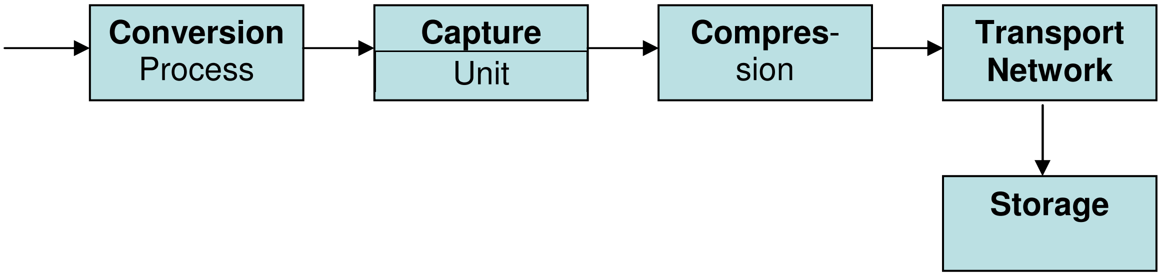

Figure 3: Outline of the CCS chain. The feedstock enters the conversion process, the CO_2 from this source is concentrated in the capture unit and next

compressed and transported to the storage site. At different stages gas-purification may be applied

4.3 Indirect requirements resulting from the EU Directive

The CCS-Directive does not contain strict limitations for component concentrations but requires that the composition does not pose a threat to the integrity of the transport infrastructure and/or storage site. It is possible to translate this formulation into a composition requirement. For different situations and streams this might again result in divergent interpretations and care should be taken to avoid the situation where two streams are mixed that individually satisfy the Directive but no longer once mixed. Examples might be found in the corrosion demands which can be dependent on combined concentrations (moisture, oxygen and acidic compounds). The precautionary principle might require low concentration for each of these components.

The second indirect concentration requirement is the required absence of risks to the environment or human health. Since each conceivable component can be dangerous when the concentration reaches high enough values, this requirement also can result in divergent interpretations. The CO_2 stream in the entire chain from capture to storage involves a certain risk, even during normal operations. The indirect requirement has been interpreted such that situations following less probable incidents should be considered. Occupational health issues are assumed to be considered in the permit application course for the different installations.

An important starting point is to explore what components are likely to be present in the CO_2-streams from different processes, and if present what concentrations can be expected. Next step then would be to explore up to what concentrations these components can be dealt with in the successive steps in the CCS chain for technical reasons. If the limiting concentrations are below the expected concentrations, the options for removal have to be investigated.

One aspect that did not receive too much attention in the various discussions is the aspect of load variations. The CCS stream is the product from a cascade of installations that once in stationary operation on design load will certainly satisfy the specifications. However, with large-scale applications it is unavoidable that frequent load variations will occur: multiple start/stop operations and switches to different partial load levels. The whole train of conversion unit, gas cleaning, capture and compression has to adapt to these variations. The different components may all require their own characteristics such as inertia and start-up procedures. It cannot be avoided that during these load variations and transitions the specifications will vary over a given range. Yet it is unclear whether the required specifications should be obeyed at any given single time, or if the specifications can be averaged over a certain period or volume (weighted average). The buffering effect of the transport system (whether by truck, ship and /or pipeline) will limit the variations to a certain extent, but these inevitable variations will impose high demands on the monitoring system. It is recommended that additional requirements on the allowable variations over time will be formulated for this issue. These requirements may result in an addition to the permit application with the licensing authority or form an element in the contract with the transport network operator. The practical experiences that will be gained in the various large-scale demo project will provide guidance for the exact formulation of these additional requirements.

4.4 Concentrations applying capture technologies

In most CO_2 producing processes the 'product' CO_2 is released in relatively low concentrations. For example the CO_2 content of the flue gas form a coal burner is around 13-15% on a volume basis (v/v). Whereas the flue gas from methane gas combustion only contains 6-8%. The remainder of the stream consist mainly of nitrogen from the combustion air. Since it would be extremely impractical to store the entire flue gas stream, the CO_2 in the flue gas stream is separated from the other substances in a capture process. The obvious way to do this is to add a capture unit behind a 'standard' production plant. Serious research effort is put in the development of such processes. The current standard is an absorption process with amine solutions. The flue gas stream is led through an absorption column where the CO_2 is selectively removed and in a successive steam-driven regeneration column the CO_2 is released at high concentrations. Although absorption columns are routine unit operations within the chemical industry, the massive volume of the low-pressure flue gas streams require large volume installations and more importantly, an impressive energy consumption that seriously reduces the energy efficiency of the power generation unit.

This high 'energy penalty' is one of the motivations for seeking alternatives. One track involves the search for alternative post-combustions techniques for example with membranes, adsorption, cryogenic techniques or the use of different sorption fluids. Except for the chilled ammonia process the alternative post combustion techniques are still in an early stage of development and not yet past pilot scale application.

Completely different approaches from post-combustion techniques are the pre-combustion capture concept and the oxy fuel processes. In a pre-combustion process the fuel, which can be represented as C_xH_y, is gasified and chemically converted to a mixture of mainly hydrogen and carbon dioxide. The hydrogen is burned after the CO_2 is separated. The H_2/CO_2-separation is easier to perform and this product stream is also considerably smaller in volume than a comparable post combustion process. In an oxy-fuel process the fuel is not burned with air but with pure oxygen instead. As a result the flue gas consists of mainly water vapour and carbon dioxide which can be easily separated to produce an almost pure CO_2-stream. The oxygen is produced in an air-separation unit which is an existing technology although the scale of a full-size power plant still constitutes a challenge. In the next section the most advanced or likely capture technology combinations in each category will be discussed in more detail to arrive at representative CO_2 stream compositions for each capture technology, summarized in a table.

The most likely installations to be equipped first with a post combustion capture unit are coal fired power stations since the CO_2 concentrations in the flue gases are relatively high compared to gas fired power stations, as is the CO_2 emission per MWh of power produced. An amine-based absorption process can selectively remove the CO_2 from the flue gas. The flue gas from a coal fired plant contains a wide range of contaminating components (such as SO_2, NO_x and fine particles) and trace elements (such as HCL, HF, Hg and other heavy metals). Since some of these contaminants bind irreversibly with the absorption liquid, thus degenerating the solvent, there is an advanced flue gas cleaning train with electrostatic particle removal, desulphurization and selective catalytic NOx-removal. After regenerating the absorption liquid with steam the CO_2-stream is saturated with water. During the successive multi-stage compression of the CO_2 the bulk of the water is removed and the remainder can be removed in a dehydration process with for example triethylene glycol. The resulting CO_2 stream has a high purity (>99%). The purity should not be confused with the removal rate or yield, the fraction of the carbon from the source that is finally captured. The value of this process parameter will vary around some 90% [IPCC, 2005]. [Post combustion CO_2 capture has the advantage that the technology can be added to an existing power plant. This retrofit option gives a theoretical huge market potential.]

Pre-combustion capture can be included in an integrated gasification combined cycle (IGCC) plant with coal as feed stock by adding a so called CO_2 shift reactor. Before the actual capture takes place fine particles and sulphur containing species are removed from the so called syngas. The relatively clean mixture of hydrogen and carbon dioxide is separated using a selective physical absorbent. The separation process can be designed to provide high purity CO_2, but some hydrogen and hydrogen sulphide (H_2S) will remain. Regeneration of the physical solvent requires less energy and since only the high pressure gasification stream has to be treated the volumes are significantly reduced. During the compression of the CO_2 any remaining water is removed, and again if necessary a triethylene glycol dehydration process is included. (Stam et al. 2007, DOE 2007).

The first separation that takes place in oxy-fuel processes is the production of oxygen from air. The nitrogen is generally separated in a cryogenic distillation unit creating an argon containing oxygen stream. It makes no sense to produce ultra-pure oxygen since it is hard to avoid any air leaking into the combustion process, certainly with frequent load variations. To reduce the combustion temperatures in the oxygen burner a part of the flue gases are recirculated. During the coal combustion several contaminating components (such as SO_2, NO_x and fine particles) are produced. As a result the production of a clean transferable CO_2 stream requires more than the simple separation of water vapour and CO_2, although many of the contaminants will be removed with the water. Given the relatively small volume of the stream and the presence of the oxy-fuel air separation unit the non-condensables in the stream could be removed by distillation. Oxy-fuel is the least matured technology of the three basic capture concepts (Stam et al. 2007, DOE 2007).

Alternative capture processes will be developed in the future but it will remain quite a challenge to produce a contaminant-free CO_2 stream with an energy efficient process. Membrane processes or membrane contactors are thoroughly investigated since they are potentially energy efficient separation units but it is difficult to obtain high purity from the large volume, low pressure flue gas streams.

Table 4 gives an indication of the concentrations for different components found in the product streams of the three main capture processes. When available the values are given for the stream leaving the capture unit, and after passage of an additional cleaning unit, frequently part of the compression train. The values are the compilation of an extensive literature search that was performed in the course of an earlier project. The numbers should be considered as indications since none of these installations was built and operated at full scale and the numbers come from a variety of sources (Aspelund 2007, Stam et al. 2007, DOE 2007). Once cleaned and compressed these composition indications suggest that the product streams are indeed contain "overwhelmingly CO_2" as required by the EC CCS Directive.

Table 4: **Indication of the concentrations for different components found in the product streams of the three main capture processes**

Component (mole %)	Postcombustion Capture (amine absorption)		Precombustion Capture (IGCC & physical abs)		Oxyfuel (coal)	
	process	Cleaned	process	cleaned	process	cleaned
CO_2 purity	98.6	99.5	95	99.9	89.4	99.2
H_20	0.14 - 1.4	<.14	0.14	<0.14	0.14	<0.14
Argon	0.02	-	0.05	-	0.6 – 5.7	0.045
N_2	0.021	-	0.03	-	0.6 - 5	0.3
O_2	0.003	-	< 0.003	?	0.6 - 5	0.3
H_2	-	-	1.7 - 5	0.1	-	-
SO_2	0.001 (10 ppm)	-	-	-	47 ppm - 760 ppm	57 ppm
NO_x	20 ppm	20 ppm	< 20 ppm	< 20 ppm	2000 ppm	20 ppm
H_2S	-	-	1-100 ppm	-	-	-
CH_4			350 ppm	-		
A wide range of trace components can be present at infinitesimal quantities						

4.5 Transport, Storage and HSE requirements

In the previous section it was explored which components, and at what concentrations, can be present in the CO_2 streams from different capture processes. An alternative would be to investigate what concentrations for the anticipated components are acceptable for the transport and storage systems and health, safety & environment (HSE) considerations. An approach from the 'other side' so to say. The first attempt in this direction was produced in the FP6-project Dynamis (De Visser and Hendriks et al, 2007). Their much quoted report was the first to produce a well-considered table with CCS-components and concentrations (see Table 5).

Table 5: **DYNAMIS CO_2 quality recommendations**

Component	Concentration	Limitation
H_20	500 ppm	Technical, below solubility limit of H_20 in CO_2
H_2S	200 ppm	Health & safety considerations
CO	2.000 ppm	Health & safety considerations
O_2	Aquifer < 4 vol%* EOR 100-1000 ppm	Technical, range for EOR because lack of practical experiments on effect underground
CH_4	Aquifer < 4 vol%* EOR < 2 vol%	As proposed in ENCAP project
N_2	< 4 vol%*	As proposed in ENCAP project
Ar	< 4 vol%*	As proposed in ENCAP project
H_2	< 4 vol%*	Further reduction of H_2 is recommended because of its energy content
SOx	100 ppm	Health & safety considerations
NOx	100 ppm	Health & safety considerations
CO_2	> 95.5 %	Balanced with other compound in CO_2

* all non condensable gasses together are limited to 4 vol%

For the components H_2S, CO, SO_2, NO_2 the maximum CO_2 stream contaminant concentration was derived using the Short Term Exposure Limits (STEL). The basic concept in this approach is that at the moment the CO_2-concentrations are reduced to below their STEL-value after an accidental release, all the other components should be below their STEL value too, making CO_2

the most harmful component. In other words: at the moment you are no longer at risk from the released CO2, the other components should also no longer present a health risk. To exclude all possibly unknown effects, an uncertainty factor of 5 was introduced in the calculations.

For the other components considered (H_2O, O_2, CH_4, N_2, H2 en Ar) the concerns were mostly related to the higher pressures required to avoid two-phase flow and free water formation. The latter would contribute to the danger of hydrate formation and corrosion. Furthermore the addition of non-condensables to a CO_2 stream can reduce the density, thus reducing the storage capacity. Non condensables also have a negative impact on the minimum miscibility pressure for CO_2 in EOR applications (making a higher pressure required). The effect of adding a few percent of non-condensables to the CO_2 stream can change the physical properties of the mixture, such as density and critical pressure, by much more than a few percent. The reduction in density for the mixture reduces both transport and storage capacity, which should be avoided. In line with earlier ENCAP recommendations the Dynamis recommendations limit the combined fraction of non-condensable gases to 4%.

Corrosion limitations are a complicated issue, since corrosion can be influenced by a combination of component concentrations. The water content, in combination with the oxygen and corrosion promoting species such as H_2S and SO_2 determines the corrosivity. From existing enhanced oil recovery (or EOR)-experience the limitations for both water and oxygen are rather strict. In the Dynamis report a pledge is made for relaxation of the water requirement to 500 ppm. This concentration limit is below the solubility of H_2O in CO_2 under transport conditions which means that free water formation is prevented and hydrate formation is very unlikely. Since the combination effects on corrosion are still not completely understood, others assume a rather conservative limit of 50 and even 20 ppm. Future research in this area seems necessary

From the Dynamis report the impression is obtained that the transport system sets the upper limits for the composition of a series of components. If corrosion and hydrates formation can be excluded for the transport system, then the mixture is safe for injection as well. The only exception is the oxygen content. When the storage site is an aquifer, then the requirement can be relaxed to 4% (or 40.000 ppm). However when the storage site is an EOR location, then the requirement can be reduced to as low as 100 ppm. As part of the exploration phase the site specific elements will be clarified and these might result in an additional requirement. Special attention should be given to minerals that could influence the injectivity into the storage site; injectivity should be maintained for full utilisation of the reservoir capacity.

4.6 Combination of results

When the two sets of requirements, one derived from the source and the other derived from the transport system and storage site are combined some interesting observations can be made:

- CO_2 content: The different capture processes are well capable to produce a CO_2-stream with a high purity. This high purity is much better than the minimum requirement of 95% as set by DYNAMIS based upon storage considerations and will certainly satisfy the "overwhelmingly"criterion.
- Non-condensables: As a logical result from the high CO_2 purity the non condensable content that is produced is much lower than the maximum requirement of 4% as set by DYNAMIS.

- H_20 content: Even with the 'relaxed' requirement of 500 ppm (or 0.05 %) an advanced dehydration unit will have to be included to process the CO_2 stream that meets this standard.
- Acid components: The concentrations of these components are well below the requirements. The water removal that has to take place during the multi-stage compression of the CO_2 stream has the positive side effect of removing a major part of the small amount of these components that made it through the capture process.
- H_2, H_2S and CO: These components are typical for pre-combustion capture processes, but when a good non-condensable removal unit is included in the process the requirements are easily met.
- The overall conclusion from these combined results is that the current capture processes are well capable of meeting the health demands and transport restrictions.
- At different stages in the process cleaning techniques will have to be applied. The main motivation for this additional purification will be to prevent corrosion and two-phase flow formation. Since these concerns are of direct interest to the operators of the capture, compression and transport facilities, the requirements in the CCS Directive do not necessarily have to be made more specific in this respect. The aspect of varying specifications during load variations and start-up procedures deserves more attention however.

One serious warning to conclude this chapter: It is not recommended to transform the good performance of the current capture processes into a new set of binding requirements. Since it is well imaginable that a new technique or new combination of techniques results in a better performing, highly efficient capture-process that does not satisfy the new set of concentrations requirements on all points. Still, the new process might be in full compliance with the current CCS Directive and should therefore certainly not be excluded. With the new insights from this chapter it can be concluded that the requirements as formulated in the CCS Directive provide good opportunity to design and operate a well-balanced capture process.

4.7 References

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5 Risk of CCS and associated (long-term) liabilities

Abstract

Within the framework of carbon capture and storage the focus is on damage caused by CO_2 in the gaseous phase. The leakage of gaseous CO_2 from the CCS chain may cause physical damage to:

- *The climate system in general. This relates to damage to the global climate system.*
- *The environment and ecosystems. This relates to the direct damage to the flora and fauna due to the exposure to CO_2, and to the damage due to changes in the quality of groundwater and surface water.*
- *Health. This relates to direct damage to the human health due to the exposure to CO_2, and to the damage due to changes in the quality of the groundwater and surface water.*
- *Property. This relates to damage to e.g. buildings.*
- *In general it can be concluded that risk associated to CCS are low or negligible.*

This chapter also describes the legal bases that exist for damage claims for damages caused by CCS, thereby mapping long-term liabilities as they are for projects currently under development. The paragraph examines who might be liable, for which damages and for how long. For each of these liabilities we will examine which possible legal debates exist (for example on causality) and in which forum this legal debate is fought out. This analysis provides information on the suitability of the national liability system in dealing with CCS in the long run and whether or not it provides sufficient legal certainty for possible investors and operators.

The assumption is that uncertainties with regard to the long-term liabilities will discourage investments in CCS. Therefore, some form of management of long-term liabilities is desirable. Both in the national legal system and in other legal systems several mechanisms for dealing with long-term liabilities have been developed. These methods of managing long-term liabilities can be compared as to the direction in which liabilities are channelled, the amount of regulation needed in advance and the timing, costs, forum and content of the legal debates that still might exist. Based on this information, an informed decision can be made on the most desirable way to manage the long-term liabilities, bearing in mind the interests of the public, the investors/operators and the government.

5.1 Introduction

For environmental and human health reasons it is important that CO_2 remains stored when it has been injected in a storage facility and that emissions are kept to a minimum at the capture site and during transport. Consequently, leakages need to be prevented, and if they occur they need to be identified as soon as possible and corrective measures need to be taken by the party in charge. This chapter will deal with the following issues:

- What risks can be identified regarding capture, transport and storage of CO_2?
- Who is liable is case of damage?
- How can safe storage be demonstrated legally so that governments can take on liability?

For this aim we will analyse the whole CCS chain.

5.1.1 Definition of risk

Hazard is commonly defined as 'the potential to cause harm'. Carbon dioxide can be classified as a hazard, as it may cause damage at certain concentrations in the air. The term risk is commonly used as 'the combination of the probability of occurrence of a defined hazard and the magnitude of the consequences of the occurrence"[12]. From this we can see that the hazard of carbon dioxide is in the nature of the substance, while the term risk can only be used in the context of an *activity*. It is therefore not possible to speak about risk of capture, transport and storage of carbon dioxide but only about risk of capture, transport and storage of carbon dioxide (Hendriks et al. 2005).

In short risk is defined as:

*Risk = Probability of occurrence of damage * Magnitude of damage.*

In the next section we will therefore first look into the type and magnitude of physical damages linked to the release of CO_2.

5.1.2 Type and magnitude of physical damages

Within the framework of carbon capture and storage the focus is on damage caused by CO_2 in the gaseous phase. The leakage of gaseous CO_2 from the CCS chain may cause *physical* damage to:

- The *climate system* in general. This relates to damage to the global climate system.
- The *environment and ecosystems*. This relates to the direct damage to the flora and fauna due to the exposure to CO_2, and to the damage due to changes in the quality of groundwater and surface water.
- *Humans*. This relates to direct damage to the human health due to the exposure to CO_2, and to the damage due to changes in the quality of groundwater and surface water.
- *Materials*. This is related to damage to e.g. buildings.

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[12] The EC Directive apparently uses the word "risk" in two different meanings in one and the same article. In article 4 sub4. "no significant risk of leakage" can have no other meaning than "no significant chance / probability that leakage occurs". The word "risk" is used here as signifying a likelihood. But in "no significant environmental or health risk exists" the word "risk" signifies the second possible meaning of this word, namely "probability times effect". It is important to make a sharp distinction between these two uses of the word "risk".

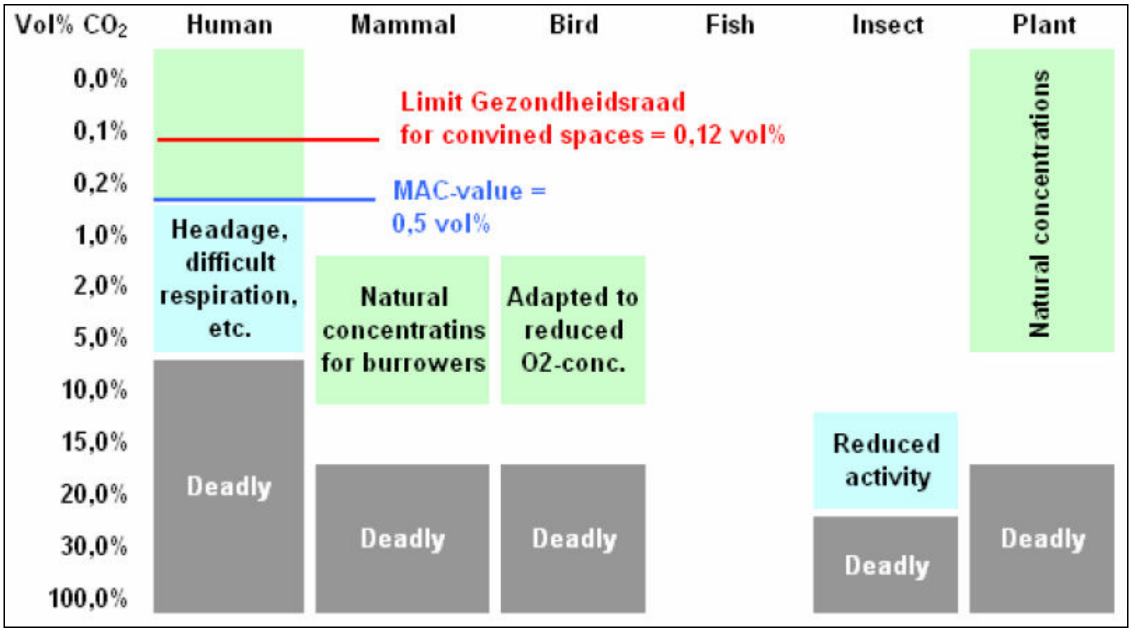

Figure 4: **Indicative dose-effect relations. Source: AMESCO (2007)**

Figure 4 provides an indication of the dose-effect relations for various levels of CO_2 concentrations for different life forms. The figure shows that (AMESCO (2007), EBN (2009)):

- *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%-5% (depending on the time of exposure) and death occurs at concentrations above approximately 10 vol% (see also Table 6). Other organisms are less sensitive to elevated concentrations in the atmosphere.
- *Plants (crops)* 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%.
- *Fish* can tolerate concentration of dissolved CO_2 up to 200 to 250 mg/l.

CO_2 influx in *groundwater* will result in acidification of groundwater leading to 1) decreased biological availability of phosphorous, magnesium, molybdenum, 2) increased washout of potassium and calcium, 3) excessive concentrations of manganese, aluminium and iron ions, and reduced microbiological activity. This in turn may lead to:

- Reduced productivity of vegetation and crops.
- Deterioration of materials quality. Primarily affected are corrodible metals (e.g. steel) and products containing portland cement such as concrete. According to AMESCO (2007) the exact level of deterioration is difficult to predict and the mechanisms resulting in materials deterioration are not always well understood or predictable.

Deterioration of the quality of groundwater does not necessarily mean that it will no longer be suitable for production of drinking water (AMESCO, 2007).

Acidification of *surface water* will result in increased pressure on fish, vegetation and other organisms.

Table 6: Acute health effects of high concentrations of carbon dioxide (DNV, 2003)

CO_2 concentrations		Time	Effects
Percentage	ppm		
17-30	170,000 - 300,000	Within 1 minute	Loss of control, unconsciousness, convulsions, coma, death
> 10-15	100,000 - 150,000	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness
7-10	70,000 - 100,000	Few minutes 1.5 minutes to 1 hour	Unconsciousness, near unconsciousness Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing
6	60,000	1 - 2 minutes < 16 minutes Several hours	Hearing and visual disturbances Headache, difficult breathing Tremors
4 –5	40,000 - 50,000	Within a few minutes	Headache, dizziness, increased blood pressure, uncomfortable and difficult breathing
3	30,000	1 hour	Mild headache, sweating, difficult breathing at rest
2	20,000	Several hours	Headache, difficult breathing upon mild exertion

5.2 Risk analysis of the CCS chain

5.2.1 Introduction to risk analysis

In this chapter we will analyze the risk in the CCS chain. This means that we first provide an overview of the *unwanted situation* that can occur when capturing, transporting and storing CO_2 (operational phase) and after closure of the storage site. Secondly we provide insight in the *probability* that these unwanted situations occur, and finally the *type and magnitude* of the damages in case CO_2 is released. For all stages in the CCS chain we distinguish between (1) fast and sudden release of CO_2 which can cause significant short term damage on the local level, and (2) gradual release of CO_2 with little short term damage on the local level but affecting the climate in the long-term. Finally, we will shortly indicate which possible grounds for *liability* exists and who will be held liable for the damages that might occur.

5.2.2 Risk analysis capture installation

Capture facilities include all above ground infrastructure, consisting of the capture installation, above ground pipes and flange connection and compressors.

Unwanted situations. Leakage of CO_2 from the capture installation, the above ground pipes and flange connection, and compressors either gradually or in large amounts in a short time due to rupture of pipes or measuring equipment.

Probability of occurrence. Compressors such as the ones planned for Barendrecht have a chance of 0.0001 per year of catastrophic failure (Tebodin, 2008).

Magnitude and type of damages. When pipes are ruptured, or measuring equipment breaks down, suddenly large amounts of CO_2 could be released over a short period. If the release is directed at the ground the CO_2 can accumulate, and can lead to potentially harmful concentrations of CO_2. The risk analysis project for the Barendrecht project (Tebodin, 2008) concluded that (1) leakage of flange connections is usually small and doesn't lead to lethal impacts outside the capture location, and (2) failure of a compressor can lead to lethal concentration of CO_2 at a distance of approximately 55 meters from the compressor.

Damage associated to CO_2 leakage at the CO_2 capture plant from the *compressor* that feeds CO_2 to the transport pipeline depends upon the state of the CO_2. The prevailing pressure and temperature may correspond to CO_2 in the gaseous phase (for example 40 bar) or to CO_2 in the supercritical phase (for instance 80 bar or more). If the CO_2 exiting the compressor is in the *gaseous phase*, the damage of an accident with the compressor necessitating venting of the CO_2 by means of pressure relieve valves is limited because the CO_2 is in the gaseous phase. Possible impacts are deemed to be limited, because the total CO_2 inventory of the compressor is limited, pressure relief valves at the compressor will react automatically at a signal of abnormal operating conditions (pressure, flow rate, etc), and the compressor is co-located with the CO_2 capture plant at an industrial site far from populated areas. If the CO_2 is in the supercritical phase (80 bar or more), the risk profile is different from that of compression up to some 40 bar (gaseous stage), as the CO_2 escaping due to an accident does not spread as fast as gaseous CO_2.

Overall it can be *concluded* that risks associated to the CO_2 capture stage are deemed to be relatively small compared to the stages of CO_2 transport and (particularly) CO_2 storage. This is because CO_2 that is normally vented to the atmosphere will be captured and concentrated at moderate pressures based on physical or chemical absorption, before it is transferred to the operator of the CO_2 pipeline for compression and transport. In the CO_2 capture stage, incidents due to too high pressure or flow rate, leakage of CO_2 may be accommodated by venting CO_2 to the atmosphere without significant risk to the environment. This is a straightforward procedure because the total CO_2 inventory of the CO_2 capture plant at any moment in time is relatively limited and pressure relief valves at the capture installation will react automatically at a signal of abnormal operating conditions. Also, the pressure of the CO_2 stream is rather low, and the CO_2 capture plant is located at an industrial site that is relatively far from populated areas.

Liabilities in case of damage. Although the Dutch Civil Code knows a specific liability for blowouts out of mining works, this regime only applies for blowouts of minerals, which CO_2 is not. Possible grounds for liability are the liabilities for goods and works (6:173, 6:174 Dutch Civil Code). The liable person then is the operator that uses the constructions and attached pipelines for professional use[13]. Both of the liabilities mentioned above qualify as risk-based liabilities, a person carrying out these activities has a duty of care to work safe and if not he will be held liable, even if there was no fault on the part of the operator. When there is fault, the more general fault-based liability also applies (6:162 Dutch Civil Code). The person suffering damages then has to prove that the operator's actions have been unlawful towards him, and that there is a causal relation between the actions and the damage that was suffered.

As capture installations are required to have an ETS permit, possible damage to the climate is compensated through the ETS system, extra allowances should be bought for extra emissions. If a sudden blow-out causes damage to the environment, the operator will be held accountable, based on the conditions of the environmental liability Directive. Capture installations fall within the fault based liability system, only when the operator is at fault, he will be held liable. However, before environmental damage can be proven significant adverse effects should appear which is unlikely in case of a rupture or leakage.

5.2.3 Risk analysis transport system

Unwanted situations. Leakage of CO_2 during transported through pipelines[14] either gradually or in large amounts in a short time due to pipeline rupture. Pipelines can rupture[15] due to:

- *Corrosion*: Corrosion can affect both the inside and outside the pipeline, and can lead to a hole in the pipeline.
- *Material:* Material fatigue can lead to a hole in the transport pipeline.
- *Outside force*: Pipelines can be damaged during excavation work.

Probability of occurrence. The incidence rate of pipeline failure is relatively small. Studies show that the incidence of failure has clearly decreased, and most of the incidents refer to very small pipelines, principally in gas distribution systems. There is substantial variation in incidence occurrence between pipelines, reflecting factors such as system age and inspection frequency (Hendriks et al, 2005). The accident record for CO_2 pipelines in the USA shows 10 accidents from 1990 to 2001 without any injuries or fatalities, corresponding to a frequency of 1×10^{-4} incidents per km per year (see for an overview of all CO_2 pipeline in the US Table 16 in the appendix) (Gale et al, 2004). A more recent study in which all accidents with CO_2 pipelines in the period 1986-2008 were analysed shows that there is a probability of a failure of a CO_2 pipeline with a length of 100 km of once in hundred years (see Table 7). A total of 13 accidents occurred between 1986 and 2008, according to the NRC's accident database URS (2009). Of these 13 accidents, none had reported human injuries or fatalities, compared to the more than 5,000 accidents and 107 fatalities in the same period caused by natural gas and hazardous liquid

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[13] Normally, the owner of the building and materials will be held liable, but in case of professional use the person carrying out business is the one being held liable and in case of pipelines etc this is specified to the operator of such an installation. Bauw,E, 2008, Onrechtmatige daad: aansprakelijkheid voor zaken, Kluwer, p. 23, 92.

[14] We did not include transport of CO_2 by means of tanker or tank lorry as this is probably less relevant for the Netherlands.

[15] Ruptures due to relief valve failure is not applicable for large-scale transport in the Netherland, because these pipelines are welded.

pipelines (Parfomak and Folger 2007). Table B in Annex I provides an overview of these 13 accidents.

Table 7: Failure rates for CO_2 pipelines based on (URS, 2009)

Failure Mode	Total Number of Accidents between 1986 and 2008	Percentage [%]	Historical Failure Rate per Mile of CO_2 Pipeline per year
Equipment Failure	6	46	7.77E-05
Corrosion	2	15.5	2.70E-05
Operation Error	2	15.5	2.70E-05
Unknown	3	23	3.89E-05
Total	13	100	1.69E-04

Magnitude and type of damages. When the CO_2 is released gradually damage is mainly global to the climate. Tebodin (2008) describes the situation in case of a full rupture of a large pipeline. They conclude that this will lead to a maximum CO_2 concentration of 10,000 ppm, which is well below the level for lethal effects. These high concentrations will last for about 6 minutes. It can be concluded that the incidence rate of pipeline failure is relatively small, based on current evidence in the USA. Even in case of severe damage – rupture of a pipeline – the maximum CO_2 concentration remains below the level for lethal effects and will not last for long.

Liabilities in case of damage. As the operator of a transport system is required to have an ETS permit, any leakage of venting of CO_2 will be measured and reported, and the operator will have to pay for allowances and possibly a fine. When environmental damages occur as a result of a rupture, the operator will be held accountable, based on the conditions of the environmental liability Directive. For transport, a fault based liability system exists. However, before environmental damage can be proven significant adverse effects should appear which is unlikely in case of a rupture or leakage. For pipeline transport, art 6:174 Dutch Civil Code also applies. The operator will be held liable for any failure of the equipment. Besides the risk-based liability, the general fault-based liabilitiy also applies, which also holds the operator liable.

5.2.4 Risk analysis storage site at the injection point

This includes well failure and failure of surface equipment.

Unwanted situations. The major risk during operation is a well failure. 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. Besides there is the risk of failure of the back-flow preventer or packer at the well site (Holloway, 1996).

Probability of occurrence. According to Holloway (1996) the likelihood of a sudden escape of all CO_2 stored in an underground reservoir is very small due to the limited capacity of the injection system. In the majority of well failures, an amount equal to the content of the well tubing will be released. In normal cases, this leak will be detected by the monitoring system, resulting in the closure of the backflow preventer and the emergency shutdown valve at the well head. Failure of the back-flow preventer or packer at the well site may result in an uncontrolled blow-out (including CO_2 but also salt water, gas, oil or a mixture) (Holloway, 1996).

Magnitude and type of damage. When the CO_2 is released gradually damage is mainly global to the climate. Blow-out could lead to casualties among operators and economic damage caused by explosion or fire when upcoming hydrocarbons are ignited or by parts of the well, which can be launched by the pressure release. Tebodin (2008) analyzed a full blow-out scenario for the Barendrecht site, and concluded that in this scenario the legal local risk contour of 10^{-6}/year[16]– this is a relevant level for external risk – lies within the interior boundaries of the injection site.

Liabilities in case of damage. As the captured and transported CO_2 fall within the ETS system, the operator needs to buy extra allowances for any leaked CO_2. When there is contamination of the water bearing layer, this might constitute to environmental damage. The CCS Directive applies the risk-based liability system to the storage process. It is likely that the injection phase is part of this process, as the Directive only distinguishes between capture, transport and storage. This means that the operator will be held liable for the costs of the repair of the damages. Furthermore, the injection installation can be qualified as a mining work, and the operator will be held liable for any blowouts of minerals that occur when injection CO_2 (6:177 Dutch Civil Code). Therefore, it is of importance to define the legal status of the facility. Note that a blowout of the injected substance itself is not covered by article 6:177 as CO_2 is not a mineral. Furthermore, any soil movement that occurs as a result of the injection will lead to liability for the operator. If a spill over is the result of a failure of the equipment, the articles 6:173, 6:174 Dutch Civil Code will be applicable. Of course, when there has been fault on the part of the operator, the general fault-based liability applies.

5.2.5 Risk analysis storage site during injection and after closure

The risks for the storage site are analyzed along the 5 categories distinguished by Damen *et al* (2006) (see Figure 5).

5.2.5.1 CO_2 leakage

Unwanted situations. When CO_2 is injected in geological reservoirs, it might potentially migrate out of the reservoir through the subsurface, migrate laterally in overburden formations and finally leak into the atmosphere/biosphere. Four potential leakage mechanisms are envisaged to apply generically to storage sites in Dutch onshore depleted gas fields (Amesco, 2007):

- *Leakage through the cap rock*. CO_2 leakage through the cap rock can happen due to various mechanical and chemical processes leading to a change in the cap rock.
- *Leakage through and along wells*. CO_2 leakage through or along wells after the injection phase can be caused by casing or cementation defects due to improper design or construction, corrosion of the casing and deterioration of cement plugs by CO_2 and/or brine. Well integrity has been the most important cause of leakage in underground gas storage facilities. 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.

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[16] On the legal local risk contour the risk of a lethal accident is 10^{-6} per year.

- *Leakage through or along geological faults*. 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.

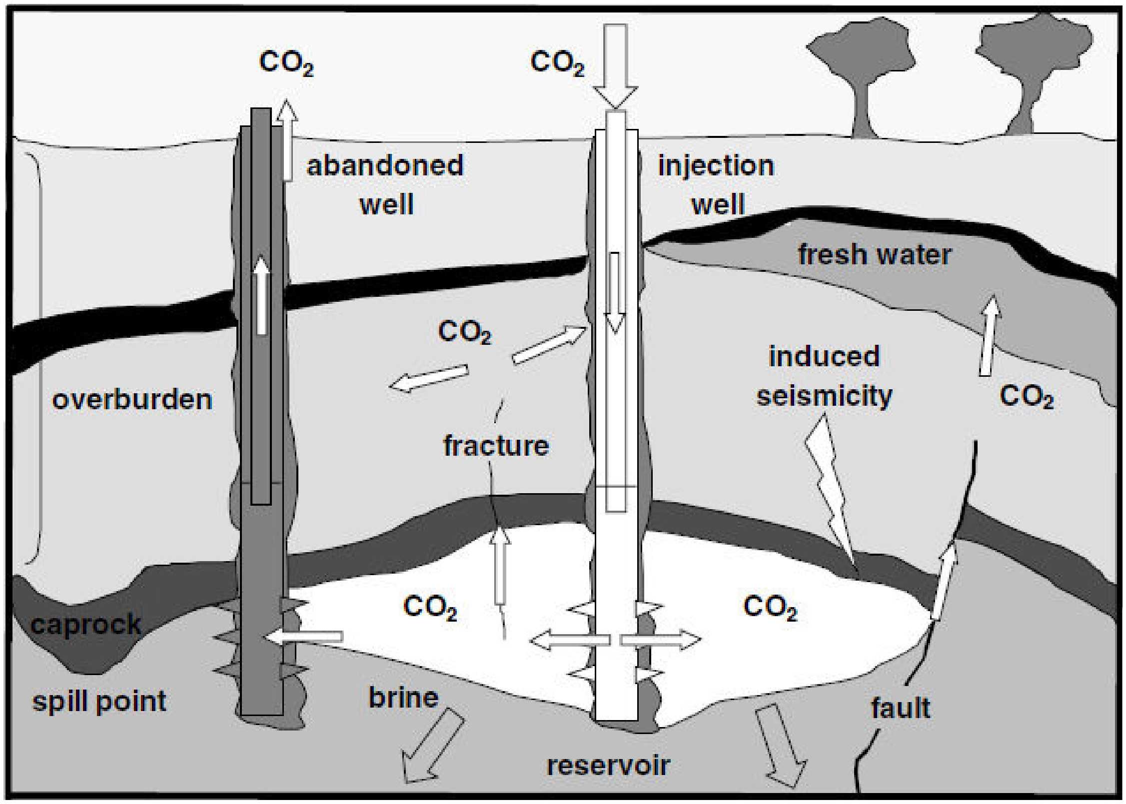

Figure 5: Risks of underground CO$_2$ storage. Black arrows represent CO$_2$ flows (along fractures, abandoned wells and faults). White arrows represent brine displacement as a consequence of CO$_2$ injection. Source: Damen et al (2006)

<u>*Probability of occurrence*</u>

- *Leakage through the cap rock*. Although highly unlikely, it is 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.
- *Leakage through or along geological faults*. In general these faults are not considered a big risks for CO$_2$ leakage to the atmosphere. (EBN, 2009). PM other sources?

<u>*Magnitude and type of damage*</u>. When the CO$_2$ is released gradually damage is mainly global to the climate.

<u>*Liabilities in case of damage*</u>. The damage to the climate as a whole, as a result of the leaked CO$_2$ into the air, is compensated through the EU ETS system. The most complex issue of leakage during storage is the measurement of the leakage, needed for the calculation of the

amount of allowances. There will be EU guidelines to clarify this, it is likely that the EU will prescribe some methods of calculation and the operator will to use these in the monitoring plans[17]. For the leaked emissions, the operator has to buy allowances under the EU ETS system. These allowances and possible fines are calculated each year. Operators are liable for these costs until the responsibility of the site is transferred to the competent authority.

5.2.5.2 CH_4 leakage:

Unwanted situations. CO_2 injection might cause CH_4 present in the reservoir to mitigate out of the reservoir to other formations, from where it may escape into the atmosphere.

Magnitude and type of damages. Like CO_2 leakage, CH_4 leakage may have both local and global impacts. On a local scale, CH_4 may affect shallow water quality and poses a lethal threat when accumulating in confined spaces such as basements. Since the global warming potential of (GWP) of methane is circa 23 times that of CO_2 (IPCC, 2001b), CH_4 leakage is an important factor to be assessed in order to verify the effectiveness as greenhouse gas mitigation option (Damen et al, 2006).

Liabilities. CH_4 leakage and migration might incur damage to the environmental. Based on the CCS Directive, the risk-based liability system of the Environmental liability Directive applies, which holds the operator liable for any measures to repair the damages to the environment. When the leakage is the result of failure of equipment, the risk-based liability of art. 6:174 applies. A legal discussion that might occur is that the damage is caused by a wrong analysis of the storage site, and a plaintiff might try to argue that tortuous/fault-based liability might also be applicable (6:162 Dutch Civil Code). Whether or not the operator can defend himself by the regulatory compliance defence depends on the nature of the rules. Only when the site selection has been conducted through a specific method prescribed by the government, the operator can use this defence.

5.2.5.3 Seismicity

Unwanted situations. The injection of large amounts of fluid into a reservoir increases the pore pressure and thereby modifies its mechanical state. This might induce fracturing or activate faults, such that micro-seismicity and even damaging earth tremors might occur (Holloway, 1996). Potential effects of reservoir-induced seismicity (RIS) are damage to the cap rock and lead to release of CO_2.

Probability of occurrence. There has been a recent, elaborate study on the induced seismicity in the Netherlands as a result of gas production (van Eijs, Mulders, Nepveu, Kenter, Scheffers, 2006, Engineering Geology 84, 99-111). A few simple dimensionless parameters were defined that appear to be good indicators (The ratio of the Young's moduli between reservoir and overburden, and a measure for the fault density). However, the study pertains to gas production, and not to injection. At the moment there is a TNO-project where seismicity as a result of injection is studied. It remains to be seen how different the results will be.

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[17] Draft Commission Decision amending decision 2007/589/EC as regards the inclusion of monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide.

Magnitude and type of damages. Slow release of CO_2 affects the global climate system. The reservoir-induced seismicity (RIS) also might damage buildings and infrastructure. Experience with extraction of oil and gas shows that induced seismic activity leads to short and weak earthquakes (Wassing *et al*, 2004). This leads to little or slight damage to buildings, such as cracks in walls.

Liabilities. Induced seismicity and ground movement may cause damage to buildings and possibly indirect to persons. These damages fall within the scope of art 6:177 Dutch Civil Code on soil movement, which holds the operator liable for these damages.

5.2.5.4 Ground movement

Unwanted situations. It is possible that the earth's surface will sink or rise because of man-made pressure changes, which might cause damage to buildings and infrastructure and might also trigger seismicity.

Probability of occurrence. Several cases of subsidence in history (mainly during exploitation of oil and gas fields) are known and well documented (e.g. Groningen gasfield). According to Holloway (1996) the mechanism of subsidence is well understood, but prediction is considered to be difficult.

Magnitude and type of damages. see section “Seismicity”.

Liabilities see Section “Seismicity”.

5.2.5.5 Displacement of brine

Unwanted situations. The injection of CO_2 in aquifers might cause displacement of saline groundwater (brine). This may cause undesirable effects such as a rise of the water table.

Probability of occurrence Probability and effects are still highly uncertain.

Magnitude and type of damages. Displacement of groundwater could have negative impact on land quality and use and an increase in salinity of sweet water reservoirs used for drinking water extraction and irrigation.

Liabilities. Displacement of brine might constitute to environmental damage. Based on the CCS Directive, the risk-based liability system of the Environmental liability Directive applies, which holds the operator liable for any measures to repair the damages to the environment.

5.2.6 Summary of risks

Table 8 provides a summary of unwanted situation, probability that these situations occur, and the magnitude and type of damage as described in the previous sections. In general it can be concluded that the know risks are either low or negligible.

Table 8: **Summary of unwanted situation, probability that these situations occur, magnitude and type of damage**

Stage in CCS chain	Unwanted situations	Probability of occurrence a)	Magnitude of damage a)	Type of damage b)
Capture installation	Sudden or slow leakage of CO_2 due to rupture of pipes	Low	Negligible	#1), #3), #4)
Transport system	Sudden or slow leakage of CO_2 due to: 1) Corrosion 2) Material fatigue 3) Outside force	Low	Negligible	#1), #3), #4)
Storage site at the injection point	Sudden or slow leakage of CO_2 due to well failure	Low	Low	#1), #3), #4)
Storage site during injection and after closure	CO_2 leakage through: 1) Cap rock 2) Through and along wells 3) Trough and along geographical faults	Low	Low	#1)
	CH_4 leakage	Low	Low	#1)
	CO_2 leakage due to reservoir-induced seismicity (RIS)	Low	Low	#1)
	Ground movement inducing seismicity or damaging building and infrastructure	Low	Low	#1), #4)
	Displacement of brine leading to rise of groundwater levels	Uncertain	Uncertain	#2)

a) Scaling for Probability and Magnitude	b) Type of damage
Negligible	#1) Climate system
Low	#2) Environmental and ecosystems
Medium	#3) Third parties
High	#4) Materials

The existing liabilities are summarised in the table below. The next paragraph will discuss these liabilities in more detail.

Table 9: Overview of existing liabilities

Damage to:	Liabilities covered under	Liable person	Plaintiff
Climate	EU-ETS	Licensee[18] (operator)	Competent Authority (Dutch emissions authority)
Health & Property (third parties)	Dutch Civil Code	Licensee (Operator)	Third parties that suffered the damage
Environment	ELD Directives as implemented in the Dutch environmental management act.	Licensee (operator)	Government/local authorities

5.3 Liabilities in case of damage

5.3.1 Introduction

As we have seen in section 5.2, CCS entails risks that might lead to several categories of damage. In most situations the operator can be held liable for the compensation of this damage. We have seen that there are several bases for liability. This paragraph starts with a general introduction on liability and liability systems (5.3.2). Paragraph 5.3.3 provides an overview of the liability regimes that are applicable for the different categories of damage and define who will be held liable. One of the unresolved issues mentioned in chapter 2, is the long-term permanence and liability. The central question of this paragraph is to examine which legal bases in the Dutch legal system are relevant in case of long-term liability and to determine whether or not the legal system is suitable for dealing with long-term storage. If not, the long-term liabilities need to be managed in order to prevent that these might hinder the development of CCS. Several options with regard to the management of long-term liability will be provided in section 5.3.4.

5.3.2 Liability and liability regimes

Liability is the legal responsibility that one has to another or to society, enforceable by civil remedy or criminal punishment. The legal discussion on liability always involves three questions: Who can be held liable, to whom and under which conditions? Liability rules shift loss from a person suffering damage, to another person that is held responsible for that damage. Liability is an instrument that can be used for various purposes. The most commonly known objectives of liabilities are that it provides for compensation and victim protection, that the threat of liability stimulates companies to operate as safe as possible (deterrence), and that liability for certain damages transfers the possible costs from society to the liable person. Furthermore, liability can be used for wealth-redistribution and corrective justice (Bergkamp 2001). What we see in environmental liability is that liability is used as an instrument not to spread the costs for damage, but to channel it to those who caused the damages, rather than let all people suffer the damages.

In legal theory, generally two types of liability can be distinguished: tortuous or fault-based liability and strict or risk-based liability (Bauw, Brans, 2003, p 59, 153, Van Dam, 2000, p 163, 297). In

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[18] Although licensee and operator are often the same, it is possible that the operator is another corporate entity than the licensee, and is instructed by the licensee. In general the legal entity having control over de actions and decisions of the operator will be the liable person. See also paragraph 5.3.3.4.

case of fault-based liability, there are five conditions to be met before one can be held liable. These conditions are that the actions or omissions of the respondent are unlawful (1), towards the plaintiff (2) that the actions are imputable to the respondent (3) and that the actions are the legal cause (4) to the damage suffered by the plaintiff (5) (Wissink, 2009, 238). These conditions are rather abstract and cases are judged based on the specific characteristics of the case, using standards that are developed in case law. Courts thus play an important role in determining the liability in specific situations.

Risk-based liability is a more stringent type of liability than fault-based liability. The legislator has determined that some categories of actions are that uncertain or carry such high risks, that for these actions the respondent will be liable even if the act was not unlawful (Bauw, Brans, 2003, p 59, 154). When compared to fault-based liability, the plaintiff does not have to prove that the actions that caused damage were unlawful and that the actions were imputable to the respondent. More differences between fault-based liability and risk–based liabilities are that:

- Risk-based liability occurs in certain defined situations;
- Risk-based liability can be limited to types of damages;
- Defences against risk-based liability are limited;
- Liability does not depend on a fault on the part of the respondent;
- Risk-based liabilities already define which persons might be held liable for which risks, so they are able to take insurance coverage.

Most Member States have a general fault-based liability system, with a few risk-based liabilities for specific categories of activities. The CCS Directive has left the regulation of liabilities for as far as not regulated in the Directive, to the Member States. In order to determine who might be liable, for which damages and for how long, this paragraph describes the different liability regimes or systems that might be applicable to the long-term storage of CO_2. A liability system consists of a few core elements that provide the structure for describing the liabilities that exist for CCS and that will help to detect the possible problems that might occur in dealing with the long-term liabilities.[19] For the purpose of this paragraph we describe a liability system by defining:

- The damages that are to be compensated and how they can be measured/proven;
- The liable persons for that damage;
- The type of liability (fault-based or risk-based);
- The period for which liability exists (liability horizon);
- The possible defences the liable person might use to defend himself against liability.

This provides insight in the possible liabilities that operators in the CCS chain face and the possible thresholds for the development of CCS that exist in the liability regime as it is today.

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[19] This system for describing liability is derived from Bergkamp, 2001, p259-366.

5.3.3 Damage and liable persons

When analysing the possible grounds for liability, based on the possible damages (see paragraph 6.2.6), three different liability regimes can be distinguished:

- Liability for damage to the climate as a whole (category 1);
- Liability for damage to the environment, and (category 2);
- Liability for damage to health and property (category 3,4).

The international, European and national legal system provide for different arrangements per type of damage that might occur.

The *first liability regime* is the compensation for damage to the climate as a result of the leakage of CO_2 into the air. Although there is no directly measurable damage and it is hard to link it to a specific emitter, in the literature there is agreement on the use of the term climate damage as a result of CO_2 emissions. For this situation we do not have a specific liability regime, but the EU ETS system functions as a compensation mechanism for the damage that is done to the climate. The CCS Directive links CCS directly to the EU ETS system, by counting stored CO_2 as not emitted under the ETS permit. This should provide emitters with and incentive to apply CCS. During capture, transport and storage, possible causes for damage are the leakage of the storage site, possible leakages during transport and injection, through failure of equipment or venting.

A *second liability regime* is for damages to the environment as a result of CCS operations. Damage to the environment might be caused by sudden blow-outs, leakage, displacement of brine and the leakage of other substances into the air as a result of the migration of the $CO_{2.}$ Causes can be found in the characteristics of the site, as well as in the operation of the transport and storage facilities. Although the same causes might also lead to personal injuries and damage to property, there is a separate liability regime for the damages to the environment, with its specific compensation mechanisms. The environmental liability regime is based on the environmental liability Directive of the EU (2004/35/EU), in the Netherlands, implemented in the Environmental Management Act.

A *third liability regime* is for damage to property and personal injuries that might occur during capture, transport and storage of CO_2. The occurrence of a sudden blow-out might lead to personal injuries and damage to the equipment in the direct surrounding of the site. Furthermore, once the CO_2 is stored, or during injection, induced seismicity and ground movement might lead to small earthquakes and might cause damage to buildings and houses. Persons suffering these types of damages might call upon the liability arrangements in national law.

Paragraph 5.2 shows that in the storage phase[20] all three liability regimes are relevant if damage occurs. In this paragraph we will describe each of these arrangements, focussing on the elements as set out in the previous section. We will examine whether or not the liability regimes are suitable for dealing with the long-term storage of CO_2.

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[20] The arrangements are also relevant during capture and transport, but this section focuses on the specific analysis for the long-term storage.

5.3.3.1 Damage to the climate

Possible damages to be compensated

Although the purpose of CCS is to prevent emissions of CO_2 causing climate damage, it is inevitable that during the CCS process some of the CO_2 will still be released as a result of venting, leakage or seepage. Since stored CO_2 counts as prevented emissions under the ETS, the leakages and emissions as a result of venting also count as emitted under the ETS, and the holder of the emissions permit should pay allowances for the emitted $CO_{2.}$

If the emitted CO_2 is defined as damaging to the climate, would the owner or operator of the installation be held liable for the compensation of that damage? A traditional liability system for this type of damage is rather difficult, who should ask for compensation? And how do we measure the damage? Instead of seeing any emissions as damage, one might view it more as a breach of an administrative system registering emissions for the ETS.

Per tonne of CO_2 lost by leakage, the holder of the emissions permit will have to pay a certain amount, determined by the price of emission rights. When a company does not meet its amount of allowances, it might be fined and it should surrender the missing allowances in the following year. So the compensation will be on a yearly basis. Once the carbon is stored permanently, the compensation for the leaked emissions will transfer to the state, based on art. 18 of the Directive (except in the case of fault by the former operator).

As there is already experience with the ETS system: the functioning of the ETS for storage seems quite clear. Possible complications exist for the measurement of leakages occurring during storage. The ETS system requires a high degree of certainty, for the interests of the permit holders that are involved, there is discussion on the certainty of measurements of leakages in case of storage (Wartmann, Groenenberg, Brockett, 2009, Bode, Jung, 2006). During transport, emissions can be calculated on a input/output basis. For a spill over at the injection point this already becomes a problem, and not more than an estimate is possible. Furthermore, there will always be a certain small degree of seepage, which cannot be measured. The EU has issued draft decision on monitoring and measuring the leaked CO_2 in case of CCS.[21] This decision prescribes measurement techniques which should be part of the monitoring plan of the storage site. Furthermore, methods approved by the competent authority are allowed. These prescribed methods of calculation include an uncertainty percentage to compensate for the immeasurable seepage. For leakage the prescribed calculation includes monitoring from the day of occurrence of the leakage to the date by which the corrective measures have been taken.

Possible legal debates that might exist occur between the operator and the emissions authority. Due to the prescribed or authorised calculation methods in the draft decision, the legal debates will not include the methods for quantification and monitoring. What might be subject of legal debate is the start of monitoring and measurements in case of leakage. Although the technical specifics might differ for the different phases of the CCS chain, the principle of starting monitoring when the regular data suggest a leakage event is used for all phases. So the legal debate might be on the interpretation of the data and the date at which the interpretations lead tot the

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[21] Draft Commission Decision amending decision 2007/589/EC as regards the inclusion of monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide.

conclusion that an event is occurring. In case of legal debates, the emissions authority and the dispute settlement arrangements for the emissions authority are where this debate will be fought out.

Party responsible for compensation

Another factor that needs to be determined is who is responsible for buying extra credits on the market. For CCS, all parties involved in the different phases have an ETS permit, the operator of the capture installation, the operator of the transport network and the operator of the storage site. The EU ETS system prescribes that the holder of the permit is responsible for buying the extra credits. In the situation in which the holder of the permit is a joint venture, one of the participants is appointed as holder of the permit. The joint venture should regulate the possible liability for the extra allowances in advance, as generally all participants in a joint venture can be held liable (joint and several). When disputes occur between participants in a joint venture, these kinds of disputes will be fought out before courts in the private judiciary system. As in most company law systems, Dutch legislation prevent abuse of the company structure in order to avoid liability by breaking through the company structure and placing liability by the person or company influencing the actions and decisions of the licensee.

The operator (often holder of the permit)[22] will be held liable for the ETS allowances until the responsibility for the site is transferred to the competent authority, based on art 18 of the Directive (except in the case of fault by the former operator). The liability horizon for the operator thus is determined by the conditions in the ETS Directive and the conditions to be formulated by the Member State with regard to the transfer of responsibility.

Table 10: Overview of climate liability

Climate liability	
Damage	For the amount of leaked CO_2 allowances have to be paid, the accuracy seems to be a problem in measuring the amount of leakage
Liability horizon	Yearly compensation until transfer (app. 20 years)
Liable persons	Before transfer the licensee (operator), after transfer the competent authority
Type of liability	Not really a liability regime, more a breach of an administrative system registering emissions for the ETS
Legal debate[23]	Debate might occur on the interpretation of data and the decision when these data indicate an event

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[22] Although licensee and operator are often the same, it is possible that the operator is another corporate entity than the licensee, and is instructed by the licensee. The licensee then is a joint venture in which several companies cooperate. In this situation the joint venture and its participants are held liable, joint and several, so most joint ventures will negotiate possible liabilities in advance.

[23] As the ETS system is more of an administrative program than a liability regime, possible defences do not really apply, so the term legal debates is chosen here.

5.3.3.2 Damage to the environment

Damages that should be compensated

Significant leaks of CO_2, CH_4 and displacement of brine could lead to eco system damage. When there is leakage, it hardly ever is a significant amount, and in case of leakage along the well, there are several mechanisms that control the amount of CO_2. However, when such damage occurs, the damage to species, habitats, land and water is dealt with in the environmental liability Directive, in the Netherlands implemented in the Environmental Management Act (EMA). Since storage falls within the list of activities of annex III of the environmental liability Directive, the liability regime for these activities can be characterised as risk-based or strict. The environmental liability Directive sets out rather stringent requirements for defining damage that leads to liability. For damage to the water not only should there be a measurable effect, but it should also have a significant adverse effect. Possible damages thus will always be in relation to the state of the water at the moment of occurrence of the damaging event (Backes, 2005). For damage to the land, the Directive requires a measurable adverse effect focusing on the risk to humans (Jans, Vedder, 2007, p 341). Legal debates before the courts will focus on whether or not there is a significant adverse effect. The debate will have a technical character, not only in determining the state of water or land, but also in proving the causal relation between the leakage and the damage that might occur.

Liable person and liability horizon

The liability regime provides that the operator (and holder of the license under the EMA) of an annex III activity is responsible to take and pay for preventive and/or remedial action, to be taken under supervision of the competent authority. If the authority takes these actions itself, it may hold the operator liable for the costs. Natural persons or interest groups may bring the possibility of damage to the attention of the competent authority and have access to judicial proceedings for review of the procedural and substantive legality actions and decisions.

The competent authority should recover the costs within 5 years after the measures have been executed. Liability exists for 30 years following the event that caused the damage. According to the Directive, the operator is the liable person. Environmental liability will be transferred to the competent authority, once the storage is closed or in the other situations as mentioned in art 18 of the CCS Directive.[24]

In general it will be the competent authority who will try to recover the costs of the measures that are taken, that will have to prove causation. That might be difficult when the damage is the result of more than one activity, by more than one party. This might be the situation when several small storage locations are operated by different operators and are in the same area. It might be hard to determine which of the activities or locations has caused the damage to the environment. In these situations, all parties are held liable, joint and several and the defendants have a right of contribution against co defendants (Bergkamp 2001, p 299).This means for companies involved

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[24] There is one exception, if the competent authority can prove that the former operator was at fault (deficient data, concealment of relevant information, negligence, wilful deceit or failure to exercise due diligence), the competent authority can recover further costs after the transfer. This legal debate will be fought out before the courts for private law.

in a joint venture, that they either negotiate such issues beforehand, or face a court battle once one of them is held liable.

Possible defences

Environmental liability does not apply in situations in which the damage is caused by armed conflict or natural phenomena. In those situations, the operator did not cause or could have prevented the damage from occurring. Furthermore, the Directive leaves room for Member States to implement a regulatory compliance defence and a state of the art defence. The Environmental Management Act contains both of these defences (Wissink, 2009, p 236). This means that if the defendant can demonstrate that he was not at fault or negligent and that the damage was caused by emissions in accordance with the conditions of the storage permit and the environmental permits that are required, or that the damage was not considered likely according to the state of technical and scientific knowledge at the time of the emission, he will not be held liable. The regulatory compliance defence is limited to rules prescribing specific methods for the prevention of damages. Such might be the case if the storage permit and environmental permits prescribe a specific monitoring technique or specific type of remedy that in the end contributed to the damages that occurred. The more specific the rules and conditions of the permits, the more likely that the operator might use the regulatory compliance defence.

Special situation: damage to the environment during capture and transport

The situation for environmental damages as a result of the capture and transport of CO_2 is different. Transport and capture are not categorised within the strict liability regime of the environmental liability Directive. This means that there should be compensation for damage to the environment as a result of leakage or rupture, but it is on a fault-based regime. Only when fault or negligence has caused the rupture, the operator will be held liable. Furthermore, liability in non annex III cases exists only for damage to protected species and natural habitats. In this situation environmental liability exists for very specific damages and in situations in which fault can be proven.

Table 11: Environmental liability

Environmental liability	
Damage	Significant adverse effect for species and water, measurable adverse effect for land/humans, costs made by plaintiff to prevent, limit or repair damage.
Liability horizon	30 years following the event that caused the damage, recovery within 5 years after execution of the measures.
Liable persons	Before transfer the licensee (operator, joint and several in case of a holding or joint venture), after transfer the competent authority
Type of liability	Strict or risk-based liability
Possible defences	- damage caused by armed conflict - damage caused by natural phenomena - regulatory compliance defence - state of the art defence

5.3.3.3 Damage to health and property - general tort law

As the Directive indicates, the liabilities that are not mentioned in the Directive are to be dealt with on a national level (consideration 34 CCS Directive). Prevention and remedial actions, which are the purposes of the ETS system and the environmental liability system, do not cover the liabilities towards third parties that have suffered damage. National legislation does provide for legal bases for third parties to claim liability. Since the proposal for implementation of the CCS Directive does not contain specific regulation for liabilities, the current national legislation is relevant. In this and the following section we will examine and analyse the legal bases for liability in Dutch legislation.

General tort law and possible damages

The most general basis for liability is art 6:162 Dutch Civil Code. This is a form of fault-based liability. If ones actions cause harm to someone else, that person should be compensated when the actions were unlawful. All situations in which an operators actions can be qualified as unlawful, might lead to possible claims. An act is unlawful if it violates statutory law, unwritten rules of law or infringes a right of another (Wissink, 2009, p246).[25] Whether or not the operator can be held liable is highly dependent on the circumstances of the case. Possible indicators are the predictability of the damage, possible negligence in taking measures and whether or not sufficient warning was provided. When the operator has failed to comply with the conditions of the different permits that are required, this causes his actions to be unlawful. Even if the operator did comply with the rules, the operator might still be liable towards third parties (as opposed to being liable to the government), because the permit does not necessarily protect the interest of third parties. Furthermore, the operator might even be liable for damages that he could not have known, and case law requires the operator to stay aware of the state of the art, be aware of new insights and consider whether in certain cases more extensive measures could be taken. If the actions of the operator are qualified as unlawful, possible damages to be compensated are: personal injuries, damaged goods, costs made to prevent damage (also for others), costs made to establish the damage and costs for the procedure. As we have seen above, there is a broad range of actions that might qualify as unlawful. Once an incident occurs and there is damage, and

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[25] Damage as a result of infringement of a right does not seem to apply to CCS.

the operator did not comply with the conditions of the different permits, he will be held liable. When the interests of third parties are not explicitly protected by the different permits, he even might be liable when he did comply with the permits. If an incident causing damage to third parties occurs, liability claims will follow, because the permits generally cover interest of society as a whole or the environment, but not the specific interests of third parties.[26]

Possible defences.

In order to claim the damage all of the components of fault-based liability have to be met, which leaves room for a lot of possible defence strategies for the operator. In general liable parties will defend themselves by stating that the act is not imputable to the liable person or that he could not have known the possibility of the damage at that time. In case law several grounds for justification of the actions of the liable person have been developed, so that he cannot be held accountable. The legal debate on what caused the damage and the degree to which the operator can be held responsible will be fought out in court. This discussion will be highly technical, and since the relevant courts depend on where the claim is brought before the court, case by case relevant but different standards might develop.

Liable person and liability horizon

For third parties, the liable will person will always be the responsible party for the site. If this is a joint venture, all participants can be held liable, joint and several. Once liability is established, the participants can negotiate how they divide the costs, or they can start court proceedings against each other. The liability based on art 6:162 Civil Code ends when the responsibility for the site (and thus the event causing damage) is no longer with the operator. The legislator also regulated the period in which plaintiffs might claim damages. This might be either be 5 years after the plaintiff knew of the damage and knew of the liable person (short period). Or this might be 20-30 years after the event that caused the damage occurred (long period). The law appoints specific categories for which the 30 year period applies; most common is the 20 year period. However, in case of personal injury only the short period applies, which means that within 5 years after the discovery of the damage, the operator or former operator might face a claim, even if the event causing the damage occurred 50 years ago. Of course this is only the case when the damage is the result of fault or negligence on the side of the operator.[27]

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[26] Theoretically, if the storage permit would be designed to take into account the interests of third parties, this might provide some certainty for operators, because this would allow a regulatory compliance defense.

[27] When an event occurs after the closure of the site and the transfer of responsibility, there might be a legal debate on the cause of the event and who is to blame for the event: the former operator or the competent authority.

Table 12: Civil law liability, tortuous/fault-based liability

Civil law liability, tortuous/fault-based liability	
Damage	Personal injuries, damaged goods, costs made to prevent damage (also for others), costs made by plaintiff to establish the damage and costs for the procedure
Liability horizon	5 years after the damage and liable person are known to the plaintiff in case of personal injury, for other damages 20 years after the event
Liable persons	Operator (responsible party for the site)
Type of liability	Fault-based liability
Possible defences	- State of the art defence (unlawfulness of the act) - Grounds for justification - The causal relation between act and damage - The act is not imputable to the operator - The damage of the plaintiff is not specific, the damage is suffered by all equally

5.3.3.4 Damage to health and property - specific liabilities

Possible damages for which specific liabilities might apply

The Dutch Civil Code has appointed a few categories of activities for which strict or risk-related liability applies. If risk-based liability applies, the plaintiff does not have to prove that the actions were unlawful or imputable to the operator. The risk-related liabilities are only applicable to specific types of damage. It should be noted that only victims can invoke the risk-based liabilities, professional risk bearers, such as insurance companies cannot. Damages, for which risk-based liability exists, are damages as a result of the use of dangerous substances, damage as a result of pollution of air, water or soil caused by substances deposited on a waste disposal site and damage as a result of blow-outs or soil movement triggered by mining works. We will first examine to which extent the possible risk categories apply to the long-term storage of CO_2.

It can be questioned whether or not CO_2 can be qualified as dangerous substance. According to European legislation CO_2 is not a dangerous substance, but in national legislation CO_2 is viewed as posing a danger under certain circumstances (Wissink, 2009, Braam, Brans, 2009). In the absence of a uniform view on the matter, the courts will have to decide whether or not this liability is applicable to CO_2, which provides for uncertainty for the operators.[28]

Under current law the liability for waste disposal site applies to CO_2 storage sites. It should be noted that a storage site only qualifies as a waste disposal site if the CO_2 that is stored is from other sources than the operator itself.[29] However, once the CCS Directive is implemented, CO_2 is not qualified as waste and this liability will most likely no longer apply.[30] A logical ground for liability seems to be the article on liability for mining activities (art. 6:177 Dutch Civil Code). Both

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[28] In the decree on liability for dangerous substances and environmental damage, more certainty could be provided by adding CO_2 to the list, or explicitly excluding it.

[29] A location where one stores ones own waste does not qualify as a waste disposal site.

[30] It should be noted that the disqualification of CO_2 does not necessarily mean that a storage location will not be qualified as a waste disposal site. Although it seems likely that it will not, government may decide to qualify storage locations as waste disposal sites.

the risk of blow-outs and the risk of soil movement are dealt with in the article on mining activities, although the liability horizons are not the same. Since CO_2 is not qualified as a mineral, the liability based on this article does not exist for the blow-out of CO_2, but does exist for the blow-out of other minerals caused by the injection of CO_2. This is not a problem, since the operator is already liable for a blow-out caused by failure of equipment or a man-made structure that is part of the mining work (leakage along the well).[31] The other situation dealt with in art 6:177 Dutch Civil Code, is soil movement. This liability is applicable since it covers the use and exploitation of mining works, such as the installation used to inject CO_2. This might result in damage to property, houses and buildings in the area of the storage location. There is a lot of experience in dealing with the damages, as a result of producing and storing gas. The plaintiff should prove causation between the storage and the damage to the property. In the Netherlands a technical committee for ground movement can be asked to advise on the matter, since the technical nature of the debate is too complicated for plaintiffs and judges.

Liable person and liability horizon

For all risk-bases liabilities the operator is the liable person. Art. 6:174 refers to the owner, but in case of mining works, the liable person is the one using or exploiting the facility, which is the operator, and after closure of the site, the last operator. For liability based on dangerous substance and the liability based on waste disposal the liable person is the one keeping the site or substance, which indicates that after a transfer of responsibility as prescribed in article 18 of the CCS Directive, the liability for the operator will end. The liability based on 6:177 is channelled to the operator, which is specified as the holder of the permit under the Mining Act.[32] In the situation in which several risk-related liabilities apply, the liability is channelled to one person, the one being liable for the mining work. The short liability horizon for blow-outs (5 years after closure) limits the liability to the operator. However, the possibility of an ending of liability for the damage as a result of soil movement is excluded in the wording of the article, which is also the case for liability based on failure of the equipment.[33] The liability horizons are to be found in the text of the Dutch Civil Code.[34] In case of personal injury the plaintiff has to make the claim within 5 years after the discovery of the injury and the liable person and there is no limitation applicable. This means that even up to 100 years after closure, if a plaintiff discovers an injury caused by the activities of the operator, the operator will still be liable. For all other damages statutes of limitations are applicable, varying from 20 to 30 years. For the blow-out based on art 6:177 a

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[31] Articles 6:173, 174 BW.

[32] Art 6:177 (2) states that the person operating a facility without a permit is also liable. When an operator without a permit acts on behalf of the permit holder (in the situation in which operator and permit holder are not the same), the permit holder is the liable person. A possible legal debate in such a situation might occur when the permit holder denies having instructed the operator. However, for third parties, this is of little relevance, permit holder and operator may have a case against each other, not against the third party. Note that the operator operating a site without a permit is not liable if he acts under instruction of a person of which he believes and might have trusted that this person owns a permit under the Mining Act. In doing so, the Dutch Civil Code channels liability to the one that controls and influences the actions and decisions of the operator.

[33] Articles 6:174 (3) and 6:177 (4) BW.

[34] Article 3:310 BW.

specific horizon is mentioned. Liability for ground movement for example, extends to 30 years. The different liability horizons for the risk-related liabilities are found in table 13.

Possible defences

As was mentioned before, the defences in case of risk-based liability are limited. Possible defences are prescribed by law, which are: armed conflict, unavoidable natural events, and an explicit order by the government, medical treatment, and intentional damage caused by a third party and the situation in which the damage is considered an ordinary burden that one has to carry. Since the risk-based liabilities are based on the idea that these activities are known to create risks, therefore, persons bearing these risks are identified in advance, and a state of the art defence is not applicable. However, the wording of article 6:175 BW (known effects) does leave room for a state of the art defence, and although legal debate is not always clear, the wording of articles 6:176, 177 does not (Wissink, 2009, p 255). Furthermore, the wording of art 6:174 indicates that the defences for general tort could also be available in case of defect equipment causing damage (Braam, Brans, 2009). So, much of the legal debate will be about the cause of the damage, thereby taking into account the relevant conditions in the storage permit. For ground movement, the legal debate will be based on the advice of the technical committee for ground movement.

In the table below, the different risk-related liabilities are summarised. From the analysis of the applicability of the different liabilities can be concluded that for some liabilities it is clear that these are applicable in case of long-term storage of carbon dioxide (soil movement, failure of equipment). These liabilities are printed in black. For other liabilities it is not sure whether they will apply or not. Whether or not these liabilities will apply, will be determined by courts and by governments and local authorities. These liabilities are printed in grey. Furthermore, the liability for waste disposal is printed in grey, this liability does apply at the moment, but that will change after the implementation of the Directive.

Table 13: Civil law liability, strict/risk-related liability

Civil law liability, strict/risk-related liability					
Relevant article	Dangerous substance 6:175	Waste disposal 6:176	Blow-out of minerals 6:177	Failing Equipment 6:173/174	Soil movement 6:177
Damage	Same damage as torturous liability	Limited to occurrence of environmental damage	Same damage as torturous liability	Same damage as torturous liability	Same damage as torturous liability
Liability horizon	30 years after the event causing damage, or 5 years after the discovery of personal injury	Liability lapses 20 years after closure of the site	Liability lapses 5 years after closure or the site	20 years after the event causing damage, or 5 years after the discovery of personal injury	30 years after the event causing damage, or 5 years after the discovery of personal injury
Liable persons	Licensee/Operator (until the transfer)	Licensee/Operator, after closure the Province	Licensee/Operator at the time of the blow-out or the last operator after the site is closed	Owner/Operator at the time that the damage became known, or the last operator after the site is closed	Licensee/Operator at the time that the damage became known, or the last operator after the site is closed
Type of liability	Risk-based liability	Risk-based liability	Risk-based liability	Risk-based liability	Risk-based liability
Possible defences	art 6:178 + state of the art	art 6:178	art 6:178	art 6:178 + tort defences	art 6:178 + technical committee

5.3.3.5 Assessment

This section deals with the question whether or not the liability arrangements that already exist and are applicable are suitable for dealing with the long-term storage of CO_2. It is in the interest of operators and investors that they can predict the possible liabilities (and insurance or compensation costs) that might exist in order to assess the costs of an incident. As mentioned before, liabilities are an area in which the courts play an important role. Especially for the civil liabilities, courts determine in the end which liabilities apply and which damages to which extent are being compensated. For the risk bearing operators this creates uncertainty. They will try to get insurance in order to spread the costs for the possible liabilities and create more certainty for themselves. From the perspective of companies and operators the costs that they face after the injection are the financial contribution that they will have to provide based on art 20 of the CCS

Directive (monitoring costs, and further costs to be determined by Member States)[35] and the possible liabilities that might exist as a result of their activities (which will increase the costs, by insurance or compensation). Both of these costs cannot be qualified as normal operating costs.[36] CCS exposes stakeholders to a new and unique situation, which often means that the costs for insurances for these new liabilities are high. The long-term nature creates potential for liabilities to manifest itself over timeframes that are beyond the scope of the private sector. There is much debate on the question which of the possible costs has to be carried by the operators and which of the costs should be dealt with otherwise.

When we assess the applicable liability regimes we see that the three regimes have different liability horizons. The liability horizons for climate liability and environmental liability are limited for companies, by transferring these liabilities to the competent authority after a certain period of time (which is in fact a way to manage these liabilities for companies). Art. 18 of the Directive provides for the transfer of responsibility towards the competent authority. The final text of the Directive states that after the transfer, the competent authority is responsible for all legal obligations relating to monitoring and corrective measures, the surrender of allowances within the ETS system and the measures to be taken under the environmental liability Directive (Wissink 2009, p 261-265). The competent authority takes on the responsibility for the site and the risk of unknown or unforeseen events. The competent authority will have the funds to do so, because of the financial contribution that will be paid before the transfer. Further recovery can only take place when there has been fault on the part of the operator. So even when an event (such as soil movement) already started to take place under the responsibility of the operator (unless he was at fault), the liabilities as mentioned in the Directive are to be dealt with by the competent authority. This provides certainty for the operator, the operator has a limited liability horizon and the type of remedy is relatively clear. Therefore we can conclude that the liabilities for damage to the climate and damage to the environment seem to be adequately dealt with.

There is however still a complication in the liability regimes for climate and environment: the amount of the financial contribution based art 20 of the CCS Directive (monitoring costs, and further costs to be determined by Member States)[37]. The amount of the financial contribution is a source of uncertainty for companies, as Member States are free to decide which costs to include in the financial contribution. Article 20 of the CCS Directive states that the Commission may adopt guidelines for the estimation of the costs in order to provide more certainty for the companies. A concept guidance document is available (Commission, draft consultation document, Implementation of the storage Directive, guidance document 4, 18 june 2010). The debate on the guidance documents focuses on the division of responsibilities for the costs and the type of costs that are part of the financial contribution. As long as there is no agreement on the financial contribution, this might become an obstacle in the development of large-scale CCS.

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[35] Especially if remediation for climate damage is incorporated in the financial contribution, the price of future allowances might be very high.

[36] Presentation by Philips, 30 June 2010, IEA Regulators Network (webinar on financial security).

[37] Especially if remediation for climate damage is incorporated in the financial contribution, the price of future allowances might be very high.

Recital 34 under the Directive states that liabilities other that those covered by the Directive are to be dealt with on a national level. These claims are not incorporated in the Directive and are not transferred to the competent authority. Claims based on national law are mostly claims for compensation of damage to third parties, where liabilities based on community law are liabilities towards the competent authority/government. When we assess the possible liabilities that exist on a national level, we see that in case of a major event, such as a rupture of a pipeline, or a sudden blow-out, damage might occur that might lead to liability claims from third parties. There are several bases on which claims can be brought before the courts. In these cases the debate will be on the causal relation between the damage and the actions of the operator. When based on fault-based liability, the plaintiff also has to prove the unlawfulness of the actions of the operator, which is closely related to the nature of the rules of the storage permit. The technical discussions that might rise in these cases might be too complex for non-experts.[38] Furthermore we see that the horizons for liability in the national liability arrangements stretch further than liabilities that are transferred to the competent authority. This means that the operator faces possible liability claims from third parties for damage to health and property even after the transfer to the competent authority. So the statutory time limits for liability and for making claims determine whether or not the operator will be held liable. The question is whether or not we find this extended liability horizon reasonable.

The civil law liabilities are not dealt with as adequately as the environmental and climate liabilities. There is an endless liability horizon for operators, which is highly costly and creates uncertainty. Furthermore, the possible legal debate will be highly technical, whereby one might question the capability of judges to review these matters. Finally, we see that the case law as developed by these courts does not necessarily follow the same direction, due to judicial freedom. Involvement of a technical committee as is the case with soil movement might solve a few of these issues. The national legal system thus is not really suitable for dealing with liability for the long-term storage of CO_2, and the uncertainties might even hinder the development of CCS. The following paragraph will address possible ways to manage these long-term liabilities, which might solve these issues of long-term liability.

5.3.4 Management of long-term liability

Where climate liability and environmental liability are limited to a certain period, civil liability is not. Where compensation for damage to the climate and the environment is meant to prevent, limit or repair damage, compensation in the civil liability system is meant to financially compensate for various kinds of losses. Where in case of climate and environmental liability the operator will face the government or other public authorities, the liabilities in the civil liability system are towards third parties. The civil liability system thus is a necessary addition to the other liabilities. The lack of management of the long-term liabilities might function as an obstacle for market parties to invest and participate in CCS. Therefore, management of these costs and liabilities is important.

This paragraph will explore the possibilities that exist for the management of long-term liabilities. Paragraph 5.4.4.1 explores some of the mechanisms that can be used to manage long-term

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[38] However, difficult and technical causality debates are not that strange in the legal system, and the legal system has developed mechanisms for dealing with uncertain causal relation, such as proportional compensation (Klaassen, 2007, p 23).

liabilities. Since there is already experience with managing these types of liabilities, these experiences will be described in paragraph 5.4.4.2. Paragraph 5.4.4.3 will analyse the different options for the management of long-term liability for CCS.

5.3.4.1 Mechanisms for managing long-term liabilities

Relevant considerations in choosing the instruments for management of long-term liabilities are that one wants to ensure that there will be compensation in case of damages, that the industry will have an incentive to develop a standard of care and that the liability does not function as a obstacle to making CCS economically viable. Liability ensures that there will be compensation, but it does not necessarily force the industry to maintain a high standard of care.[39] And when the companies are not economically strong, it can be questioned if there will be any compensation in case of damages, for instance when the operator has gone bankrupt.[40] Several instruments are available to deal with the long-term nature of the possible damage so that liability does not function as an obstacle and there are enough funds to provide for compensation in the event of damages. Instruments that manage risk and compensation that are found in the literature are: private insurance, liability caps, government indemnification/liability exemption and compensation funds (De Figueiredo, 2007, p 62, Bergkamp 2001, De Figueiredo, Herzog, Joskow, Oye, Reiner, 2007). Each of these instruments will be discussed by shortly describing the function of the instrument and how the instrument affects the parties involved (government, industry, public).

Private insurance

A first instrument to manage liability and to make sure that there will be compensation when needed is private insurance. Liability insurance provides three functions: it has a risk-transferring function (from risk-averse parties to risk-preferring parties), it has a risk-spreading function by combining individual risk into a pool and it has a risk-allocating function by charging premiums to reflect the level of risk posed by the insured (De Figueiredo, 2007, p 62). Environmental liability insurance often functions different than other forms of insurance due to the fact that there is hardly information on the manifestation of risks and it is insurance for future possible unknown risks. The party carrying the risk will have to deal with the financial responsibility for the risk. As we have seen with the strict liability for environmental damage, companies are able to get insurance and insurance companies are willing to take on these risks (Klass, Wilson, 2008).[41] However, insurance might be impossible in cases in which the damage occurs gradually and precise timing is hard to determine, or when causality is hard to prove (Faure, Hartlief, 2002, p. 222). Private insurance shifts the risk between parties in the market, but the government might also take on some of the responsibility. Instead of having the private sector manage the risks by itself, the government could function as a risk bearer. In using the government (with its powers of

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[39] The standard of care in a fault based liability regime is determined by the courts, in a risk-based liability regime, a standard of care is almost irrelevant (Bergkamp 2001, p 212).

[40] The financial security demand of article 19 of the CCS Directive is to guarantee that CCS is carried out by economically strong companies.

[41] Ad Hoc National Resource Damage Group Report, insurance and other financial security instruments and remediation of environmental damages under the EU environmental liability Directive, Brussels 2010.

coercion and taxation) as a risk bearer, some of the possible private market failures can be prevented or corrected (De Figueiredo, 2007, p 64).[42]

Liability cap/exemption

Another way of managing long-term liabilities is by stating a financial liability cap for the operator. The operator would be liable for the amount of the cap, but the damages above the amount are taken on by the government. The cap could be set on a per-incident basis or a per-person-injured basis (De Figueiredo, 2007, p 66). This instrument is also used in the nuclear energy industry. It should be noted that although the liability cap provides for certainty and predictability for the industry, it might undermine the credibility of CCS in the eyes of the public (Klass, Wilson, 2008).

A variation on the liability cap is the liability exemption; this would exempt a party from being liable for a given cause of action or injury. It could mean that the injured parties would be left without compensation, or that the government would take on the liability, thereby indemnifying the operator. An example is a situation in which the companies would be liable for environmental damage, but claims from third parties are taken on by the government, so there will always be compensation available. The personal injuries are then exempted. However, the experience with this shift of the risks from the operator to the government might be that the development of storage sites might be discouraged, since government or local governments are not willing to take on this risk within their borders (De Figueiredo, Herzog, Reiner, 2005). Furthermore, the absence of possible liability could lead to a moral hazard for the operators. This effect could be managed by temporarily limiting the liability exemption.

Compensation fund

A final mechanism is the administrative compensation fund. The industry makes contributions to a fund that compensates possible damages. The types of injuries for which compensation is available are regulated and compensation can be required through different proceedings (court, prescribed situations). The three issues that must be dealt with are: the event to be compensable (to solve the causation issue), the method of financing and the measure of compensation to be awarded to the victims (De Figueiredo, 2007, p 70). In determining the method of financing, the contribution could be determined based on the amount of stored CO_2, or the characteristics of the site. The compensation fund ensures a single entity to be addressed for compensation and provides for a financially viable entity. The costs are predictable for the operators and the liability horizon can be limited. There might be problems when the industry collapses and the fund can no longer be filled and there might be jurisdictional problems in cases of cross border leakage. This is for example the mechanism that is chosen for compensation of damages as a result of soil movement (Guarantee Fund for the Mining Act). In general, compensation funds are used in cases in which the matter is highly specialised and for situations for which insurance coverage is hardly possible (Faure, Hartlief, 2002, p 223).

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[42] Negative effects of the market might be: adverse selection, biases in risk perception, lack of credible commitments, risk externalisation.

5.3.4.2 Experiences with management of long-term liability

Dutch civil law contains an example of management of long-term liability in the liability for waste disposal sites. Implementing such as liability for CCS would mean that a specific risk-based liability rule for underground storage sites is developed. Analogous to the liability for waste disposal sites, this liability would channel liability to a single entity and might be applicable for specific types of damage, such as personal injury and property damage. It would also be possible to exclude certain damages (loss of profit). The risk is channelled to one entity that might look for insurance or set up a fund. Such funds already exist in the Netherlands, for example the fund set up by provincial authorities for closed waste disposal sites, or the Guarantee Fund for the Mining Act. Such a liability regime would provide the victims with an identifiable and financially strong defendant. It would also limit the liability horizon for the operator.

Table 14: Suggestion for a specific CCS liability (based on the example from the Waste legislation)

Civil law liability: suggestion for art 6:177a	
Damage	Personal injuries, damaged property, costs made to prevent damage (also for others), costs made to establish the damage and costs for the procedure, excluding loss of profit or immaterial damages.
Liability horizon	Liable until transfer
Liable persons	Operator, specific fund after the transfer
Type of liability	Risk-based liability
Possible defences	Limited defences based on 6:178

Another example of managing long-term liability is the regime applicable to nuclear energy. The nuclear energy regime is regulated in the Law on Nuclear Energy. All companies that process nuclear material have to dispose of their nuclear waste by a specific company, COVRA, which is owned by the Dutch government. As soon as the activities of the operators with the nuclear material have ended, the government takes over responsibility and liability for the long-term; in essence the government has exempted the operators from liability for the long-term. Companies are liable for the time that they work with the nuclear material; a system of insurance is available. There is a nuclear insurance pool, pool members declare their annual amount and when payments will have to be made, each will pay his share. In the Netherlands, the liability of the operator of a power plant is limited to 340 million euro, the government provides for an additional amount of 1930 million euro and an extra 136 million euro is available through participation in international treaties.

CCS and nuclear energy for now have in common that they face opposition from the general public. Furthermore, both deal with long-term storage of substances, although the possible damages of an incident with nuclear waste are far more extensive than for CCS. However, the comparison shows more differences than similarities. The amount of stored nuclear waste is much smaller than the amount of CO_2 that we need to store. Furthermore, the need to make CCS commercially viable makes it necessary to involve companies and thus have them take on some of the risks. This need is absent in the small scale nuclear energy market.

5.3.4.3 Options for managing long-term liability in CCS

In assessing the different options in managing long-term liabilities, several considerations have to be taken into account. A first decision to be made is whether or not the liability for CCS should fall within the responsibility of the private sector or that it should be shared with the public authorities. For climate liability and environmental liability, the CCS Directive has chosen to share the responsibility (transfer of responsibility and financial contribution). As we have seen above, the liability for health and property lies entirely with the private entities. Should this responsibility be shared, just as is the case with the other liabilities? Reasons for doing so are that the time-line for CCS is incongruous with the lifetime of private entities. Other reasons are that in relying on liability detecting and assigning blame for harm is a matter for court proceedings (which causes uncertainties for companies) and that it might be hard to get the necessary resources for compensation (Klass, Wilson, 2008). As we have seen in our assessment of the existing liability regimes, the endless liability horizons in civil liability might functions as a roadblock for large-scale CCS. Therefore it seems sensible to manage the national liabilities as well. The question is which of the discussed methods is the most sensible for CCS.

Sharing the responsibility for long-term liability can be designed along different variables. The CCS Directive has chosen a *time limit*; a certain amount of years after closure the liability will be transferred. This approach could also be adopted for the civil liabilities. The scientific and legal debate then will focus on what the specific conditions should be before a transfer of the responsibilities is desirable for both the operator and the competent authority. Another variable is sharing the *amount* of damages, by setting a liability cap such as is done for nuclear waste. Discussion then will be on the calculation of the possible amount of compensation to be made for event and the possibility of these events. The discussion thus is on risk assessment. Finally, the responsibility can also be shared based on *channelling of liability*, by creating a fund to be filled by the industry (or partially by the government). The discussion then will be on the events to be compensated, the contribution to be made by each of the participants and the calculations for compensation. In order to further develop the management of long-term liability and to further elaborate these options, a choice has to be made for a specific direction.

Considerations to be taken into account in making this choice are (Bergkamp, 2001, p 231):

- *What objective is pursued?* Deterrence, risk spreading, lowering or stimulating activities or guaranteeing compensation? If the objective is to stimulate the development of CCS, one should provide certainty for the operators and investors. Such certainty is provided through a liability cap or limited liability horizon. If we want the risks to be spread, a fund seems a sensible solution. This is also the case when we want to guarantee that there will always be compensation available for plaintiffs. On the other hand, if we want the polluter to pay, liability as it is seems sensible.
- *Who do we want to make the decision on compensation?* Judges, experts, legislators? If judges are the ones to decide, endless and costly legal disputes are the result, not to mention that standards applied by judges are not necessarily the same, which creates uncertainty for operators. Appointing a specific court court solve this issue. Another issue is the question whether or not we are we willing to accept the risk that polluters will not pay due to the fact that causation cannot be proven? If we want experts to decide, we might get the technically most correct advice, but do we always want this, or are there alternative objectives to meet.

Experts can play a role in insurance or in a compensation fund. The legitimacy of such panels might be a problem. On the other hand, leaving the decision to the legislator in advance almost always creates a static incomprehensible set of rules.

- *How quickly should the instrument adapt itself to change?* If the decisions on compensation are left up to legislation and judges, we have created an instrument that is not likely tot adapt itself to change easily. In court proceedings, recent knowledge might change decisions, but those decisions will often be subject to judicial review, which slows down the process. If a set of conditions is created outside of the legal order, in the form of conditions for compensation by a fund, we can create a far more flexible instrument.

Designing the instrument for managing long-term liabilities cannot be seen separate from the design of the financial contribution to be paid before the transfer of responsibility. Both financial arrangements deal with the question *who should pay for what* with regard to CCS: government or companies.[43] The financial contribution deals with the liabilities and costs based on the Directive; eventual national management of long-term liability deals with the national liabilities towards third parties. A general conclusion of the debate on the division of responsibilities is that the representatives of the work field generally feel that in order to deal with the uncertainties of CCS, governments should take on some of the costs, where in the view of governments, a larger percentage of the costs are for the work field.[44] The outcome of the debate on the financial contribution shapes the possible choices for an instrument to deal with long-term liability on the national level.

Another element that is relevant in weighing the options is that not all costs and liabilities are suitable for insurance. When we analyse possible costs with regard to their suitability for insurance (predictable, limited, logical causation) we find that insurable costs are: remediation costs (during injection and post injection) and minor leakage (including ETS) (during injection and post injection) and premature decommissioning.[45] So in the discussion on who should pay for major events, we should take into account that insurance for major events is not likely to be possible or just too expensive. The advantage of a fund over insurance is that depending on de design of the fund, almost all costs and liabilities can be incorporated in the fund.

The discussion should not only involve who (polluter pays) has to pay what (amount), but might also involve when and how the costs are to be paid (timing). Where the amount is a more ethical and political discussion, the timing is a more economical discussion. In balancing the different options, the above mentioned considerations should be taken into account, as well as the guidelines currently being developed by the Commission. Furthermore, it is always wise to draw upon experience that is already available. As a revision of the legal framework for mining

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[43] Relevant costs and liabilities are: monitoring costs (during injection and post injection), remediation costs (during injection and post injection), minor leakage (including relevant liabilities) (during injection and post injection), major leakage (including relevant liabilities) (during injection and post injection), decommissioning, premature decommissioning. Regular operating costs are the monitoring and remediation costs during injection, as well as decommissioning. Liabilities for minor leakages also seem to fall within the regular operating costs of companies.

[44] 30 June 2010, IEA Regulators Network (webinar on financial security).

[45] Presentation by Philips, 30 June 2010, IEA Regulators Network (webinar on financial security).

activities is planned for 2015, the issue of management of long-term liability might be incorporated in this review.

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6 Appendix: Summary EU CCS Directive

This Annex provides a summary of the main issues covered in the EU CCS Directive (EC, 2009):

Chapter 1 Subject matter and purpose

Art 2) Scope and prohibition
The Directive shall not apply to geological storage of CO_2 undertaken for research, development or testing of new products and processes with a total intended storage below 100 kilotonnes. Furthermore, storage of CO2 in a storage complex extending beyond the frontiers of the EU will not be permitted.

Art 3) Definitions
The article provides definitions of many terms used throughout the Directive.

Chapter 2 Selection of storage sites and exploration permits

Art 4) Selection of storage sites
Member States have been assigned the right not to allow for any storage in parts or in the whole of their territory. If they intend to allow CO_2 storage they are obliged to assess the storage capacity in their country.

Art 5) Exploration permits
- The procedures for the granting of exploration permits must be open to all entities possessing the necessary capacities and permits must be granted or refused on the basis of objective, published and non-discriminatory criteria.
- Exploration permits have to be granted for a limited volume area.
- The holder of an exploration permit has the sole right to explore the potential CO_2 storage complex.

Chapter 3 Storage permits

Art 6) Storage Permits
- Member States shall ensure that there is only one operator for each storage site, and that no conflicting uses are permitted on the site.
- Criteria for the granting of storage permits should be based on objective, published and transparent criteria.
- Priority for the granting of a storage permit for a particular site shall be given to the holder of the exploration permit for that site, under a number of provisions.

Art 7) Application for a storage permit
Applications shall include inter alia;
- Proof of technical competence of the potential operator
- Characterisation of storage site and complex
- Description of measures to prevent significant irregularities
- Proposed monitoring plan
- Proposed corrective measures plan
- Proposed provisional post-closure plan
- Proof that the financial security required will be valid and effective before commencement of CO_2 injection.

Art 8) Conditions for a storage permit
The competent authority shall only issue a storage permit if certain conditions are met. These include the financial soundness of the operator. Furthermore, in the case of more than one storage site in the same hydraulic unit, the potential pressure interactions are such that both sites simultaneously can meet the requirements of the Directive.

Art 9) Contents of a storage permit
Storage permits should contain inter alia:
- Precise location and demarcation of the storage site
- Requirements for storage operation
- Requirement for the composition of the CO2 stream

- The approved monitoring plan and associated requirements
- The requirement to notify the competent authority in case leakages occur
- The conditions for closure and the approved provisional post-closure plan
- Requirement to establish and maintain the financial security

Art 10) Commission review of draft permit
Member states are obliged to make the permit applications and related material available to the Commission. The Commission may issue a non-binding opinion on it; whether it decides to do not, it is required to notify the Member State. The competent authority has to notify the final decision to the Commission and to provide reasons for any deviation from the Commission's opinion.

Art 11) Changes, review, update and withdrawal of a permit
This article states the conditions for changing, review, update and withdrawal of storage permits. These conditions concern mainly the competent authority. The operator has only to inform the competent authority of changes planned in the operation of the storage site.

Chapter 4: Operation, closure and post closure obligations

Art 12) CO_2 stream acceptance criteria and procedure
A CO_2 stream shall consist overwhelmingly of carbon dioxide. A CO_2 stream may contain incidental associated substances from the source, capture or injection process and trace substances added to assist in monitoring and verifying CO_2 migration. Therefore, provisions for limiting concentrations of all incidental and added substances have been set to prevent risks to the storage site, relevant transport infrastructure and more broader, environment or human health. Furthermore, monitoring provisions regarding the CO_2 stream composition have been set; Member States shall ensure that operators carry out a risk assessment of that composition as well as to register quantities and properties of the CO_2 streams delivered and injected.

Art 13) Monitoring
Member States shall ensure that the operator carries out monitoring of the injection facilities, the storage complex, and where appropriate the surrounding environment for different purposes. Purposes include:

- An assessment whether the stored CO2 will be completely and permanently contained
- An update of the assessment of the safety and integrity of the storage complex in the short and long-term.

The monitoring should be based on a monitoring plan designed by the operator on a number of requirements. The plan has to be updated, at least every five years, and should include

- changes in the assessment whether the stored CO2 will be completely and permanently contained
- new scientific knowledge
- improvements in best available technology.

Updated plans have to be re-submitted for approval to the competent authority.

Art 14) Reporting by the operator
The operator has to submit to the competent authority, at least every year:

- All monitoring results, including information on the monitoring technology employed
- The quantities and properties of the CO2 streams delivered and injected
- Proof of the putting in place and maintenance of the financial security
- Any other information the competent authority considers relevant for the purposes of assessing compliance with storage permit conditions and increasing the knowledge of CO_2 behaviour in the storage site.

Art 15) Inspections
Competent authorities must organise a system of routine and non-routine inspections of all storage complexes. Conditions for routine and non-routine inspections are elaborated upon. For instance, routine inspections shall be carried out at least once a year until three years after closure and every five years until transfer of responsibility to the competent authority has occurred. Following each inspection, the competent authority has to prepare a report on the results of the inspection, which has

to be communicated to the operator concerned and has to be made publicly available within two months of the inspection.

Art 16) Measure in case of leakages or significant irregularities
Member States shall ensure that in the event of leakages or significant irregularities, the operator immediately notifies the competent authority, and takes the necessary corrective measures. The competent authority may at any time require the operator to take the necessary corrective measures. These may be additional to or different from those laid out in the corrective measures plan. The competent authority may also at any time take corrective measures itself.

If the operator fails to take the necessary corrective measures, the competent authority shall take the necessary corrective measures itself. The competent authority shall recover the associated costs incurred from the operator, including by drawing on the financial security.

Art 17) Closure and post closure obligations
A storage site shall be closed:
a) if the relevant conditions stated in the permit have been met;
b) at the substantiated request of the operator, after authorisation of the competent authority; or
c) if the competent authority so decides after the withdrawal of a storage permit.

If a storage site has been closed pursuant to points (a) or (b), all measures, obligations and actions shall be the responsibility of the operator, while in case a storage site has been closed pursuant to point (c), responsibility for all measures, obligations and actions rests with the competent authority.

Art 18) Transfer of responsibility
Where a storage site has been closed according to points (a) or (b) of Article 17, transfer of responsibility for the site to the competent authority is dependent on a number of conditions;
a) all available evidence indicates that the stored CO_2 will be completely and permanently contained;
b) a minimum period, to be determined by the competent authority has elapsed. This minimum period shall be no shorter than 20 years, unless the competent authority is convinced that the criterion referred to in point (a) is complied with before the end of that period;
c) the financial obligations referred to in Article 20 have been fulfilled;
d) the site has been sealed and the injection facilities have been removed.

These conditions are further elaborated upon in the Article. Among others, the Commission may adopt guidelines on the assessment of technical criteria relevant to the determination of the minimum periods.
A draft decision of the approval of the transfer of responsibility has to be issued by the competent authority, where the Commission may issue a non-binding opinion. The final decision of the authority shall be notified to both the operator and the Commission.

Art 19) Financial security
The potential operator has to present proof that financial security can be established as part of his application for a storage permit. The financial security has to cover all obligations under the permit issued and effective before commencement of injection. The financial security shall be periodically adjusted to take account of changes to the assessed risk of leakage and the estimated costs of all obligations arising under the permit.

Art 20) Financial mechanism
A financial mechanism has been constructed to ensure that the operator makes a financial contribution available to the competent authority before the transfer of responsibility has taken place. The financial contribution may be used to cover the costs borne by the competent authority after the transfer of responsibility to ensure that the CO_2 is completely and permanently contained in geological storage sites after the transfer of responsibility. The contribution from the operator shall cover at least the anticipated cost of monitoring for a period of 30 years.

Chapter 5 Third Party Access

Art 21) Access to transport networks and storage site

Potential users should be able to obtain access to CO_2 transport networks and storage sites. National access arrangements should guarantee provision of access in a transparent and non-discriminatory manner. Transport network operators and operators of storage sites are allowed to refuse access because of lack of capacity. However, at the same time those operators are obliged to make any necessary enhancements when they are either economic viable or the potential customer is willing to pay for them.

Art 22) Dispute settlements

Disputes relating to access to transport network and to storage sites should be settled quickly by national dispute settlement arrangements that have to be put in place. In case of cross-border disputes, dispute settlement arrangements of the country having jurisdiction over the transport network or the storage site to which access has been refused, should be applied. In case the dispute concerns the transport networks or storage sites of two countries or more, the Member States concerned shall consult in order to apply the Directive consistently.

Chapter 6 General provisions

Art 23) Competent Authority

Member States have to establish or designate the competent authority responsible for fulfilling the duties of the Directive.

Art 24) Transboundary cooperation

In case of transboundary transport or storage, the competent authorities of both Member States have to meet jointly the duties of the Directive.

Art 25) Registers

The competent authority shall establish and maintain a register of the storage permits granted and a permanent register of all closed storage sites and surrounding storage complexes.

Art 26) Information to the public

Member States shall make available to the public environmental information relating to the geological storage of CO_2 in accordance with Community legislation.

Art 27) Reporting by Member States

Every three years the Member States have to submit to the Commission a report on the implementation of this Directive. The report has to be drawn up on the basis of a questionnaire or outline drafted by the Commission. The first report has to be sent to the Commission by 30 June 2011.

Art 28) Penalties

Infringements of the national provisions pursuant to this Directive should be penalized by Member States. Penalties should be effective, proportionate and dissuasive.

7 Appendix: Existing pipelines and incidents

Table 15: Existing long-distance CO_2 pipelines in the USA

Pipeline	Location	Operator	Capacity [Mt CO_2/a]	Length [km]	Year finished
Cortez	Colorado to Texas	Kinder Morgan	17.5	808	1984
Sheep Mountain	Colorado to Texas	Occidental	8.6	660	-
Bravo	Colorado to Texas	Occidental, Kinder Morgan, Crosstimbers	6.6	349	1984
Canyon Reef Carriers	Texas	Kinder Morgan	4.7	224	1972
Val Verdes	Texas	Petrosource	2.3	130	1998
Weyburn	North Dakota, US, to Canada	North Dakota Gasification Co.	4.5	327	2000
North East Jackson Dome	Mississippi	Denbury	10.4	293	1986
Free State	Mississippi	Denbury	6.1	138	2005
Delta	Mississippi	Denbury	7.0	50	2008
Cranfield	Mississippi to Louisiana	Denbury	2.6	82	1963
Total			70.4	3,060	

Source: Duncan et al, 2008.

Table 16: Detailed report on CO_2 pipeline accidents USA between 1986 and 2008

Date of incident	Description	Cause	Location	Suspected Responsible Party	Medium Affected
02/27/1994	Hazardous Liquid Pipeline / Gasket Failure	Equipment Failure	Texas	Inron Liquids Pipeline Co.	Air
04/15/1994	8-Inch Pipeline / External Corrosion	Equipment Failure	Oklahoma	Arco Permian	Air
06/15/1998	12-Inch CO_2 pipeline / DOT Regulated / semi-truck ran into a structure	Equipment Failure	Oklahoma	Tranpectco	Air
11/19/2000	Strong odour reported and confirmed release from pipeline 12 inches below ground	Equipment Failure	North Dakota	Dakota Gasification Co.	Air
01/13/2001	8-Inch transport line discovered leaking due to unknown cause	Unknown	North Dakota	Dakota Gasification Co.	Air
02/25/2001	14-Inch distribution line leaked CO_2 and H_2S	Equipment Failure	Texas	Borger CO_2 Pipeline LLC	Air
03/07/2002	Third-party company contracted a backhoe and hit underground CO_2 pipeline	Operator Error	Oklahoma		Air
02/25/2003	8-Inch transmission pipeline failed due to corrosion	Equipment Failure	Texas	Chaparral Energy	Air
11/14/2003	Release of CO_2 due to valve failure	Equipment Failure	Mississippi	Denbury Resources	Air
10/14/2004	Leak found on CRC pipeline releasing CO_2	Under investigation	Texas	Kinder Morgan CO2 Co.	Land
09/22/2006	Magnetic flux leakage (MFL) pig struck in pipeline	Equipment Failure	North Dakota	Dakota Gasification Co.	Air
01/09/2007	CO_2 released from a 20-inch underground pipeline	Unknown	Mississippi	Denbury Onshore LLC	Air
03/15/2007	Ice mound formed on a line used for liquid CO_2 injection	Equipment Failure	Texas	Chaparral Energy	Other

8 Appendix: Save site selection in the EU Storage Directive

On 23 January 2008 the European Commission issued a proposal for a Directive establishing the legal framework for “environmentally safe capture and geological storage of carbon dioxide (CO_2) in the EU” [www.ec.europe.eu]. In December 2008 the European Parliament decided on finalisation of the proposal. On 23 April 2009 the EU Directive was signed. The EU Storage Directive covers the main phases of the site selection phase of the CO_2 storage cycle: the screening and the site investigation phase. According to the Storage Directive the suitability of a potential storage site must be demonstrated as a result of characterisation and assessment of the storage site as well as the surrounding area. The criteria specified in the Directive are presented in Table 17.

Table 17: EU Storage Directive criteria for selection, characterisation and assessment of the storage site as well as the surrounding area [European Commission, 2009].

		EU Storage Directive
Type and Source		European Directive published in the Official Journal of the European Union
Scope		Territory of the Member States, their exclusive economic zones on their continental shelves
Project Scale		Does not apply to research projects, but do apply to demo projects with a total intended storage of 100 kilo tonnes or more. Covers the screening to post-closure stages.
Comments		Adopted on April 23rd, 2009. Published on June 5th, 2009. Entry into force on June 25th, 2009.
Storage Site	Screening	Member States retain the right to determine the areas from which storage sites may be selected. Member States which intend to allow CCS in their territory should undertake an assessment of the storage capacity available within their territory.
	Site Investigation permit	Named “Exploration permits” Requirement determined by Member States (MSs), Open to all entities possessing the necessary capacities, Permits granted on the basis of objective, published and non-discriminatory criteria, Granted for a limited volume area, for a limited time, Holders have the sole right to explore the potential storage complex. If no activities carried out, MSs ensure that the permit is withdrawn.
	Site Investigation	Data Collection to construct a volumetric and static three-dimensional earth model: • Geology and geophysics, • Hydrogeology, • Reservoir engineering, • Geochemistry, • Geomechanics, • Seismicity, • Presence and condition of natural and man-made pathways with could be leakage pathways, Domains surrounding the storage complex that may be affected by the storage site, • Population distribution in the region, • Proximity of valuable natural resources, • Possible interactions with other activities, • Proximity to the potential CO_2 sources.
		Computerised simulation of the storage complex

		Static geological earth model to characterise the complex in terms of: • geological structure of the physical trap, • geomechanical, geochemical and flow properties of the reservoir overburden and surrounding formations, • fracture system characterisation and presence of any man-made pathways, • areal and vertical extent of the storage complex, • pore space volume, • baseline fluid distribution, • any other relevant characteristics, • uncertainties assessed (range of scenarios and confidence limits). Security, sensitivity and hazard characterisation Factors to consider: • possible injection rates and CO_2 properties, • efficacy of coupled process modelling, • reactive processes, • reservoir simulator used, • short and long-term simulations. • Security characterisation based on dynamic modelling (variety of time-step simulations of CO_2 injection) to provide insight to: • pressure and temperature of the storage formation vs injection rate and accumulative injection amount over time, • areal and vertical extent of CO_2 vs. time, • nature of CO_2 flow in the reservoir, including phase behaviour, • CO_2 trapping mechanisms and rates, • secondary containment systems in the overall storage complex, • storage capacity and pressure gradients in the storage site, • risk of fracturing the storage formation and caprock, • risk of CO_2 entry into the caprock, • risk of leakage from the storage site, • rate of migration, • fracture sealing rates, • changes in formation fluid chemistry and subsequent reactions and inclusion of reactive modelling to assess effects, • displacement of formation fluids, • increased seismicity and elevation at surface level. Hazard characterisation undertaken to characterise the potential for leakage. Consider: • potential leakage pathways, • potential magnitude of leakage events for identified leakage pathways, • critical parameters affecting potential leakage, • secondary effects of storage of CO_2 including displaced formation fluids and new substances created by the storing of CO_2, • any other factors which could pose a hazard to human health or the environment.
		Geological formation selected as a storage site, if under the proposed conditions of use there is no significant risk for leakage, and if no significant environment or health risks exist

9 Appendix: London Convention (1972) and Protocol (1996)

One of the oldest global conventions is the London Convention which concerns the dumping of waste in marine waters. In 1996 the London Protocol was agreed on to modernise the 1972 Convention, with the purpose of eventually substituting it. The London Protocol entered into force in March 2006 and replaces the London Convention in the contracting states.

In 2006 the convention was amendment to allow captured CO_2 to be stored into sub-seabed geological formations under certain restrictions. The amendment forms a basis in international law to regulate storage of CO_2 in geological reservoirs under the seabed. The Commission of the London Convention stresses that carbon capture and storage is one option as part of a package of possible measures reducing CO_2 emissions. The amendment contains the following restriction [www.imo.org]:

- disposal is into a sub-seabed geological formation;
- disposal consists overwhelmingly of CO_2 (but may contain incidental associated substances derived from the source material and the capture and sequestration processes used);
- no waste is added for the purpose of its disposal.

National authorities are presumed to be responsible for the correct implementation of the Protocol in national regulation and the continuation of safe and permanent containment of CO_2 in sub-seabed geological formations in order to avoid significant adverse effects to the surrounding environment. 37 countries are Parties to the London Protocol in 2009. In Figure 6 the Parties of the London Convention and Protocol are presented in Yellow and Green.

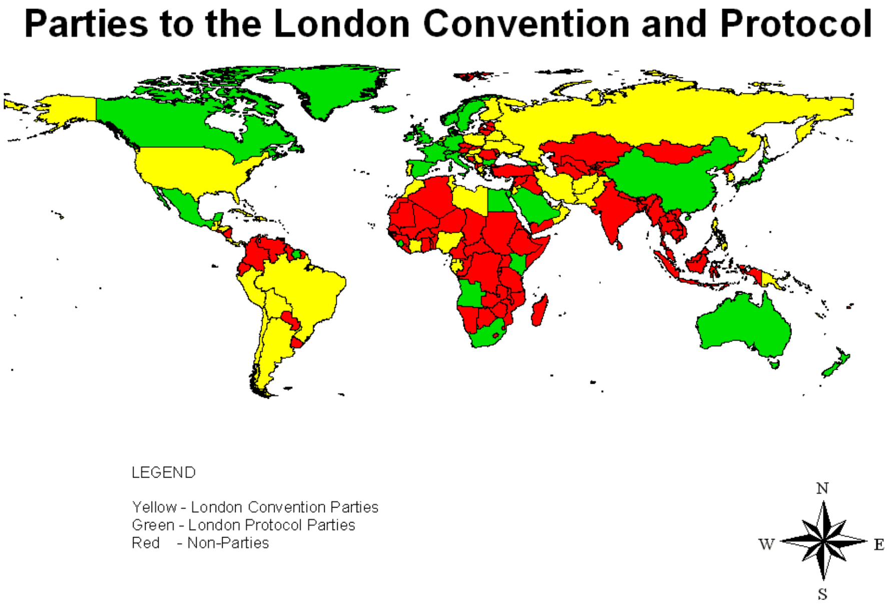

Figure 6 **Parties of the London Convention and Protocol**

The criteria concerning selection of storage site specified in the London Protocol and London Convention are respectively presented in Table 18 and Table 19.

Table 18 London Protocol - Risk assessment and management framework concerning site selection for CO2 sequestration in sub-seabed geological structures (Synthesis of London Protocol (2006b))

Reference		Risk assessment and management framework for CO_2 sequestration in sub-seabed geological structures. LC/SG-CO2 1/7, annex 3.
Type and Source		Adopted by concensus in November 2006. http://www.imo.org/includes/blastDataOnly.asp/data_id%3D19064/CO2SEQUESTRATIONRAMF2006.doc
Scope		• Deals with off-shore storage only, at depths comparable to those in continental shelf and upper continental slope environments. • Aims at retaining the stored CO_2 permanently in geological strata at least several hundred meters below the layer of unconsolidated sediments on the seabed. • Type of storage reservoirs and trapping mechanisms : o oil and gas reservoirs and saline aquifers (in this last case, importance of verifying the integrity of the sealing rock), o other possible geological structures for CO_2 storage, but not explicitly considered. • Trapping mechanisms include pressure increase, buoyancy, pore trapping, dissolution of CO_2 and mineral trapping.
Project Scale		Figure 6.
Comments		Industrial sources of CO_2 considered. CO_2 injection stream may contain other substances derived from the source material, but not intentionally added.
Storage Site	Screening	
	Site Investigation permit	
	Site Investigation	Site selection and characterisation : *Key goals* : • Assess how much CO2 can be stored at a potential storage site, • Demonstrate that the site is capable of meeting storage performance criteria, • Establish a baseline for the management and monitoring of the CO2 injection and storage. *Requires* : • Collection of a wide variety of geological and environmental data, • Integration of these data into geological models intended to simulate and predict site performance. • Important issues : o storage capacity and injectivity of the formation, o storage integrity, o suitability of the vicinity and surrounding area, o potential migration and leakage pathways over time and potential effects of leakage of CO2. • Characterisation in terms of geology, o characterisation of the reservoir, o characterisation of the cap - rock, o characterisation of the geological stability, o characterisation of possible leakagepath, o characterisation of trapping mechanisms. o hydrogeology,

		○ geochemistry, ○ geomechanics, ○ biology. ○ analyses based on well core sampling, acquisition of well logs, seismic surveys, data available from existing wells or fields in neighbouring locations. Information facilitating this phase : • Location, geographical and geological factors (water depth, structure depth, nearness of population centres, regional geology, hydrogeology, stratigraphy and structure, regional tectonics and seismicity, faults and fractures), • Historical uses of the area (man made structures : active and abandoned wells, well integrity with respect to CO2), • Existence of amenities, biological features and uses of the sea, • Reservoir/seal evaluation (geological interpretation, stratigraphic interpretations and well - log cross sections of the reservoir intervals, reservoir/seal heterogeneity, temperature, pressure, fluid composition; Geophysical mapping – 3D maps of potential migration pathways, structure and thickness of reservoirs and cap rocks ; Petrophysics – permeability, relative permeability, porosity, capillary pressure, mineralogy ; hydrodynamics – displacement of formation water - ; Sealing capacity of caprocks – capillary entry pressure - ; Geomechanics and geochemistry – CO2 water - rock interaction, stress, stiffness and strength ; Reservoir simulation – shortterm behaviour : reservoir response, longterm behaviour: reservoir containment) • Marine environment characterisation (ocean current and sea floor topography in the region, physical and chemical characteristics of sediments and overlying waters – pH, benthic fluxes of CO2, nutrients and other substances ; biological communities and biological resources – composition, structure, dynamics ; areas of special scientific or biological importance – sanctuaries, fishing areas) • Economic factors : economic feasibility, impact on other resources such as oil and gas. typically include a reservoir simulation to assess a potential storage site (three - dimentional geological model). ○ consider proximity of the site to sensitive or endangered habitats and species, ○ consider other possible use of the area. This phase provide baseline information for latter stages, such as monitoring strategy and evaluation of the monitoring results.
		Exposure assessment: *Goals :* ○ inform the characterisation of effects, ○ provide an input into the wider risk characterisation and risk migration. *Chemical and physical characterisation of the* CO_2 *stream, including other substances* ○ identify and quantify other substances in the CO_2 stream and identify uncertainties, ○ verify the consistency with the primary purpose of mitigating greenhouse gas emissions.

		Exposure processes and pathways from transport and injection equipment o process and pathways for leakage of CO_2 (from the capture site, pipeline transportation and injection facilities) addressed and uncertainties identified, o plans to deal with the excess CO_2 if the injection well(s) need to be shut in, o proper maintenance of site facilities and injection wells, o materials designed to anticipate peak volume, pressure and temperature. *Exposure processes and pathways from geological storage reservoirs* o assess processes and pathways for migration of CO_2 from geological storage reservoirs and leakage to the marine environment (both long-term and short-term), o processes include that free gaseous CO_2 and supercritical CO_2 tend to rise towards the seabed under typical geological conditions, o potential pathways : pore system in low-permeability cap rocks, cap rock absent, faults and fractures in the cap rock, inadequately completed and/or abandoned wells. *Water/Biosphere – exposure processes and pathways* o assess transport, mixing processes and rates of leakage. *Likelihood of exposure* o assess the probabilities of the exposure processes. *Scale of exposure* o assess the amount of CO_2 and additional substances being mobilised, the scale of spatial and temporal fluxes.
		Effects assessment *Output* : concise statement of the expected consequences of CS-SSGS. *Goals* : o provide input for deciding whether to approve or reject the proposed waste management option, o inform site selection, o provide input for monitoring to verify the hypothesis and management measures, o provide input for defining environmental monitoring requirements, o Demonstrate that "no impact on human health, the marine environment and other legitimate uses of the sea will occur". *Sensitivity of species, communities, habitats and processes* : o *Effects to consider*: those resulting from the increase of CO_2 concentration and other contaminants in the CO_2 stream in the ambient water and sediments. o *Receptors to be considered:* the environment, potential effects of human health, marine resources, amenities and other legitimate uses of the sea. o *Parameters to consider* : magnitude and rate of release, chemical buffer capacities of the water body, transport and dispersion processes, potential substances of concern (Action List under Annex 2 to the Protocol), displacement of saline water, information on Assessment of Potential Effects in Chapter 7 of the Generic Guidelines. o *Temporal and spatial issues* : total amount of CO_2 with which the ecosystem could come into contact, spatial extent of the waters with increased CO_2 content and decreased pH, prevailing environmental conditions at the ocean bottom, resilience of marine ecosystems *Uncertainties and data gaps:* existing data mainly limited to deep-sea situations, effects of ocean acidification due to increased atmospheric CO_2 concentrations. o *Define*: effects at the level of individual species and the ecosystem, performance of field studies of ecosystem consequences, studies long in duration and large in scale. o *Recommendations* : use increasing CO_2 concentrations and not acids to simulate

		the pH effects, include the effect on vulnerable life stages for a range of representative species found at the site,consider the effects of CO_2 on physiological and ecological processes, including abundance, biodiversity, and biological/geological/chemical cycles, use ecosystem models where available and validated, determine a quantitative relation between exposure concentrations and the related effects, include receptors for which sensitivity is not quantifiable in a monitoring programme.
		Risk characterisation *Output :* likelihood and severity of impacts on the marine environment. *Goals :* establish relationships between stressors, effects, and ecological entities, provide an overall assessment of the potential hazards associated with an activity. *Steps :* o Estimate the risk posed to the receptors and assess endpoints identified in the problem formulation. o Describe the risk estimate in the context of the significance of any adverse effects and the lines of o evidence supporting likelihood. o Identify and summarise the uncertainties, assumptions, and qualifiers in the risk assessment. o Report the conclusions. *Based on* : o site-specific considerations of the potential exposure pathways, o probabilities of leakage, o effects on the marine environment, human health and other legitimate uses of the sea, o important to define nature, temporal and spatial scales and duration of expected impacts. *Recommendations :* o Characterise the risks at different stages of the project: during the injection phase, consider buoyant behaviour of CO_2, pressure build-up in the reservoir, quality of the seal and well completion. Over longer term, consider any change in the integrity of the seal and of the plugs in the abandoned wells, effects of CO_2 dissolution and mineralisation, o use models or other analytical tools to determine potential spatial extent of the impacts, consider injection volumes, geological characteristics of the storage reservoir, o update the risk characterisation based on the collection of new data. *Methods :* o identify risks and underlying mechanisms, o build scenarios describing possible future evolution or state of the site, o develop dedicated models for the critical scenarios, o apply the models in the assessment proper. o use probabilistic or deterministic models (in this last case, use a conservative approach). *Requirements :* o Comprehensive evaluation, o Determination of “where” and “when” the impacts can be expected, o Consequences described in terms of affected habitats, processes, species, communities and uses, o Strong interactions between the risk characterisation, the monitoring programme, and the management measures,

		○ Identification of sources and consequences of uncertainties. Uncertainties and data gaps: *Origins* : limitations to the static geological model, the predictive models and environmental effects assessment. *Research needs* : ○ additional knowledge of the long-term behaviour and impact of CO_2 on reservoir fluids and rocks, ○ long-term integrity of wells, ○ effects of CO_2 leakage on marine ecosystems, ○ potential for displaced brines and the effects, ○ fate of other substances in the CO_2 stream and their effects.

Table 19: London Convention – Final draft specific guidelines for the assessment of the carbon dioxide streams for disposal into sub-seabed geological formations (Synthesis of London Convention (2007)), especially concerning site selection

Reference		Final draft specific guidelines for the assessment of carbon dioxide streams for disposal into sub - seabed geological formations.
Type and Source		Adopted at the 30th session of the London Convention Scientific Group, Validated by the Scientific Group in June 2007, Adopted by the contracted parties in November 2007. http://www.nrcan.gc.ca/es/etb/cetc/combustion/co2network/pdfs/g8_london_protocol_finaldraft.pdf
Scope		Storage in an offshore geological formation
Project Scale		See Figure 8
Comments		CO_2 stream consists of: CO_2 and incidental associated substances derived from the source material and the capture and sequestration processes. CO_2 stream must consist overwhelmingly of carbon dioxide.
Storage Site	Screening	Action List: provides a screening mechanism for determining whether a material is considered acceptable for dumping. For carbon dioxide streams, Action List used to assess acceptability for disposal into sub-seabed geological formations. Acceptable concentrations of incidental associated substances related to their potential impacts on the integrity of the storage sites and relevant transport infrastructure and the risk they may pose to human health and the marine environment.
	Site Investigation permit	
	Site Investigation	- Proper characterisation of the carbon dioxide stream, - Specific characterisation of the carbon dioxide stream, including incidental associated substances (origin, amount, form and composition, chemical and physical properties, potential for interaction among stream components, toxicity, persistence, potential for bio-accumulation).

		Site selection and characterisation:
		Information required :
		- physical, chemical and biological characteristics of the water-column and the sea-bed,
		- location of amenities, values and other uses of the sea in the area under consideration,
		- assessment of the constituent fluxes associated with dumping in relation to existing fluxes of substances in the marine environment,
		- economic and operational feasibility.
		
		Characterisation of the sub - seabed geological formation
		- Information required : geological assessment :
		    - water depth and injection and storage depth,
		    - storage capacity, injectivity and permeability of the geological formation,
		    - long-term storage integrity of the geological formation,
		    - surrounding geology, including the tectonic setting,
		    - potential migration and leakage pathways over time and potential effects to the marine environment of leakage of CO_2,
		    - potential interactions of the injected carbon dioxide with the geological formation and the impacts on the relevant infrastructures and the surrounding geology, including potential mobilisation of hazardous substances,
		    - possibilities for monitoring,
		    - mitigation and remediation possibilities,
		    - economic and operational feasibility.
		- Data to establish feasibility of CO_2 injection and provide evidence of the integrity of the site.
		- Capacity and injectivity of the sub-seabed geological formation.
		
		Characterisation of the marine area under consideration
		- location of amenities, values and other uses of the sea, injection and storage site, transport infrastructure where relevant, surrounding potential affected area (physical, hydrological, hydrdynamical, chemical and biological characteristics),
		- some of the important amenities :
		    ○ coastal and marine areas of environmental, scientific, cultural or historical importance,
		    ○ fishing and mariculture areas,
		    ○ spawning, nursery and recruitment areas,
		    ○ migration routes,
		    ○ seasonal and critical habitats,
		    ○ shipping lanes,
		    ○ military exclusion zones,
		    ○ engineering uses of the seafloor (mining, undersea cables, desalination or energy conversion sites,…).
		
		Evaluation of potential exposure
		- potential exposure pathways,
		- probabilities of leakage and associated effects of the CO_2 stream.
		    Potential migration or leakage pathways include : injection well, other abandoned or active wells in the same geological formation, areas where permeable rock reaches the surface of the seabed, transmissive fractures, the pore system in low-permeability cap rocks, areas where the cap rock is locally absent, lateral migration along the storage formation.

		Assessment of potential effects: - Address risks posed by the leak from the carbon dioxide stream sequestration process, - Evaluation of potential effects - Main effects: o result from the dissolution of carbon dioxide in the overlying water and sediments o depend on the magnitude and rate of release, the chemical buffering capacities, the transport and dispersion processes. o the extent of adverse effects depends on the level of exposure, which in turn depends on the physical, chemical and biological processes that control the transport, behaviour, fate and distribution of a substance. - Attention should be given to sensitive ecosystems or species, sensitive areas and habitats, migratory species and marketable resources. - Assessment should be comprehensive: integrate information on characteristics of the carbon dioxide stream, conditions at the proposed sub-seabed geological formation, injection operations and proposed disposal techniques, potential effects on human health, living resources, amenities and other legitimate uses of the sea. **Risk assessment** - described in terms of the likelihood of exposure, - take into account the capacity to intervene or mitigate in the event of leakage, - when evaluating exposures and effects from incidental associated substances and substances mobilised as a result of the disposal of the CO_2 stream, consider : o the magnitude to which the release increases the concentration of the substance in seawater, sediments or biota, o the degree to which the substance can produce adverse effects on the marine environment or human health. - Consider characterisation of the risk at different stages of the project, - Compare the risk associated with this disposal option to other options. **Impact hypothesis** - Correspond to the expected consequences of disposal. - Used to approve or reject the proposed disposal option and to define environmental monitoring requirements. - Key elements : o Characterisation of the CO_2 stream, o Conditions at the proposed storage site, o Preventive and/or mitigating measures, o Injection rates and techniques, o Potential release rates and exposure pathways, o Potential impacts of amenities, sensitive areas, habitat, migratory patterns, biological communities and marketability of resources and other legitimate uses of the seas, o Nature, temporal and spatial scales and duration of expected impacts. - In case of multiple storage projects, consider the potential cumulative effects of such operations, - Assessment should conclude with a statement supporting a decision to issue or refuse a permit for disposal, - Monitoring programmes required to test the impact hypothesis.

10 Appendix: OSPAR Convention

The OSPAR Convention applies to waste disposal and other activities in geological reservoirs under the seabed. The OSPAR Commission amended the Convention in 2007 to allow for environmentally safe storage of CO_2 in the Northeast Atlantic and at the same time excluding the injection of CO_2 in the water column and the disposal onto the seabed.

The OSPAR convention concerns the Northeast Atlantic. It is seen as one of the most comprehensive and strict legal frameworks in place for the protection of the marine environment. The Commission of the OSPAR Convention stresses that carbon capture and storage is one option as part of a package of possible measures reducing CO_2 emissions [www.iea.org / www.OSPAR.org].

The OSPAR Convention (2007) was ratified by all the neighbouring countries of the North‐Eastern Atlantic Ocean: Germany, Belgium, Denmark, Spain, France, Ireland, Island, Norway, the Netherlands, Portugal, Great‐Britain and Sweden, as well as Finland, Switzerland, and the European Union.

The criteria concerning selection of storage site specified in the OSPAR Guidelines are presented in Table 20.

Table 20: OSPAR guidelines for Risk Assessment and Management of Storage of CO2 Streams in Geological Formation (OSPAR, 2007)

Reference	**OSPAR guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological. Formation. Reference Number: 2007‐12**
Type and Source	International Convention. Adopted by the contracting parties in June 2007. http://www.ospar.org/v_ospar/strategy.asp?v0=1&lang=1
Scope	Focus on the process of CO_2 injection and post-injection risks of leakage. Storage in geological formation underlying waters deeper than 500 meters.
Project Scale	
Comments	Ultimate objective: ensure permanent containment of CO_2 streams. CO_2 stream includes CO_2 and incidental associated substances derived from the source material and the capture, transport and storage processes used (source and process derived substances; and added substances). CO_2 sources considered : those of industrial activities releasing large quantities of CO_2 to the atmosphere.

Storage Site	Screening	Initiator of a project should: o assess the suitability of a potential injection-site for permanent containment of CO_2 streams and identify and characterise the necessary measures for hazard reduction; o characterise the risks to the marine environment from the storage of CO_2 streams in geological formations on a site-specific basis; and o collect the necessary information (including baseline data for monitoring) and develop a strategy o to address uncertainties and manage and minimise risks. **Problem formulation** o Scoping of a risk assessment, o Major issues to be addressed : • Suitability of deep geological formations to retain the CO_2 streams permanently, • Nature of the overburden, • Potential mobilisation of substances by CO_2 streams directly or indirectly in the formation and overburden, • Characteristics of the marine environment above and around the storage site, • Need for records associated with the authorisation and licensing process, together with monitoring data, to be maintained for much longer periods than those associated with other authorised practices and most other human activities. **Potential migration or leakage of CO2 streams into the marine environment** Two distinct considerations: o Potential leakage during the operational phase of storage of CO_2 streams in geological formations, o Migration and leakage of CO_2 streams from the geological formation following the injection process. **Potential leakage during injection** Result from : o seal failure or disruption of the means of emplacement of the CO_2 stream in the geological formation, o capped wells locations, o leakage through cap rock. **Potential post-injection leaks** o similar to the operational risks.
	Site Investigation permit	

		Site selection and characterisation Key objectives: o assess how much CO_2 can be stored at a prospective storage site (important parameters: volume, porosity, permeability), o demonstrate that the site characteristics are consistent with expectations of long-term storage and protection of the marine environment and future uses of the maritime area; o establish a baseline for the management and monitoring of the injection and storage of CO_2 streams. Types of storage considered : o oil and gas reservoirs o leakage through cap rock considered unlikely (if not damaged during oil and gas operations), o good knowledge of the geology and sealing potential, o additional information may be needed to know the behaviour of a CO2 stream in the formation. o saline aquifers o verify integrity of the cap rock. Trapping mechanisms considered: o structural and stratigraphic trapping, o residual and solubility trapping, o mineral trapping, o Pore trapping. Important issues: o the storage capacity and injectivity of the formation; o the long-term storage integrity; o the technical and environmental suitability of the vicinity and surrounding area; o potential migration and leakage pathways over time and potential effects of leakage of CO_2 streams; and o possibilities for monitoring, remediation and/or mitigation. Consider: o proximity of the site to sensitive or endangered habitats and species, o other uses of the area, o possible lateral migration through porous and permeable layers. Information sources: o sampling of well cores, o acquisition of well logs, o seismic and biological surveys, o data available from existing wells or fields in neighbouring locations.

Parameters to include in the process

Characterisation of the injected CO_2 stream:
- Type and properties of other substances,
- Concentrations of other substances.

Location and geographical factors
- Water depth, formation depth,
- Human health and safety.

Existence of amenities, biological features and legitimate uses of the maritime area: areas of special ecological, economical or scientific importance, e.g.:
- European marine sites,
- OSPAR MPAs,
- Sanctuaries,
- (Sensitive) species, communities or habitats,
- Breeding areas,
- Potable or irrigation water resources,
- Fishing areas.

Regional geological setting
- Regional geology, hydrogeology, hydrology, stratigraphy and structure,
- Regional tectonics and seismicity,
- Faults and fractures.

Historical uses of the area
- Man-made structures, including:
  - Integrity of active and abandoned wells with respect to CO2 that are likely to be affected by the injection process
    - Proximity to other wells (hydrocarbon producers, former or present) or fields,
    - Proximity to potable, irrigation or industrial water producing wells,
    - Proximity to other injection wells,
    - Age, depth and condition of the wells,
    - Geometry of plugs and casing and composition of plugs of abandoned wells,
- Conversion of existing well for injection: information is needed on well age, its construction details, and its history.

Reservoir/seal evaluation
- Geological interpretation
    - Stratigraphic interpretations and well-log cross sections of the reservoir intervals,
    - Reservoir/seal heterogeneity,
    - Temperature, pressure, fluid characteristics (salinity).
- Geophysical mapping
    - 3-D maps of potential migration pathways (faults),
    - Structure and thickness of formations and cap rocks.
- Petrophysics
    - Permeability, relative permeability (injectivity),
    - Porosity,
    - Capillary pressure,
    - Mineralogy.
- Hydrodynamics
    - Displacement of formation water,
    - Vertical hydraulic gradient.
- Sealing capacity of cap rocks
    - Seal thickness,
    - Capillary entry pressure.

- Faults
o Location, orientation and properties of faults or fractures that are likely to intersect the formation.

- Geomechanics and geochemistry
o CO_2 stream – water – rock interaction

		o Faults • Location, orientation and properties of faults or fractures that are likely to intersect the formation. o Geomechanics and geochemistry • CO_2 stream – water – rock interaction, • Stress, stiffness and strength, • Potential of the injected fluid to cause plugging of the formation, • Compatibility with injected formation chemistry, • In-situ stress profile in the various layers, Other components in the input-stream o Reservoir simulations • Short-term behaviour: formation response (pressure changes for a given injection rate), • Long-term behaviour: formation containment, • Sufficient capacity of the formation for planned CO_2 storage. o Data quality • History, current status and age of information available on the geological formation. Marine environment characterisation o Ocean current and see floor topography in the region, o Physical, chemical and biological characteristics of seabed, sediments and overlying waters: • Natural fluxes of CO_2 in the seabed and across the seabed surface, • Chemical characteristics of the seawater, • Nutrients and other substances (potential contaminants/pollutants), • Biological communities and biological resources : composition, structure, dynamic. o Economic/regulatory factors o Economic feasibility, o Impact on other sub - seabed resources such as oil and gas extraction and other natural gas/CO2 storage sites, o Regulatory framework, o Applicable regulations, codes and standards, and regulatory restrictions and restraints.

		Exposure assessment Provides: ○ the characterisation of potential effects, ○ an input into the wider risk characterisation and risk mitigation processes. **Chemical and physical characterisation of the CO2 stream, including incidental associated substances** ○ no substances can be deliberately added to the CO2 stream for the prupose of waste disposal, ○ new substances originating from the reaction of CO2 and incidental associated substances with the storage formation can be identified and quantified for the effects assessment, risk assessment and management. **Exposure processes and pathways from injection equipment** ○ potential for leakage along the chain of storage of CO2 streams: from the capture site to the final storage formation. Potential pathways: • connecting pipeline from the CO_2 recovery plant to the storage site, • sub-sea template and injection well(s) (if no surface installation), • platform injection well or CO_2 riser, pipeline and injection well. ○ plans to deal with the excess CO2 if the injection well(s) need to be shut in, ○ proper maintenance of site facilities and injection wells, ○ materials designed to anticipate peak volume, pressure and temperature. **Exposure processes and pathways from geological storage formations** Consider: ○ substances mobilised by the CO2 stream, ○ long - term and short - term processes, ○ migration through the pore system in low - permeability cap rocks, ○ migration, because the cap rock is locally absent, in combination with lateral migration of free or dissolved CO2 and incidental associated substances (spilling), ○ migration through faults or other fractures in the cap rock, ○ migration through inadequately completed and/or abandoned wells, ○ migration due to degradation of the cap rock or wells by reaction with acidic formation waters. **Water/biosphere – exposure processes and pathways** ○ assess fate of CO2 and incidental associated substances. **Likelihood of exposure** ○ Probablities of exposure processes assessed using techniques such as numerical modelling and simulation tools. **Scale of exposure** ○ assess fluxes of CO2 and incidental associated substances and their scale of spatial and temporal variability.

		Effects assessment o Output : concise statement of the expected consequences of storage of a CO2 stream in geological formations. **Sensitivity of species, communities, habitats and processes** o Main effects to consider: o those resulting from increased CO2 concentrations in ambient marine sediments and waters and biological sensitivity to such increases. **Temporal and spatial issues** o temporal and spatial scales of the leak will have different impacts, o worse - case scenario defined by the rate of CO2 leakage and the total amount of CO2 and incidental associated substances with which the ecosystem comes into contact and the sensitivity of the receiving environment, o Resilience of marine ecosystems largely unknown. **Human health and other legitimate uses of the maritime area** o effects assessment on the environment, human health, marine resources, amenities and other legitimate use of the maritime area.

Risk characterisation

- provide an overall assessment of the potential hazards associated with an activity,
- establish relationships between exposures and sensitivity of ecological entities.

Basis steps:

- identify potential hazards related to an activity,
- estimate the probability of these hazards occurring and the severity of effects posed to exposed species and ecosystems and the risks to human health and other legitimate uses of the maritime area,
- describe the risk estimate in the context of the significance of any adverse effects and the lines of evidence supporting their likelihood,
- identify and summarise the uncertainties, assumptions and qualifiers in the risk assessment,
- report and communicate the conclusions.

Risk characterisation for storage of CO2 streams in geological formations

- based on site - specific considerations of the potential exposure pathways, the probablities of leakage, and the potential effects on the marine environment, human health, and other legitimate uses of the maritime area,
- characterise the risks at different stages of a project,
- update the risk characterisation periodically,
- important factors: injection volumes, geological characteristics of the storage formation,
- use model,
- risk characterisation should lead to the development of an “Impact Hypothesis”. Key elements for its development:
    - characterisation of the CO_2 stream;
    - conditions at the proposed storage-site(s);
    - preventive and/or mitigating measures (with appropriate performance standards);
    - injection rates and techniques;
    - potential leakage rates and exposure pathways;
    - the potential impacts on amenities, sensitive areas, habitat, migratory patterns, biological communities and marketability of resources and other legitimate uses of the maritime area, including fishing, navigation, engineering uses, areas of special concern and value, and traditional uses of the maritime area;
    - potential impacts on human health;
    - nature, temporal and spatial scales and duration of expected impacts.
- Qualitative and quantitative performance criteria should be set for elements of the impact hypothesis such that as a whole, these are consitent with the objective: permanent contaminment of CO2 streams in a manner that avoids significant adverse consequences for the marine environment, human health, and other legitimate uses of the maritime area.
- If deviation from anticipated behaviour: mitigation measures should be implemented.
- Principles regarding development and application of an Impact Hypothesis:
    - evaluation of whether the performance criteria are met comprehensive,
    - determine "where" and "when" any impacts are likely to be expected;
    - expected consequences described in terms of any effects on human health, amenities, sensitive areas, habitat, migratory patterns, biological communities and marketability of resources and other legitimate uses of the maritime area,
    - monitoring programme linked to the hypotheses through the performance criteria and to serve as a feedback mechanism to verify the predictions and review the adequacy of management measures applied,
    - identify the sources and consequences of uncertainty;
    - include one or more steps of stakeholder involvement in the process of the development of an impact assessment in order to include all relevant endpoints and to reach the required level of community acceptance.

Risk management

- demonstrate how an event of leakage would be managed in order to prevent it leading to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.

Prevention of CO2 escape from the formation

- OGP Guidelines for injection of produced water and those published by OSPAR applicable,
- Planning, design and construction of storage site should lead to a risk of CO2 leakage reduced to an insignificant level,
- Maximum estimated extend to which CO2, incidental associated substances and mobilized substances could migrate defines the zone to be characterised for risk management purposes,
- Factors that will assist in the definition of the geographic volume to be reviewed:
    - regional and local geology,
    - regional stratigraphy,
    - regional structure,
    - regional hydrogeology,
    - seismic history,
    - injection, static and dynamic properties of containment and confinement zone,
    - vertical hydraulic gradient.

Well integrity

- Well design and construction should account for operating conditions (pressure, fluid composition and acidity, furation, etc.), and address identified potential well failure scenarios.
- Well integrity depends on: quality of materials used, management of the operation, proper siteclosure procedures so that long - term isolation has been accounted for.
-

Formation flow and fracture propagation prediction

- predictive modelling should:
    - include flow simulation, prediction of fracturing and fracture propagation,
    - establish the transport and fate of the injected CO2 stream,
    - provide the operator with an integrated knowledge sufficient to manage the injection process in an environmentally protective manner.
    - provide predictions during the operational injection period, and an assessment of the residual pressure fields during the period after shut - in of the injection well and prior to decommissioning.

Preventive maintenance and contingency planning

- potential failure modes should be evaluated at the planning stage,
- Potential failures include:
    - pressure build - up exceeding security levels,
    - confinement problems,
    - mechanical complications.
- Archive documentation so that future generations are informed of the existence of the CO2 storage site and its history (authorisation and licensing process, site closure and decommissioning procedures, data of long-term monitoring and management response capabilities).

Monitoring migration of CO2 streams and mobilised substances within and above the formation during the injection phase

Goals:

- detection of potential leakages from sub - seabed geologic storage,
- verification that such leakage does not occur.
- Monitoring programme:
- Goal: quantify the mass and distribution of CO2, record related biological and geochemical parameters,
- Should include:
  - monitoring for performance confirmation,
  - monitoring to detect possible leakages,
  - monitoring of local environmental impacts on ecosystems,
  - monitoring of the effectiveness of CO_2 storage as a greenhouse gas mitigation technology.

Elements included in the process monitoring and control:

- the injection rate,
- continuous pressure monitoring,
- injectivity and fall - off testing,
- the properties of the injected fluid (including temperature and solid content, the presence of incidental associated substances and the phase of the CO2 stream),
- mechanical integrity of seals and (abandoned) wells,
- containment of the CO2 stream,
- control measures, overpressure, emergency shut down system.

Techniques for monitoring described in IPCC SRCCS (IPCC, 2005) and “Guidelines for National Gas Inventories (IPCC, 2006).

Elements that may be included in the monitoring of CO_2 containment and migration:

- performance monitoring,
- monitoring the geological layers above the formation to detect and measure possible migration of the CO2 stream out of the intended formation.

Other elements that may be included:

- monitoring the seafloor and overlaying water to detect and measure possible leakage of CO2 (and incidental associated substances) into the marine environment,
- monitoring biological communities to detect and measure the effects of leakages on marine organisms.

Long-term, post injection, monitoring of migration of CO2 streams and mobilised substances

- Methods should not compromise the integrity of the sealed formation or the marine environment,
- Records should be kept for authorisation, licencing and site - closure processes together with data on long - term monitoring and management response capabilities.

Mitigation or remediation of CO2 escape from the storage site or formation

- Determined, among others, by the likelihood that CO_2 will reach living marine or water resources and the extent of significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.
- Most likely avenues for leaks:
  - the injection well, possibly due to overpressure;
  - other abandoned or active wells;
  - areas where permeable rock reaches the surface of the seabed; and
  - fractures of, or high permeability zones, within the cap rock.

  - If leakage occurs through an active or abandoned well, remediation methods may include:
    - recapping wells or repairing faults in cement between rock and casings; and
    - drilling intersecting wells followed by controlling the leak with heavy mud followed by recapping.

		o If leakage occurs through faults or fractures, remediation methods may include: • lowering the injection pressure or the formation pressure by removing water or other fluids; • halting the injection until the project is stabilised; • transferring CO_2 streams to a more suitable formation; and • plugging the pathway by injecting sealing material. **Risk assessment and management reports** should include: o characterisation of the CO_2 stream (including composition); o characterisation of the proposed storage-site(s); o preventive and/or mitigating measures (with appropriate performance standards); o injection rates and techniques; o potential leakage rates and exposure pathways; o the potential impacts on amenities, sensitive areas, habitat, migratory patterns, biological communities and marketability of resources, including fishing, navigation, engineering uses, areas of special concern and value and other legitimate uses of the maritime area; o the nature, temporal and spatial scales and duration of observed and expected impacts; o cumulative number of permits issued; o whether guidelines are implemented; o amount CO_2 stored (tonnes); o net amount of CO_2 stored (tonnes); o chemical composition of the CO_2 stream; o any observed leakage rates and exposure pathways; o any expected impacts from this leakage; o any observed impacts on the marine environment and other legitimate uses of the maritime area; and o any (mitigative) measures taken.
	Well Drilling and Testing	
	Site Development Plan	