ANNEX 7
(Ref. §2.10d)

OSPAR CONVENTION FOR THE PROTECTION OF THE MARINE ENVIRONMENT OF THE NORTH-EAST ATLANTIC

MEETING OF THE OSPAR COMMISSION (OSPAR)

OSTEND: 25-29 JUNE 2007

OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations[1]

(Reference Number: 2007-12)

I. Preliminary considerations

1. OSPAR has recognised that climate change and ocean acidification and other effects on the marine environment caused by elevated emissions of CO_2 are a cause of serious concern. Mitigation of these impacts necessitates a portfolio of options to reduce levels of atmospheric CO_2. The storage of CO_2 in geological formations is considered as one such option.

2. OSPAR has concluded that it is technically feasible to store CO_2 streams safely in geological formations, using existing, established technologies. The ultimate objective of such storage of CO_2 streams in geological formations is to ensure permanent containment of CO_2 beyond the biosphere (including the atmosphere). Although permanent containment is the ultimate objective, application of these guidelines should ensure that, if leakage does occur, it does not lead to significant adverse consequences for the marine environment, human health or other legitimate uses of the maritime area.

3. The aim of these guidelines is to assist in the management of storage of CO_2 streams in geological formations, so that at least the following aspects will be considered:

   a. assessment of the suitability of a potential injection-site for permanent containment of CO_2 streams and identification of the necessary measures for hazard reduction, remediation and mitigation;

   b. characterisation of the risks to the marine environment from storage of CO_2 streams in geological formations on a site-specific basis; and

   c. collection of necessary information (monitoring) and development of a strategy to manage uncertainties and minimise risks.

4. The Framework for Risk Assessment and Management of storage of CO_2 streams in geological formations (FRAM) at Annex 1 is an integral part of these guidelines. This Framework has been developed for OSPAR, making use of relevant developments within the framework of the London Convention/Protocol (LC/LP), including developments relating to the draft Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Formations and developments relating to a specific LP waste assessment guideline.

II. Scope of the Guidelines

5. Although the storage of CO_2 streams in geological formations also involves a process of capturing the CO_2 (either onshore or offshore) and transport of CO_2 streams to the injection site, the scope of the guidelines focuses on the process of CO_2 injection and post-injection risks of leakage. Transport (e.g. by pipelines or ships) should be sufficiently covered in other (national and international) regulations and standards.

[1] Geological formations means geological formations in the sub-soil of the OSPAR maritime area, including sub-seabed geological formations.

6. These Guidelines (including the Framework for risk assessment and management in Annex 1) provide generic guidance for Contracting Parties, when considering applications for permits for the storage of CO_2 streams in geological formations. Although not all elements of these Guidelines are necessarily relevant or applicable to every CO_2 storage project, Contracting Parties will ensure that these Guidelines have been applied to the extent possible when issuing permits for such CO_2 storage operations.

7. These guidelines encompass the iterative process described in the FRAM (see Annex I) that should be used for continual improvement of the management of a CO_2 storage project during the project life cycle, in accordance with the principles of internationally- recognized environmental management standards. The six stages of the FRAM are:

a. *Problem formulation*: critical scoping step, describing the boundaries of the assessment;

b. *Site selection and characterisation*: collection and evaluations of data concerning the site;

c. *Exposure assessment*: characterisation and movement of the CO_2 stream;

d. *Effects assessment*: assembly of information to describe the response of receptors;

e. *Risk characterisation*; integration of exposure and effect data to estimate the likely impact; and

f. *Risk management*: including monitoring, mitigation and remediation measures.

8. Storage of CO_2 streams in geological formations underlying waters deeper than 500 metres, such as geological structures under the pelagic ocean, may require further updating of the guidance to take account of differing exposure and effects pathways.

III. Risk Assessment and Management of CO_2 storage projects

9. The life cycle of a CO_2 storage project consists of the following phases:

a. planning;

b. construction;

c. operation;

d. site-closure; and

e. post-closure.

The planning, including design, construction and operation should lead to an inherently safe storage site. Each phase of the project requires all, or a selection of, the above-mentioned stages of the FRAM to be carried out. The following table indicates which stages are applicable to each phase of the project:

	Problem formulation	Site selection & characterisation	Exposure assessment	Effects assessment	Risk characterisation	Risk management (monitoring & mitigation)
Planning	☑	☑	☑	☑	☑	☑
Construction		☑	☑	☑	☑	☑
Operation		☑	☑	☑	☑	☑
Site-closure			☑	☑	☑	☑
Post-closure			☑	☑	☑	☑

10. A detailed description of each of the stages of risk assessment and management is provided in the Framework that is included as Annex 1 of these guidelines, which is reflecting the current state of scientific knowledge. It is important to point out that these stages should be followed in an iterative manner rather than as a strictly sequential once-through process.

11. In Appendix II of Annex 1 there is a compilation of several issues that require further research in order to improve the process of risk assessment and management for the storage of carbon dioxide streams in geological formations.

IV. Reporting and communication

12. With the aim of executing a transparent management of CO_2 storage projects, and in accordance with paragraph 3.5 of OSPAR Decision 2007/2 the competent authorities are obliged to require reports, including post-closure reports, on the results of the risk assessment and management process from the operator. In order to fulfill the reporting requirement as stated in OSPAR Decision 2007/2, the data from these reports are to be made available to the Commission.

13. The risk assessment and management reports should, for each phase of the project (see table in paragraph 9), where appropriate, elaborate on the relevant elements of the Impact Hypothesis (see paragraph 19 and paragraphs 5.6-5.9 of Annex 1 to these Guidelines), including the comparison with the various performance criteria:

a. characterisation of the CO_2 stream (including composition);

b. characterisation of the proposed storage-site(s);

c. preventive and/or mitigating measures (with appropriate performance standards);

d. injection rates and -techniques;

e. potential leakage rates and exposure pathways;

f. 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;

g. the nature, temporal and spatial scales and duration of observed and expected impacts;

h. cumulative number of permits issued;

i. whether guidelines are implemented;

j. amount CO_2 stored (tonnes);

k. net amount of CO_2 stored (tonnes);

l. chemical composition of the CO_2 stream;

m. any observed leakage rates and exposure pathways;

n. any expected impacts from this leakage;

o. any observed impacts on the marine environment and other legitimate uses of the maritime area; and

p. any (mitigative) measures taken.

14. It must be recognised that the assessment of hazards and risks related to storage of CO_2 streams in geological formations may include a significant level of uncertainty. This uncertainty should be identified and, wherever possible, quantified in the reports. This information should be used to identify areas for which further research or monitoring is required.

15. Sufficient stakeholder involvement is required in the process of risk assessment and management, as to ensure completeness in the assessment process. The objective is to promote a high level of public acceptance.

V. Evaluation of this guideline

16. These guidelines, as well as the Framework in Annex 1, should be evaluated and, if necessary, revised once practical experience has been gained through the actual application of these guidelines to CO_2 storage projects. Such evaluation and revision should take place in 5-year cycles.

VI. Consultation in relation to transboundary pollution

17. With respect to transboundary pollution, reference is made to Article 21 of the Convention.

VII. Permit and permit condition

18. In accordance with paragraph 3 of OSPAR Decision 2007/2:

a. the storage in geological formations of carbon dioxide streams from carbon dioxide capture processes shall not be permitted by Contracting Parties without authorisation or regulation by their competent authorities. Any authorisation or regulation shall be in accordance with the OSPAR Guidelines for Risk Assessment and Management of Storage of CO2 Streams in Geological Formations, as updated from time to time. A decision to grant a permit or approval shall only be made if a full risk assessment and management process has been completed to the satisfaction of the competent authority and that the storage will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area;

b. the provisions of the permit or approval shall ensure the avoidance of significant adverse effects on the marine environment, bearing in mind that the ultimate objective is permanent containment of CO_2 streams in geological formations. Any permit or approval issued shall contain at least:

(i) a description of the operation, including injection rates;

(ii) the planned types, amounts and sources of the CO_2 streams, including incidental associated substances, to be stored in the geological formation;

(iii) the location of the injection facility;

(iv) characteristics of the geological formations

(v) the methods of transport of the CO_2 stream;

(vi) a risk management plan that includes:

.1 monitoring and reporting requirements ;

.2 mitigation and remediation options <u>including</u> the pre-closure phases; and

.3 a requirement for a site closure plan, including a description of post-closure monitoring and mitigation and remediation options; monitoring shall continue until there is confirmation that the probability of any future adverse environmental effects has been reduced to an insignificant level.

c. permits or approvals shall be reviewed at regular intervals, taking into account the results of monitoring programmes and their objectives.

19. If the information thus provided is inadequate to formulate an Impact Hypothesis, the permitting authority will request additional information before issuing a permit.

20. Review of monitoring results will indicate whether monitoring programmes need to be continued, revised or terminated, and will contribute to informed decisions regarding the continuance, modification or revocation of permits. This provides an important feedback mechanism for the protection of human health, the marine environment and other legitimate uses of the maritime area.

Annex 1 to the guidelines

Framework for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations[2] (FRAM)

Result of the Expert Workshop on Technical and Environmental issues of storage of CO_2 in sub-seabed geological formations, October 25-27 2006, London, United Kingdom. Further updated during the OSPAR ICG-CO_2 workshop, February 14-16 2007, Rijswijk, the Netherlands and following the meetings of the Offshore Industry (12-16 March 2007) and Biodiversity (26-30 March 2007) Committees of OSPAR and the meeting of the OSPAR Commission (25-29 June 2007).

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2 Geological formations means geological formations in the sub-soil of the OSPAR maritime area, including sub-seabed geological formations.

0. Introduction and Summary

0.1 This Framework for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations (FRAM) is developed to provide generic guidance to the Contracting Parties to the OSPAR Convention. The ultimate objective of storage of CO_2 streams in geological formations is to ensure permanent containment of CO_2 streams as one of a portfolio of options to reduce future levels of atmospheric carbon dioxide and further ocean acidification.

0.2 Although permanent containment is the ultimate objective, it is necessary to show that, if leakage does occur, it does not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area. Therefore, the initiator of a CO_2 storage project should:

a. 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;

b. characterise the risks to the marine environment from the storage of CO_2 streams in geological formations on a site-specific basis; and

c. collect the necessary information (including baseline data for monitoring) and develop a strategy to address uncertainties and manage and minimise risks.

0.3 Although the storage of CO_2 streams in geological formations also involves a process of capturing the CO_2 (either onshore or offshore) and transport of the CO_2 stream to the injection site, the focus of this framework for risk assessment and management is limited to the process of injection and post-injection risks of leakage. Some issues that relate to transport are addressed, where relevant. Transport (e.g., by pipelines or ships) should be sufficiently covered in other (national and international) regulations and standards.

0.4 For the purpose of this framework for risk assessment and management, the following categories of substances are distinguished:

a. CO_2 stream

(i) CO_2;

(ii) incidental associated substances derived from the source material and the capture, transport and storage processes used, consisting of:

.1 source and process derived substances; and

.2 added substances (i.e. substances added to the CO_2 stream to enable or improve the capture, transport and storage processes); and

b. substances mobilised as a result of the disposal of the CO_2 stream.

0.5 This framework describes an iterative process that should be used for *continual improvement of the management of the project* during the project lifecycle, and improving the assessment and management of other similar projects. A simple conservative deterministic assessment is sufficient if the adverse consequences are insignificant, but if they are likely not to be, then as a precautionary approach the assessment should include probabilistic approaches to achieve acceptable results. The six stages of this framework can be summarised as follows:

a. *Problem Formulation* is a critical scoping step as it defines the boundaries of the assessment, including the scenarios and pathways to be considered. Major issues to include in the assessment are:

(i) the suitability of deep geological formations to permanently retain the CO_2 stream reliably;

(ii) the nature of the overburden;

(iii) the characteristics of the marine environment above the site; and

(iv) the need for monitoring over a long period (also after site-closure). The latter is especially important with respect to the long-term safety of storage and any future handover of the responsibility for the storage site (liability for future risk);

b. *Site Selection and Characterisation* concerns the collection of data necessary for describing the physical, geological, chemical, and biological conditions necessary for determining the suitability of a site proposed for storage (and its surrounding area) and to establish a baseline for management and monitoring;

c. *Exposure Assessment* is concerned with the characterisation and movement of the CO_2 stream within geological formations and, potentially, the marine environment as a basis for an effects assessment. The processes and pathways of potential migration of CO_2 streams from geological storage formations and leakage to the marine environment, during and after injection of the CO_2 stream, should be assessed. This should include an assessment of additional substances, already present in or mobilised by the CO_2 stream and displaced saline formation water, based on an informed decision of the relevance of such substances. The probabilities of the exposure processes, the amount of CO_2 and the spatial and temporal scale of fluxes may be assessed using appropriate numerical modelling tools. The processes involved in such migration behaviour will be governed by site-specific factors. The uncertainties associated with such an assessment should be identified and, wherever possible, quantified;

d. *Effects Assessment* assembles the information necessary to describe the response of receptors within the marine environment resulting from potential exposure to the CO_2 stream if leakage were to occur. The main effects of concern to such an assessment include effects on human health, marine resources, relevant biological communities, habitats, ecological processes, and other legitimate uses of the maritime area. Effects of exposure to other contaminants in the CO_2 stream, as well as metals and other substances mobilised in a decreased pH environment, should be included in the assessment;

e. *Risk Characterisation* integrates the exposure and effects information to provide an estimate of the likelihood of adverse impacts. Risk characterisation should be performed on the basis of site-specific information. Factors evaluated in a risk characterisation may change over time given the operational status of the project and ongoing data collection used to update predictive models. The sources and levels of uncertainty associated with a risk estimate will be a function of the data and modelling assumptions used. Given the long time-scales involved for the intended storage of CO_2 streams in geological formations, it will be useful to distinguish between processes relevant to characterizing risks in the near-term during the period of active operations and injection at a site and long-term processes operating after site closure;

f. *Risk Management (including Monitoring and Mitigation).* In the planning phase, risk management is used to design *preventive* measures based on prediction (derived from the risk assessment process and in particular the outcome of the risk characterisation stage). Risk management further includes the definition of the requirements for monitoring, during and after injection of CO_2 streams. When injection starts, the results of monitoring are valuable and, if necessary, can lead to the identification of additional *preventive* and/or *mitigative* measures. Although the process of monitoring continues after site closure, its intensity is expected to decrease and, eventually, monitoring may be discontinued when there is confirmation that the probability of any future adverse environmental effects has been reduced to an insignificant level.

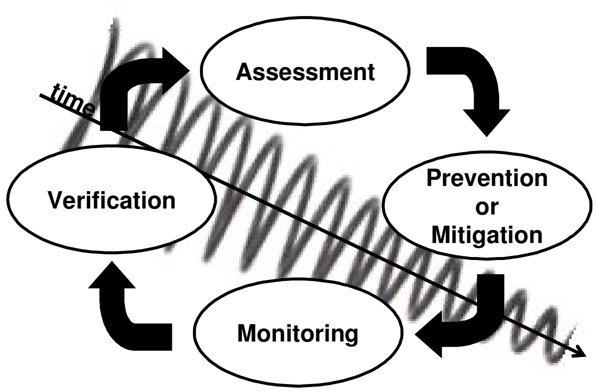

Figure 1 *Cyclic process of risk assessment and management during the lifecycle of a CO_2 storage project.*

0.6 The depths of water below which CO_2 storage in geological formations is likely to be considered in the near future are generally less than 500 metres (i.e. predominantly beneath continental shelves). This is sufficiently shallow such that most forms of CO_2 potentially escaping from the underlying sediments will have positive buoyancy. Should interest in CO_2 storage extend to geological formations beneath much greater depths than in continental shelf and upper continental slope environments, this framework may need to be further developed to take account of other potential exposure and effects pathways.

0.7 Stakeholder involvement is not defined as a separate element in the framework, but it is included as part of risk management and risk characterisation. Stakeholder involvement is an important feature of these processes, as to ensure completeness of the assessment. The objective is to promote a high level of public acceptance.

0.8 It must be recognised that the assessment of hazard and risk related to storage of CO_2 streams in geological formations may include a significant level of uncertainty, especially since extremely long time horizons are involved. This should be accounted for by using uncertainty analysis and included in the results. It should further identify areas for which further research or monitoring is required.

0.9 In Appendix II there is a compilation of several issues that, at the time of issuing these guidelines, required further research in order to improve the process of risk assessment and management for the storage of CO_2 streams in geological formations.

1. Problem formulation

Scope of the problem

1.1 Problem formulation is the scoping of a risk assessment and includes the collection of information that will be used to develop a site-specific conceptual model to direct a site-specific risk assessment. It is important to identify gaps and uncertainties at this stage.

1.2 The ultimate objective of storage of CO_2 in geological formations is to ensure permanent containment of CO_2 streams beyond the biosphere (including the atmosphere) as one of a portfolio of options to reduce future levels of atmospheric carbon dioxide and additional ocean acidification.

1.3 In sub-seabed storage, for the purposes of climate change mitigation and prevention of ocean acidification, CO_2 streams are injected into geological strata at least several hundred meters below the layer of unconsolidated sediments on the seabed. Therefore, it should be stressed that the locations of disposal will differ from most other operations currently permitted under the OSPAR Convention (it most resembles injection and re-injection of produced water) and consequently the site selection and assessment considerations will also require a geological assessment.

1.4 The sources of CO_2 considered here are those industrial activities releasing large quantities of CO_2 to the atmosphere. The objective of CO_2 capture and storage is to capture CO_2 from the emission streams of these sources for storage in geological formations. It is not to be considered as an alternative waste disposal mechanism for other substances. However, CO_2 streams may contain incidental associated substances from the source or capture process. Furthermore, it should be stressed that no substances may be deliberately added to the CO_2 stream for the purposes of waste disposal but may be added to enable or improve the efficiency of capture, transport, and storage. In all cases, acceptable concentrations of substances should be related to their potential impacts on the integrity of the storage site(s) and relevant transport infrastructure, the risk they pose to the marine environment, and to requirements of the applicable EU regulations.

1.5 Major issues to be addressed include:

a. the suitability of deep geological formations to retain the CO_2 streams permanently;

b. the nature of the overburden to act as a barrier to prevent or retard upward migration of CO_2 streams;

c. the potential mobilisation of substances by CO_2 streams directly or indirectly (e.g., heavy metals released due to a pH reduction) in the formation and the overburden;

d. the characteristics of the marine environment above and around the site of storage of CO_2 in geological formations in relation to concerns regarding potential adverse effects of any CO_2 streams leaking from the formation that succeeds in reaching the unconsolidated sediments and/or the overlying water column; and

e. the 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.

1.6 A generic conceptual model of potential environmental pathways and effects that are relevant to the consideration of the potential consequences of the leakage of CO_2 streams and/or mobilised substances from geological formations to the marine environment from storage of CO_2 streams in geological formations is shown in Figure 2. It is important to point out that the problem formulation and the FRAM itself should be followed in an iterative manner rather than as a strictly sequential once-through process.

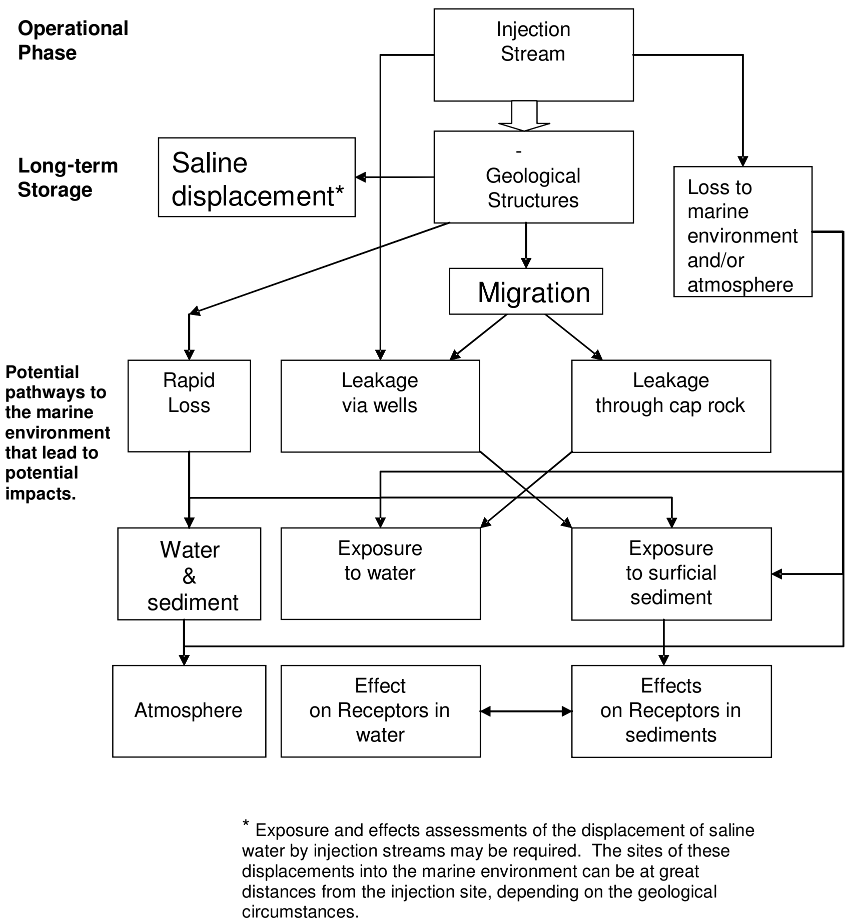

Figure 2 Potential pathways and effects.

Potential migration or leakage of CO_2 streams into the marine environment

1.7 This comprises two distinct considerations:

a. Potential leakage during the operational phase of storage of CO_2 streams in geological formations; and

b. Migration and leakage of CO_2 streams from the geological formation following the injection process.

Potential leakage during injection

1.8 These would most likely result from major seal failure or disruption of the means of emplacement of the CO_2 streams in the geological formation (i.e. the pipeline or means of insertion from a vessel and the injection well). Capped well locations are also potential sources of leakage and their potential is dependent upon well integrity and age. The probability of leakage through cap rock is unlikely with proper site characterisation and selection, barring an unpredictable seismic event. However, if leakage does occur during this phase, then remediation and/or mitigation is likely to be possible e.g., by relieving formation pressure.

1.9 The physical effects associated with major, sudden leaks of gaseous CO_2 are primarily the disturbance of unconsolidated bottom sediment caused by the flow and expansion of CO_2 as it passes through the upper sediment column and into the overlying water column. Associated with such events would also be turbulence and therefore increased vertical mixing in the water column. At the extreme, a large and rapid gas leak at the seafloor could cause damage to the marine environment, interference with other legitimate uses of the maritime area, including fishing and maritime transport, with the potential for associated risks to human health.

1.10 In the event of slower, more diffusive CO_2 leak, the CO_2 enriched stream, including any associated substance, could potentially contact the marine sediments and/or the water column. This contact could potentially alter the physiochemical nature of marine sediments, the surrounding boundary layer of marine waters, and/or the water column, e.g., depression of pH. The spatial and temporal nature of such a leak, and the underlying nature of the surrounding hydrodynamics will determine the degree of any exposure in the water column. Short and long-term effects as well as population level effects and species-specific impacts need to be considered. Impact Hypotheses derived from these potential impacts should be used to define monitoring and mitigation plans.

Potential post-injection leaks

1.11 These will be similar to the potential operational leaks in the case of leakages via a capped well and the cap rock or by unpredictable geological events (such as earthquakes) but with the significant difference that they will probably occur over longer timeframes. In addition, the capacity to mitigate is likely to be reduced as the infrastructure and associated resources may not be immediately available and much more costly. Any necessary cautionary (precautionary) measures should be taken, to the extent possible, prior to closure of the injection site.

2. Site selection and characterisation

Introduction

2.1 Key objectives for geological CO_2 storage site selection and characterisation are to:

a. assess how much CO_2 can be stored at a prospective storage site. Formation parameters like volume, porosity, permeability need to be characterised in order to calculate the storage capacity;

b. 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;

c. establish a baseline for the management and monitoring of the injection and storage of CO_2 streams.

2.2 Site characterisation requires the collection of a wide variety of geological and environmental data that are needed to achieve these objectives. Much of the data will necessarily be site-specific. Most data will be integrated into geological models that will be used to simulate and predict the performance of the site. These and related issues are considered below. Characterisation should explicitly take into account uncertainties (see Appendix II). Results of site characterisation feed into the next stages of risk assessment and management in the lifecycle of a CO_2 storage facility.

Different types of storage formations and trapping mechanisms

2.3 Oil or gas reservoirs and saline aquifers have the largest potential for safe and long-term CO_2 storage. A large part of the identified storage capacity is located offshore.

Oil and gas reservoirs

2.4 CO_2 streams can be injected in oil and gas reservoirs, either for storage or for enhanced oil recovery. The latter falls outside the scope of this framework. The existence of abandoned oil and gas wells within the relevant geological domain of the storage site provides potential avenues for leakage pathways. Because the capillary seal for oil and gas reservoirs has already proven its sealing integrity, the potential for leakage through these types of seals is considered most unlikely, provided that the seal has not been damaged during exploitation of gas or oil. There is a wealth of knowledge on the geology and sealing potential of these formations and structures to facilitate the site selection and characterisation. Additional information may be needed, once a reservoir is selected for the storage of CO_2 streams in geological formations, as the behaviour of a CO_2 stream may differ from the original formation content.

Deep saline formations

2.5 Deep saline formations are geological formations or structures containing saline water. For such formations that have not been storing oil or gas, the verification of the integrity of the sealing rock is generally more challenging than for oil or gas fields, due to the more limited information and experience. In some areas, the geology of such formations is well documented, e.g., where oil and gas exploration has take place, while in other areas such data will need to be collected and modelled in order to verify the formation's capability of storing CO_2 streams.

Other possible geological formations for CO_2 storage

2.6 Unminable coal beds, basalts, oil and gas shales, salt caverns and other geological formations and structures may also be considered for storage of CO_2 streams. However, these formations have not been explicitly considered during the development of this Framework for Risk Assessment and Management.

Trapping mechanisms

2.7 In the selection of appropriate sites, the different mechanisms retaining CO_2 streams underground are relevant. Driving forces that could promote the migration of CO_2 streams out of the formation are the pressure increase caused by the injection of CO_2 streams and the buoyancy due to the density of CO_2, which is lighter than brine. This density difference is about the same as the density difference between oil and brine. There are several mechanisms that are effective in preventing injected CO_2 from escaping from a formation. The most important is the presence of a cap rock acting as an upper seal to prevent CO_2 streams flowing out of the formation. Nevertheless, attention has to be given to the possibility of faults in existing seals. This is relevant for both storage in oil and gas reservoirs and for deep saline aquifers. The types of trapping mechanisms (Figure 3) are strongly related to the characteristics of the site. Structural and stratigraphic trapping is an important trapping mechanism for conventional oil and gas reservoirs and traps in saline formations. Residual and solubility trapping become important in storage formations where CO_2 is able to migrate and disperse. If reactive minerals are present in these storage formations, mineral trapping becomes an additional trapping mechanism.

2.8 Other trapping mechanisms include pore trapping of CO_2 (residual gas trapping), dissolution of CO_2 in brine and mineral trapping of CO_2.[i] For well-selected, designed and managed geological storage sites, the vast majority of the CO_2 will gradually be immobilised by these trapping mechanisms. These mechanisms should enhance the security of CO_2 storage (IPCC 2005).

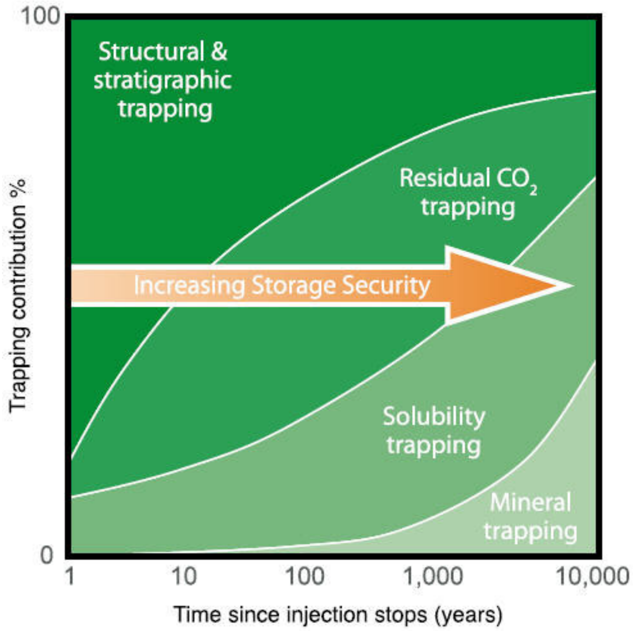

Figure 3 *Storage security depends on a combination of physical and chemical trapping. Over time, the physical processes of residual CO_2 trapping, geochemical processes of solubility trapping and mineral trapping increase (from IPCC, 2005).*

Site selection process and site characterisation

2.9 Important issues during the site screening and selection process for the storage of CO_2 streams include:

a. the storage capacity and injectivity of the formation;

b. the long-term storage integrity;

c. the technical and environmental suitability of the vicinity and surrounding area;

d. potential migration and leakage pathways over time and potential effects of leakage of CO_2 streams; and

e. possibilities for monitoring, remediation and/or mitigation.

2.10 Appendix I to this Framework outlines the information that facilitates the selection and characterisation of sites for storage of CO_2 streams in geological formations. The appendix shows elements that should be considered rather than constituting formal requirements. A storage site and its surroundings, including the overlaying sediment and water column, need to be characterised in terms of geology, hydrogeology, geochemistry, geomechanics and biology. A significant amount of data may be needed to establish both the feasibility of injection of a CO_2 stream and also to provide evidence of the integrity of the site over the time-scale relevant for the sequestration issue. The site selection will typically include a reservoir simulation to assess a potential storage site, e.g., by a three-dimensional geological model. Relevant factors for the assessment of the suitability of geological formations for storage of CO_2 streams in respect of both the protection of the marine environment and climate-change include characterisation of the formation, the cap rock, geological stability, possible leakage-pathways, trapping mechanisms and modelling of the behaviour of the CO_2 stream.

2.11 Considering the potential consequences to the environment in the event that a CO_2 stream leaks to the sea floor, the characterisation and selection of sites should take into account the proximity of the site to sensitive or endangered habitats and species, including natural resources such as fish. Other uses of the area such as oil and gas exploration and exploitation and fisheries should also be taken into consideration. Finally, possible lateral migration through porous and permeable layers to onshore surface locations should also be considered.

2.12 The sources of information will vary, but analysis will mainly rely on the sampling of well cores (both in the formation and the overlying structures), the acquisition of well logs, seismic and biological surveys, and also data available from existing wells or fields in neighbouring locations.

2.13 This information is useful for the site selection and characterisation, and thus establishes a geological and marine environmental baseline before the site is used for storage of CO_2 streams (i.e. at the pre-injection stage). It should also be noted that, as the project moves into the injection and the post injection stages, this baseline information should be used for the development of a monitoring strategy. Evaluation of the results of the monitoring may be used to update the monitoring strategy and other operational practices.

3. Exposure assessment

3.1 Exposure assessment provides the characterisation of potential effects and provides an input into the wider risk characterisation and risk mitigation processes. Information gathered at this stage should be appropriately recorded and documented. Although permanent containment is the ultimate objective, it is advisable to show how any leakage will be managed in such a way that that it does not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.

Chemical and physical characterisation of the CO_2 stream, including incidental associated substances

3.2 Characterisation of the injection stream is essential. While no substances will deliberately be added to the CO_2 stream for the purposes of waste disposal, the composition of the injection stream should be consistent with the primary purpose of mitigating CO_2 emissions to the atmosphere. Incidental associated substances may be present in the CO_2 stream, which is defined in paragraph 0.4.

3.3 CO_2 and incidental associated substances may react in the storage formation to form new substances and they may mobilise substances in the formation. These new and mobilised substances could have practical impacts on CO_2 storage systems and also have potential impacts on health, safety and environment. Such substances can be identified and quantified and uncertainties can be characterised, for the purposes of gathering information required for the effects assessment (see Chapter 4) and the wider process of risk assessment and management (Chapters 5 and 6). Particular attention should be given to those substances that may reduce the integrity of storage and/or are known to have significant effects on the marine environment.

3.4 The types and concentrations of such other substances vary, depending mainly on the basic source process (e.g., gasification, combustion, natural gas cleanup), the source material, and the type of capture process. As an example, the following table from the IPCC SRCCS[ii] demonstrates the types and magnitudes of other substances that may be found in CO_2 streams from fossil-fuelled power plants. Note that these substances may be different for CO_2 streams from other sources, such as refineries, steel plants, etc.

Table 1 Concentrations of impurities in dried CO_2, % by volume

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

a. The SO_2 concentration for oxy-fuel and the maximum H_2S concentration for pre-combustion capture are for cases where these impurities are deliberately left in the CO_2, to reduce the costs of capture (see Section 3.6.1.1). The concentrations shown in the table are based on use of coal with a sulphur content of 0.86%. The concentrations would be directly proportional to the fuel sulphur content.

b. The oxy-fuel case includes cryogenic purification of the CO_2 to separate some of the N_2, Ar, O_2 and NO_x. Removal of this unit would increase impurity concentrations but reduce costs.

c. For all technologies, the impurity concentrations shown in the table could be reduced at higher capture costs.

3.5 The IPCC SRCCS states that the fate in the capture plant of other substances that may occur in the feed gas (such as heavy metals) is not well known, and therefore attention should be paid to identifying these substances in the injection stream.

Exposure processes and pathways from injection equipment

3.6 Processes and pathways for the leakage of CO_2 and any incidental associated substances to the marine environment and the atmosphere during transport and injection equipment should be addressed, and uncertainties should be identified. There is potential for leakage along the chain of storage of CO_2 streams in geological formations, i.e. from the capture site, during compression, pipeline transportation and injection phases, to the final storage formation. These will be site-specific. Potential pathways to the water column from equipment during the injection phase can occur from:

a. the connecting pipeline from the CO_2 recovery plant to the storage site;

b. the sub-sea template and injection well(s) (if no surface installation); and

c. the platform injection well or CO_2 riser, pipeline and injection well.

3.7 The IPCC SRCCS noted that, at the storage site, adequate plans need to be in place for dealing with excess CO_2 if the injection well(s) need to be shut in. Options include having a backup injection well or, in the most extreme cases, methods to safely vent the CO_2 stream to the atmosphere. Proper maintenance of site facilities and injection wells is necessary to avoid leakage and well failures. For injection through old wells, key factors include the mechanical condition of the well, the quality of cement and the degree of maintenance. All materials used in injection wells should be designed to anticipate peak volume, pressure and temperature. In the case of gas containing free water, use of corrosion-resistant materials is essential. There are several analogues from offshore transport and injection of hydrocarbon gas and onshore CO_2 injection projects that can provide data for risk assessment and management.

Exposure processes and pathways from geological storage formations

3.8 A proper risk assessment should address, amongst others, any risk of leakage to the marine environment. Processes and pathways for migration of CO_2 and incidental associated substances from geological storage formations and leakage to the marine environment, during and after injection of CO_2 streams, should be assessed. This assessment needs to include the consideration of substances, mobilised by the CO_2 stream and also displaced saline formation water, based on an informed decision on the relevance of these issues. Such assessments should be site-specific. Attention should be paid to both long-term and short-term processes.

3.9 Processes to be considered should take account of the fact that free gaseous CO_2 and supercritical CO_2 are less dense than either water or brine under typical geological conditions, so that they tend to rise towards the seabed. For example, if the formation pressure is high and leakage pathways exist, migration of free and dissolved CO_2 and incidental associated substances out of the storage formation may result. Low-pH formation water resulting from the dissolution of CO_2 may promote corrosion of well-construction and plugging materials.

3.10 The IPCC SRCCS[iii] indicates that potential migration and leakage pathways from geological formations include:

a. migration through the pore system in low-permeability cap rocks if the capillary entry pressure at which CO_2 may enter the cap rock is exceeded;

b. migration, because the cap rock is locally absent, in combination with lateral migration of free or dissolved CO_2 and incidental associated substances (spilling);

c. migration through faults or other fractures in the cap rock;

d. migration through inadequately completed and/or abandoned wells; and

e. migration due to degradation of the cap rock or wells by reaction with acidic formation waters.

3.11 Site characteristics and numerical simulation of the injection of the CO_2 stream and the long-term fate of the stored CO_2 (and any incidental associated substances) are appropriate to help identify potential migration pathways, leakage pathways and fluxes.

Water/biosphere – exposure processes and pathways

3.12 An assessment should be made of the fate of CO_2 and incidental associated substances, including any migration from the geological formation and the potential for leakage of CO_2 to the seabed sediments and water column. Leakage of free and dissolved CO_2, incidental associated substances and other substances mobilised by the CO_2 stream, for example saline formation water (as per "saline displacement" identified in Figure 2 in Chapter 1 of this Framework), should be considered.

Likelihood of exposure

3.13 The probabilities of the exposure processes may be assessed using appropriate techniques, including numerical modelling and simulation tools. Uncertainties should be identified, as well as sensitivity for the choice of models by comparing different simulation techniques.

3.14 Data from existing CO_2 storage projects contributes to improving the quality of long-term performance predictions and the knowledge base is growing. The IPCC SRCCS[iv] concluded that, assuming that sites are well selected, designed, operated and appropriately monitored, the balance of available evidence indicates that it is likely that the fraction of stored CO_2 retained in a geological formation is more than 99% over the first 1,000 years.

Scale of exposure

3.15 An assessment of the fluxes of CO_2 and incidental associated substances and their scale of spatial and temporal variability should be undertaken using appropriate numerical modelling and simulation techniques. Uncertainties should be identified and quantified (see the previous sections).

3.16 Because each site is different, the possible quantities of CO_2 (and incidental associated substances) and the scale of spatial and temporal fluxes, e.g., CO_2 concentration in the water column, should be assessed on a site-specific basis, for the purposes of the Effects Assessment.

4. Effects assessment

Introduction

4.1 Assessment of potential effects should lead to a concise statement of the expected consequences of storage of a CO_2 stream in geological formations. It provides input for deciding whether to approve or reject a CO_2 storage proposal, site selection, and monitoring both to verify the Impact Hypothesis and to determine what additional preventive and/or mitigating measures are required. It therefore provides a basis for management measures and for defining environmental monitoring requirements.

4.2 Although permanent containment of CO_2 streams is the ultimate objective of storage of CO_2 in geological formations, effects and risk assessment is carried out to demonstrate that, in the event of leakage, storage does not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.

4.3 Potential risks to humans and ecosystems from geological storage may arise from leakage during injection and leakage across faults or ineffective seals. Leakage from offshore geological storage sites may pose a hazard to benthic and pelagic ecosystems as well as other legitimate uses of the maritime area, in the event the CO_2, any incidental associated substances or substances mobilised as a result of the storage of the CO_2 stream move from deep geological formations through benthic sediments into the sea[v] (see exposure assessment).

Sensitivity of species, communities, habitats and processes

4.4 This section highlights the sensitivity of species, communities, human health and other legitimate uses of the maritime area to exposures to CO_2 and incidental associated substances and data requirements including those addressing issues of temporal and spatial scales and variability.

4.5 The main effects to consider in relation to the leakage of CO_2 streams are those that result from increased CO_2 concentrations in ambient marine sediments and waters and biological sensitivity to such increases. The effects of CO_2 leaking to water bodies depend upon the magnitude and/or rate of leakage[vi], the chemical buffering capacity of the sedimentary or water body and transport and dispersion processes. Changes in pH are directly related to the partial pressure of CO_2 and the chemical buffering capacity of the aqueous phase. High CO_2 levels in the aqueous phase may impair respiration in organisms and cause lowering of pH in animal body fluids (*acidosis)*, increased concentrations of CO_2 in body fluids (*hypercapnia*) and impairment of oxygen transport in animals (*asphyxiation*). The changes in ocean chemistry caused by CO_2 leakage may have profound effects on calcareous organisms such as corals, shellfish, and specific groups of phytoplankton. Effects of *disturbed calcification rates* may include reduced levels of growth and reproduction, as well as increased mortality rates. The OSPAR report[vii] distributed as *"Effects on the marine environment of ocean acidification resulting from elevated levels of CO_2 in the atmosphere"* contains an overview of ecosystem sensitivity to CO_2 exposure

4.6 Effects of exposure to other contaminants in the CO_2 stream should be assessed as well. Also, changes of pH in sediments due to CO_2 might have effects on metal speciation (e.g., mobilising trace metals and other compounds to a higher extent of bioavailability[viii]). This may lead to direct toxic effects and/or accumulation in the food chain. The effects of displacement of saline water should be included in the effects assessment as well.

Temporal and spatial issues

4.7 Stored CO_2 and any incidental associated substances may affect the overlying marine environment with which it comes into contact through different exposure scenarios. Leaks may occur on a variety of temporal and spatial scales, ranging from local sudden, major leaks (e.g., blow-out during injection or well integrity failure) up to slow leakage over a wide area. The impacts will likely differ accordingly.

4.8 The worst-case scenario is not only defined by the rate of CO_2 leakage but also by the total amount of CO_2 and incidental associated substances with which the ecosystem comes into contact and the sensitivity of the receiving environment. The spatial extent of the waters and sediment with increased CO_2 content and decreased pH will depend on the amount of CO_2 and incidental associated substances and also on the prevailing environmental conditions at the sea bottom as these can significantly influence the behaviour and fate of the leaking CO_2. For example, stratification may trap CO_2-enriched water at the bottom of the sea.

4.9 The resilience of marine ecosystems remains largely unknown. Disturbance, re-colonisation and community recovery differs in the shallow and deep sea. It is generally assumed that recovery is faster in shallow areas (weeks/months) than in the deep sea (several years), although this should be assessed on a site-by-site basis. Prediction of future changes in ecosystem dynamics, structure and functioning benefits from data on sub-lethal effects over the entire life history of organisms.

Human health and other legitimate uses of the maritime area

4.10 In addition to effects on the environment, the effects assessment evaluates the potential effects on human health (including those associated with food chain transfer of contaminants), marine resources, amenities and other legitimate uses of the maritime area. This might especially be relevant if large amounts of CO_2 (potentially including incidental associated substances) may reach the sea surface, which consequently may endanger human life and other legitimate uses of the maritime area.

5. Risk characterisation

Introduction

5.1 Risk characterisation is used to provide an overall assessment of the potential hazards associated with an activity and establish relationships between exposures and sensitivity of ecological entities. Though permanent containment of CO_2 streams is the ultimate objective of storage of CO_2 in geological formations, it is advisable to show that the residual risk of leakage is well characterised. The following basic steps are associated with risk characterisation:

a. identifying potential hazards related to an activity (see site selection);

b. estimating 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;

c. describing the risk estimate in the context of the significance of any adverse effects and the lines of evidence supporting their likelihood;

d. identifying and summarizing the uncertainties, assumptions and qualifiers in the risk assessment; and

e. reporting and communicating the conclusions.

Risk Characterisation for storage of CO_2 streams in geological formations

Overview

5.2 Risk characterisation for the storage of CO_2 streams in geological formations should be based on site-specific considerations of the potential exposure pathways, the probabilities of leakage, and potential effects on the marine environment, human health, and other legitimate uses of the maritime area, as described in the previous chapters. A thorough site characterisation is therefore critical for defining the nature and temporal and spatial scales of potential impacts.

5.3 Given the time-scales associated with storage of CO_2 streams in geological formations, it would be useful to characterise the risks at different stages of a project. The risks during injection and in the near-term (e.g., decades) may be different than the longer-term risks (e.g., over centuries to millennia) depending on site-specific considerations. In the injection phase, consideration should be given to risks such as the buoyant behaviour of CO_2, the pressure build-up in the formation, the quality of the seal and the well completion. Particular attention should be paid to the integrity of the wells. Over the longer term, the risk assessment should also address any change in the integrity of the seal and of the plugs in the abandoned wells and might include the effects of CO_2 dissolution and mineralisation. It is important to update the risk characterisation periodically, as part of the risk management process, based on new field data and/or performance assessment data and/or new/improved scientific knowledge.

5.4 When evaluating the spatial aspects of risk characterisation, various factors are relevant to the potential area impacted, including the injection volumes and geological characteristics of the storage formation. A thorough site characterisation (see above) is therefore critical to the risk characterisation. In order to conduct an appropriate risk characterisation, the potential spatial extent of potential impacts should be estimated using models or other analytical tools.

Methods

5.5 Well-established methods exist for characterizing the risks of industrial injection operations (OGP 2000, Guidelines for Produced Water Injection). Various methods for assessing the long-term passive storage phase are being developed, building partly on the experience from hazardous and nuclear waste management. These models can vary from relatively simple to very detailed models. Where significant uncertainties in model input variables are projected to exist, it is recommended that uncertainty ranges around the most likely values be applied in the assessment. Similarly, if discrete events are not certain to occur, probability values should be assigned to such events. The assessments can be executed in a deterministic way following a conservative approach or in a probabilistic manner that quantifies the uncertainties connected with storage of CO_2 streams. Several techniques are applied to address and/or quantify the uncertainties such as Monte Carlo simulation[3], fault tree analysis and expert judgement. Natural and industrial analogues present suitable opportunities for testing the risk assessment models. These (mostly exposure-) models are integrated with effects assessment models to provide a comprehensive risk characterisation.

Impact hypothesis

5.6 The risk characterisation should lead to the development of an “Impact Hypothesis”. This is a concise statement of the expected consequences of disposal. It provides the basis for deciding whether to approve or

[3] See the Glossary in Appendix 3 to this report for an explanation.

reject the proposed disposal option and for defining environmental monitoring requirements. Key elements in the development and testing of the impact hypothesis are:

a. characterisation of the CO_2 stream;
b. conditions at the proposed storage-site(s);
c. preventive and/or mitigating measures (with appropriate performance standards);
d. injection rates and techniques;
e. potential leakage rates and exposure pathways;
f. 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;
g. potential impacts on human health;
h. the nature, temporal and spatial scales and duration of expected impacts.

5.7 The ultimate objective of storage of CO_2 streams is to ensure permanent containment of CO_2 streams in geological formations, in a manner that avoids significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area, thereby contributing to reduced atmospheric levels of CO_2. Qualitative or quantitative performance criteria should be set for elements of the impact hypothesis, such that - as a whole – these are consistent with the ultimate objective.

5.8 Results from the risk assessment and monitoring procedures should be compared with the various performance criteria in order to determine whether the system deviates from the initially anticipated behaviour in a way that gives rise to concern about achievement of the overall objective. If such situation arises, mitigative measures should be implemented with the intention of meeting this overall objective and minimizing any adverse consequences.

5.9 Several general, relevant principles regarding development and application of an Impact Hypothesis are:

a. the evaluation of whether the performance criteria are met, should be as comprehensive as possible, but it must be recognised that even the most comprehensive impact hypotheses may not address all possible scenarios such as unanticipated impacts;
b. it is essential to determine "where" and "when" any impacts are likely to be expected;
c. the expected consequences should be 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, including fishing, navigation, engineering uses, areas of special concern and value, and traditional uses of the maritime area;
d. the monitoring programme should be 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;
e. it is important to identify the sources and consequences of uncertainty;
f. it is essential to 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.

6. Risk management

6.1 While storage of CO_2 streams in geological formations aims to isolate CO_2 from the biosphere (including the atmosphere) permanently, risk management procedures are necessary to maximise the intended isolation and to minimise the effects of possible leaks of $CO_{2,}$ incidental associated substances and substances mobilised by the CO_2 stream. Permanent containment of CO_2 streams is the ultimate objective of risk management. It should, however, 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.

6.2 The general and specific information that is needed for risk management of CO_2 storage sites, including options for remediation and mitigation, are outlined in Appendix I to this Framework.

Prevention of CO_2 escape from the formation

Injection management

6.3 Because the physical state of injected CO_2 will be either supercritical or liquid and thus similar to the physical state of water, the OGP Guidelines for injection of produced water[ix] and those published by OSPAR[x] are applicable to injecting CO_2 streams in an environmentally safe manner. If these guidelines are applied to the injection of CO_2 streams, the probability of cap rock fracture is as low as that from injection of fluids in the oil and gas industry. For injection into exhausted oil or gas reservoirs, the required geological data is largely available. For injection into saline aquifers or for other types of geological storage, the information should be obtained if unavailable. Key items are the characteristics of the seal and dominant (short-term and long-term) trapping mechanisms.

6.4 The planning, design and construction should lead to an inherently safe storage site, which means that the risk of CO_2 (and incidental associated substances) escaping from the formation is reduced to an insignificant level.

6.5 The maximum estimated extent to which $CO_{2,}$ incidental associated substances and mobilised substances could migrate in the formation defines the zone to be characterised for risk management purposes. To determine the confinement zone, the following factors, among others, will assist in the definition of the geographic volume to be reviewed (see also Appendix I):

a. regional and local geology;
b. regional stratigraphy;
c. regional structure;
d. regional hydrogeology;
e. seismic history;
f. injection, static and dynamic properties of containment and confinement zone; and
g. vertical hydraulic gradient.

6.6 Collection of such information in areas where there has been no previous hydrocarbon exploration or production is even more critical.

Well integrity

6.7 The design, construction and operation of a well within the storage site are key factors in achieving the CO_2 storage objective. The well design and construction should account for operating conditions (pressure, fluid composition and acidity, duration, etc.) and address identified potential well failure scenarios. The OGP Guidelines for injection of produced water list many of the elements that need to be considered.

6.8 Well integrity additionally depends on:

a. the quality of materials used - the probability of CO_2 (including incidental associated substances) escaping through failure of the integrity of the injection well is low if the well is lined with materials known to withstand the corrosion by carbonic acid, which may be formed at the point of injection;
b. the management of the operation;
c. proper site-closure procedures so that long-term isolation has been accounted for.

Formation flow and fracture propagation prediction

6.9 Predictive modelling of injection of CO_2 streams should include both flow (reservoir) simulation, prediction of fracturing and fracture propagation, e.g., induced by CO_2 injection, and modelling of geochemical rock-fluid interaction. These will establish the transport and fate of the injected CO_2 stream and provide the operator with an integrated knowledge sufficient to manage the injection process in an environmentally protective manner. The modelling should 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.

6.10 Modelling should be updated in the light of monitoring results.

Preventive maintenance and contingency planning

6.11 Preventive maintenance and contingency planning are an integral part of a CO_2 injection operation. Potential failure modes should be evaluated at the planning stage along with the necessary remedial actions that might be taken. Examples of potential failures include:

a. pressure build-up exceeding security levels;

b. confinement problems (fracturing of the cap rock, breach to casing or cement around the casing); and

c. mechanical complications (e.g., corrosion, erosion, failures of wellhead, etc).

6.12 It is anticipated that precautions taken after injection operations have ceased will be similar to those used for oil and gas wells and by acid-gas disposal wells under which the wells are plugged to prevent hydraulic communication to the surface. Attention should be given to the procedures and materials used for sealing and cementing the wells to ensure the long-term integrity of storage of CO_2 streams, and the probability of cap rock and formation fracture.

6.13 Because the ultimate objective of storage of CO_2 streams in geological formations is to ensure permanent containment of these CO_2 streams, it will be necessary to archive documentation so that future generations are informed of the existence of the CO_2 storage site and its history. This includes keeping records of the authorisation and licensing process, site-closure and decommissioning procedures, together with data of long-term monitoring and management response capabilities.

Monitoring migration of CO_2 streams and mobilised substances within and above the formation during the injection phase

6.14 Monitoring would be done for at least two different purposes:

a. detection of potential leakages from sub-seabed geologic storage; and

b. verification that such leakage does not occur.

6.15 A monitoring programme should attempt to quantify the mass and distribution of CO_2 in each storage site and should record related biological and geochemical parameters. The monitoring programme should include:

a. monitoring for performance confirmation;

b. monitoring to detect possible leakages;

c. monitoring of local environmental impacts on ecosystems; and

d. monitoring of the effectiveness of CO_2 storage as a greenhouse gas mitigation technology.

Process monitoring and control

6.16 Essential elements of process monitoring and control include:

a. the injection rate;

b. continuous pressure monitoring;

c. injectivity and fall-off testing;

d. the properties of the injected fluid (including temperature and solid content, the presence of incidental associated substances and the phase of the CO_2 stream);

e. mechanical integrity of seals and (abandoned) wells;

f. containment of the CO_2 stream; and

g. control measures, overpressure, emergency shut down system.

While not essential, if observation wells are available they can provide useful information.

6.17 Techniques for monitoring stored CO_2 have been described in two IPCC documents: the IPCC SRCCS (IPCC, 2005) and the "Guidelines for National Gas Inventories"[xi] (IPCC, 2006). Baseline information is required on the geological structures within and above the formation so that the signal produced by stored CO_2 can be distinguished from that associated with the natural system. Seismic methods have already been shown to work for monitoring oil and gas reservoirs but such methods may not be applicable to storage of CO_2 streams in all settings. Modelling may be applied to convert monitoring signals to distribution or fluxes of CO_2. If seismic methods are used, careful consideration should be given to the effects on marine organisms of propagating seismic signals through the water column and seafloor.

6.18 Monitoring of CO_2 containment and migration may include the following elements:

a. performance monitoring (sometimes referred to as testing the Impact Hypothesis) which measures how well injected CO_2 stream is retained within the intended geologic formation; and

b. monitoring the geological layers above the formation to detect and measure possible migration of the CO_2 stream out of the intended formation;

6.19 The following items may be included, especially if it is suspected that migration of CO_2 above the formation could extend to the seafloor and in case that the storage site is in proximity to sensitive or endangered habitats and species:

a. monitoring the seafloor and overlaying water to detect and measure possible leakage of CO_2 (and incidental associated substances) into the marine environment. In this context special attention should be given to wells that intersect the storage formation; and

b. monitoring biological communities to detect and measure the effects of leakages on marine organisms.

Long term, post injection, monitoring of migration of CO_2 streams and mobilised substances

6.20 Long-term monitoring can generally be accomplished with a sub-set of the technologies used during the injection phase. Moreover, new and more efficient monitoring technologies are likely to evolve. Methods chosen for monitoring should not compromise the integrity of a sealed formation, or the marine environment. In addition, records should be kept of the authorisation, licensing and site-closure processes, together with data on long-term monitoring and management response capabilities.

Mitigation or remediation of CO_2 escape from the storage site or formation

6.21 The need for mitigation or remediation is determined by national authorities on the basis, among others, of the likelihood that CO_2 (and incidental associated substances) 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. Mitigation or remediation may begin as soon as CO_2 is known, or suspected, to have migrated from the formation. Leakage of a CO_2 stream from an injection site can occur during or after the injection phase. The most likely avenues for leaks include (see also Figure 4):

a. the injection well, possibly due to overpressure;

b. other abandoned or active wells;

c. areas where permeable rock reaches the surface of the seabed; and

d. fractures of, or high permeability zones, within the cap rock.

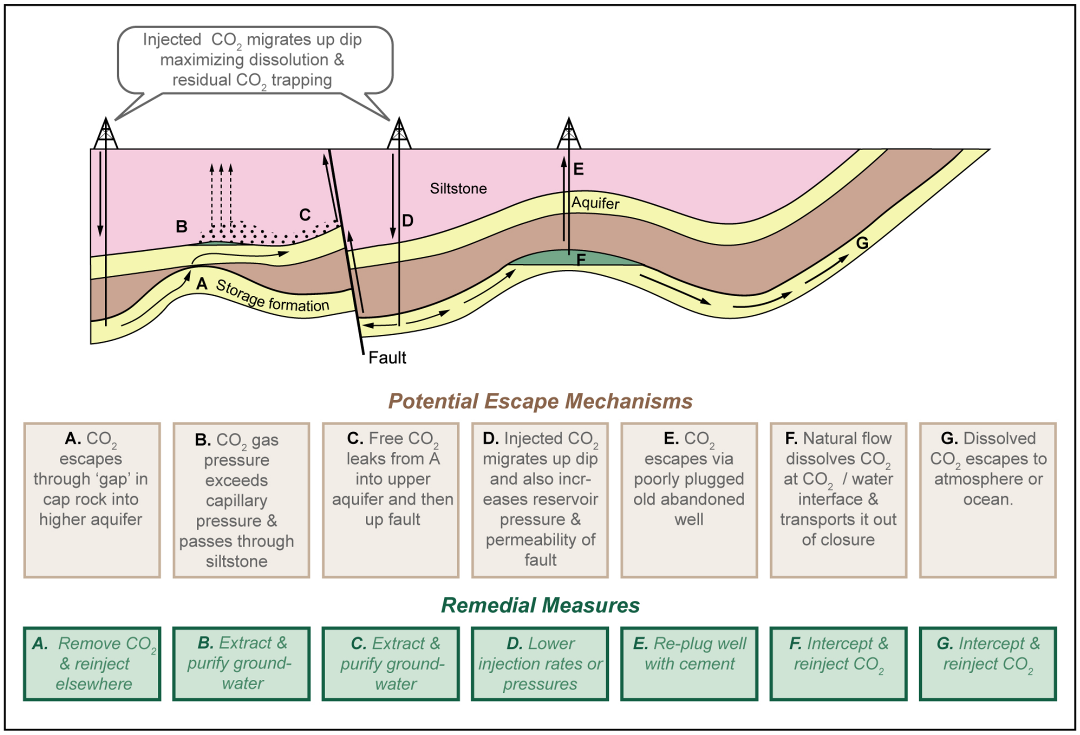

Figure4 Escape mechanisms and remedial measures (IPCC, 2005).

6.22 Methods for remediation of these leaks are analogous to techniques used in the oil and gas industry. Strategies such as transporting CO_2 streams to other parts of the same formation or to different storage sites should be available. These are described in Table 5.7 of IPCC SRCCS.

6.23 If leakage occurs through an active or abandoned well, remediation methods may include:

a. recapping wells or repairing faults in cement between rock and casings; and

b. drilling intersecting wells followed by controlling the leak with heavy mud followed by recapping.

6.24 If leakage occurs through faults or fractures, remediation methods may include:

a. lowering the injection pressure or the formation pressure by removing water or other fluids;

b. halting the injection until the project is stabilised;

c. transferring CO_2 streams to a more suitable formation; and

d. plugging the pathway by injecting sealing material.

Appendix 1 – Information needs for risk assessment and management

I.1 The information in this table may facilitate the various stages of Risk Assessment and Management of storage of CO_2 streams in geological formations. This table shows considerations rather than formal requirements. The intention is to be able to demonstrate that the site characteristics are consistent with the ultimate objective of permanent containment and protection of the marine environment, human health and other legitimate uses of the maritime area.

Issues to include in the risk assessment	**Parameters to identify, qualify and –where possible- quantify in the risk assessment**
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 CO_2 that are likely to be affected by the injection process o Proximity to other wells (hydrocarbon producers, former or present) or fields o Proximity to potable, irrigation or industrial water producing wells o Proximity to other injection wells o Age, depth and condition of the wells o 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 – Location, orientation and properties of faults or fractures that are likely to intersect the formation 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 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 Data quality – History, current status and age of information available on the geological formation
Marine environment characterisation	Ocean current and see floor topography in the region 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 o composition, structure, dynamic

Economic/regulatory factors	Economic feasibility Impact on other sub-seabed resources such as oil and gas extraction and other natural gas/CO_2 storage sites Regulatory framework Applicable regulations, codes and standards, and regulatory restrictions and restraints

Appendix II – Issues subject to further research to improve the risk assessment and management

This Appendix provides a compilation of several issues that required further research at the time of issuing these guidelines, in order to improve the process of risk assessment and management for storage of CO_2 streams.

II.1 It must be recognised that the assessment of hazard and risk related to storage of CO_2 streams in geological formations may include a significant level of uncertainty, especially since extremely long time horizons are involved. Uncertainty will arise from any limitations of the chosen models (geologic, predictive) as well as from the environmental effects data. This uncertainty should be used as a valuable source of information and included in the results, by applying uncertainty analyses in the different stages of the risk assessment.

II.2 Uncertainty can be constrained and reduced by the input of (site specific) monitoring and field test data. Uncertainty can further be reduced by establishing a better insight in processes and relations through the extension of existing and creation of new datasets.

II.3 The following paragraphs identify a number of issues where further research may improve the outcome of the risk assessment. The issues have been categorised along the major elements of the OSPAR Framework for Risk Assessment and Management (OSPAR-FRAM).

Risk Management - Improving options for remediation, mitigation and monitoring

II.4 Although a well-developed body of knowledge exists in the oil and gas industry for leak/release remediation, more experience will improve decisions on remediation and mitigation strategies to manage CO_2 leaking from geologic formations. This experience may be necessary either to:

a. confirm the similarities of behaviour between oil and gas operations and CO_2 injection sites; or
b. identify and describe possible differences in behaviour between oil and gas operation and CO_2 injection sites;
c. determine special procedures that are required for handling CO_2 streams in these situations;
d. determine the frequency and precision of monitoring during remediation and/or mitigating activities.

II.5 It may be necessary to develop research programs at existing CO_2 injection sites to develop general guidelines for leak remediation and mitigation activities. These research activities may also explore new remediation and mitigation techniques that have not previously been examined in the oil and gas industry.

II.6 Currently, there are no possibilities to determine leakage rates (in terms of volumes per time unit), once a leak would have been detected. Further, small leaks of CO_2 and incidental associated substances from the storage formation may remain undetected, when the resolution of the available monitoring techniques is less than necessary to observe such small leaks. It would be desirable to be able to detect small leaks, in view of the long time-frames involved in storage of CO_2 streams, in order to fulfil the objective of permanent containment and in order to improve possibilities of early intervention in the event CO_2 streams leaking from the storage site. Further research into refined monitoring techniques would therefore be desirable. The same applies for monitoring techniques, which may be applied in the water column or on the sea bottom.

Exposure assessment – Improving the predictions of exposure to CO_2 and incidental associated substances

II.7 Although the CO_2 stream should be characterised on a case-by-case basis, it would be beneficial to have a basic understanding of expected composition of injection streams from CO_2-generation processes. This may also help understanding the behaviour (e.g., mobilisation in low pH environments) and interaction of other substances that may be in the injection stream once in the geological and marine environment.

II.8 It appears that the availability of suitable models is limited. Development and application of simulation models is necessary to create understanding of, amongst others, abandoned well integrity and leakage processes, behaviour of CO_2 in seabed sediments and probability of exposure.

Effects Assessment – Improve the impact prediction by gaining knowledge on the effects on species and ecosystems as a result of leakage of CO_2 streams

II.9 A qualitative assessment of environmental effects is currently possible, based on available data, but further research is needed for quantitative assessments. Nowadays, effects data from exposures to increased CO_2 concentrations is available, but is mostly scarce, scattered and limited in detail[xii]. Existing field data are mainly limited to deep-sea situations (for ocean storage of CO_2) although currently also research is carried out in shallow waters. Specific data are available on the effects of ocean acidification due to increased atmospheric CO_2 concentrations (e.g., OSPAR 2006)[vii]. With regard to the available effects data, considerations include:

a. the need for studies of the response of representative species to various doses of added CO_2 and incidental associated substances for determination of a quantitative relation between exposure concentrations and the related effects. This is essential for a quantitative assessment of effects;

b. effects data should be available at the level of physiological and ecological processes (including abundance and biodiversity as well as biological/geological/chemical cycles), individual species (including vulnerable life stages) and the ecosystem (ensuring representation of ecosystem structure and function);

c. effects data should include studies that are longer in duration (intervals greater than the duration of a reproduction cycle or the lifespan of an individual) and larger in scale than currently performed[xiii];

d. effects data should be generated using the realistic mechanisms of increasing CO_2 concentrations under marine conditions (not mimicking pH effects using acids) since CO_2 effects are generally broader than pH effects only;

e. performance of experimental field studies of ecosystem consequences and monitoring studies, including endpoints/receptors that are not quantifiable;

f. application of ecosystem models (where available and validated) to consider the effects on species, communities, habitats and processes in the context of these models;

g. performance of field studies of ecosystemic consequences;

h. preferably, data acquisition should be carried out to include the effects on vulnerable life stages for a range of representative species (including microbial communities) found at the site, ensuring that ecosystems structure and functioning is represented; and

i. the inclusion of receptors - for which sensitivity is not quantifiable - in a monitoring programme in the event of leakage.

Appendix III - Glossary

III.1 This Appendix contains a glossary, acronyms and abbreviations, which have been selected from a comprehensive glossary in Annex II to IPCC SRCCS. Where appropriate these terms have been adapted for the purposes of this Risk Assessment and Management Framework.

Acid gas	Any gas mixture that turns to an acid when dissolved in water (normally refers to H2S + CO2 from sour gas (q.v.)).
Anthropogenic source	Source that is man-made as opposed to natural.
Aquifer	Geological structure containing water and with significant permeability to allow flow.
Baseline	The datum against which change is measured.
Blow-out	Refers to catastrophic failure of a well when the petroleum fluids or water flow unrestricted to the surface.
Brine	Water with a high concentration of dissolved salts.
Buoyancy	Tendency of a fluid or solid to rise through a fluid of higher density.
Cap rock	Rock of very low permeability that acts as an upper seal to prevent fluid flow out of a formation.
Capillary entry pressure	Additional pressure needed for a liquid or gas to enter a pore and overcome surface tension.
CO_2 stream	Carbon dioxide streams from carbon dioxide capture processes for storage in geological formations, which consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture, transport and storage processes used, i.e.: - source and process derived substances; and - added substances (i.e. substances added to the CO_2 stream to enable or improve the capture, transport and storage processes).
Casing	A pipe, which is inserted to stabilise the borehole of a well, after it is drilled.
CO_2 capture and storage	This is a process consisting of the separation of a CO_2 stream from industrial and energy-related sources, transport to a storage location and long-term isolation from the biosphere, including the atmosphere.
Completion of a well	Refers to the cementing and perforating of casing and stimulation to connect a well bore to a formation.
Confinement	The process by which a CO_2 stream is kept within a specified geological space.
Containment	Restriction of movement of a fluid to a designated volume (e.g., a reservoir).
D, Darcy	A non-SI unit of permeability, abbreviated D, and approximately = 1µm2.
Deep saline aquifer	A deep underground rock formation composed of permeable materials and containing highly saline fluids.
Dense fluid	A gas compressed to a density approaching that of the liquid.
Dense phase	A gas compressed to a density approaching that of the liquid.

Depletion	Of a reservoir: where production is significantly reduced.
Dissolution	With respect to CO_2, the process by which CO_2 separates into its component ions in water.
EOR	Enhanced oil recovery: the recovery of oil additional to that produced by standard production methods.
Fault	In geology, a surface at which strata are not longer continuous but displaced.
Flood	The injection of a fluid into an underground formation.
Formation	A body of rock of considerable extent with distinctive characteristics that allow geologists to map, describe, and characterise it.
Formation water	Water that occurs naturally within the pores of rock formations.
Fracture	Any break in rock along which no significant movement has occurred, but where the permeability may be significantly enhanced.
Geochemical trapping	The retention of injected CO_2 by geochemical reactions.
Geological time	The time over which geological processes take place.
Geomechanics	The process of movement or potential movement of rocks within the Earth's crust.
Geosphere	The Earth, its rocks and minerals, and its ground waters.
GHG	Greenhouse gases: carbon dioxide (CO_2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6).
Hazard	The potential to cause harm.
Hydro-geological	Concerning water in the geological environment.
Hydrostatic	Pertaining to the properties of a stationary body of water.
IEA GHG	International Energy Agency – Greenhouse Gas R&D Programme.
Igneous	Rock formed when molten rock (magma) has cooled and solidified (crystallised).
Injection well	A well in which fluids are injected rather than produced.
Injectivity	A measure of the rate at which a quantity of fluid can be injected into a geological formation.
In-situ mineralisation	A process whereby carbon dioxide injected into a geological formation reacts with silicate minerals, forming stable carbonate minerals.
IPCC	Intergovernmental Panel on Climate Change.
Leakage	In respect of storage of CO_2 streams, the escape of that CO_2 stream from the storage formation into overlying formations, the water column and the atmosphere.
Log	Records taken during or after the drilling of a well.
Long term	The term following the closure of the CO_2 storage site. This could extend to several thousand years into the future.

Mature sedimentary basins	Geological basins formed by the deposition of sedimentary particles and grains under sub-aqueous and sub-aerial conditions and in which deposited organic matter has matured into hydrocarbon reserves.
Microseismicity	Small-scale seismic activity, usually only detectable by the use of sensitive instrumentation.
Migration	The movement of fluids within or out of formations.
Mitigation	The process of reducing the adverse impact of any failure in the CO_2 storage system.
Monte Carlo simulation	A modelling technique in which the statistical properties of outcomes are tested by random inputs.
Mudstone	A very fine-grained sedimentary rock that commonly provides a seal, thus preventing the upward migration of fluids.
Observation well	A well installed to permit the direct observation of subsurface conditions.
OSPAR Convention	Convention for the Protection of the Marine Environment of the North-East Atlantic, adopted in Paris, 22 September 1992.
Other substances (or associated substances)	Associated substances originating from the source material and the capture, transport and storage processes used.
Overburden	Rocks and sediments above any particular stratum.
Overpressure	Pressure created in a formation that exceeds the pressure inherent at the formation's depth.
Permanence	The term to indicate the likelihood that the situation will stay unchanged.
Permeability	Ability to flow or transmit fluids through a porous solid such as rock.
Pore space	Space between sedimentary grains that can contain fluids.
Porosity	Measure of the amount of pore space in a rock.
Regional scale	A geological feature that crosses an entire basin, or other geological provinces.
Remediation	The process of correcting any source of failure, for example in a CO_2 storage system.
Reservoir	A subsurface body of rock with sufficient porosity and permeability to store and transmit fluids.
Risk	Probability of occurrence of an undesired event, multiplied by the (HSE) impact of that event.
Risk assessment	Part of a risk-management system, consisting of exposure assessment, effect assessment and risk characterisation.
Risk characterisation	Risk characterisation is the step in the risk assessment process which determines the likelihood and severity of impacts on the marine environment.
Saline formation	Sediment or other rock formation containing brackish water or brine.
Seal	An impermeable rock that forms a barrier above or around a formation such that fluids are held in the formation.

Seismic technique	Measurement of the properties of rocks by the refraction and reflection of sound waves generated artificially or naturally.
Shale	Impermeable very fine-grained and finely laminated sediment that commonly provides a seal to the movement of underlying fluids.
Short term	The near term prior to closure of the CO_2 storage site. This could extend to some one hundred years into the future.
Sour gas	Natural gas containing significant quantities of acid gases, such as H_2S and CO_2.
Spill point	The structurally lowest point in a structural trap (q.v.) that can retain fluids lighter than background fluids.
Storage	A process for retaining captured CO_2 streams in deep geological formations so that it does not reach the atmosphere. The terms sequestration and storage are also used interchangeably.
Storage site	The location for storage in geological formations, comprising one or more wellheads and surface facilities.
Structure	Geological feature produced by the deformation of the Earth's crust, such as a fold or a fault; a feature within a rock such as a fracture; or, more generally, the spatial arrangement of rocks.
Supercritical	At a temperature and pressure above the critical temperature and pressure of the substance concerned. The critical point represents the highest temperature and pressure at which the substance can exist as a vapour and a liquid in equilibrium.
Tectonically active area	Area of the Earth where deformation is presently causing structural changes.
Trap	A geological structure that physically retains fluids, which are lighter than the background fluids.
Well	Manmade hole drilled into the Earth to produce liquids or gases, to allow the injection of fluids, or to enable observations of subsurface process.
Well integrity	The ability of a well to prevent any leaks from occurring, either along the (cemented) annulus (casing / open hole) or between the plugs and the casing.
Wellhead pressure	Pressure developed at the top of the well.

Appendix IV - Literature

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[i] Draft Discussion paper from the Task Force for Reviewing and Identifying Standards with Regards to CO_2 Storage Capacity Measurement, CSLF 2005.

[ii] IPCC SRCCS: p. 141.

[iii] IPCC SRCCS: pp 244-246.

[iv] IPCC SRCCS: pp 244-246 and 250-251.

[v] IPCC SRCCS: p. 197; p. 249.

[vi] According to the IPCC SRCCS, there are two types of leakages, i) abrupt leakages and ii) gradual leakages.

[vii] OSPAR 2006. Effects on the Marine Environment of Ocean Acidification Resulting from Elevated Levels of CO_2 in the Atmosphere.

[viii] Poremski, 2004, in LC/SG-CO_2 1/INF.2.

[ix] OGP 2000. Guidelines for Produced Water Injection. Report 2.80/302, January 2000, International Association of Oil and Gas Producers.

[x] OSPAR. 2001. Environmental Aspects of On and Off-Site Injection of Drill Cuttings and Produced Water. Oslo Paris Commission ISBN 0 946956 69 3.

[xi] IPCC 2006. DRAFT Guidelines for National Gas Inventories. Intergovernmental Panel on Climate Change.

[xii] See IPCC SRCCS, Chapter 6, for an overview of existing data.

[xiii] IPCC SRCCS, p. 311.