Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide

Guidance Document 1

CO_2 Storage Life Cycle Risk Management Framework

Climate Action

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Disclaimer

This document reflects the view of the Commission services and is not of a binding nature.

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Purpose of Guidance Document

This Guidance Document (GD) is part of the following set of Guidance Documents:

- Guidance Document 1: CO_2 Storage Life Cycle Risk Management Framework
- Guidance Document 2: Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures
- Guidance Document 3: Criteria for Transfer of Responsibility to the Competent Authority
- Guidance Document 4: Financial Security (Art. 19) and Financial Mechanism (Art. 20)

The purpose of this set of Guidance Documents is to assist stakeholders to implement Directive 2009/31/EC on the geological storage of CO_2 (so-called CCS Directive) in order to promote a coherent implementation of the CCS Directive throughout the European Union (EU). The guidance does not represent an official position of the Commission and is not legally binding. Final judgments concerning the interpretation of the CCS Directive can only be made by the European Court of Justice.

This Guidance Document 1 (GD1) addresses the overall framework for geological storage in the CCS Directive for the entire life cycle of geological CO_2 storage activities including its phases, main activities and major regulatory milestones. Other issues addressed in the document include the high-level approach to risk assessment and management which is intended to ensure the safety and effectiveness of geological storage, and the processes by which the Competent Authority or Authorities[1] (CA or CAs) in each Member State can interact with the operators at key project stages, particularly with regard to risk management.

GD1 is structured as follows. The following section provides an introduction to the legislative context relating to the life cycle and risk management. Section 3 provides a detailed framework for the life cycle of CO_2 storage projects. Section 4 describes the geological context for CO_2 storage in Europe. Section 5 describes the nature of risks in geological storage. The subsequent section 6 deals with risk management of storage including risk identification, risk ranking and risk management. The final section is a summary of key issues.

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[1] According to Art. 23 of the CCS Directive "Member States shall establish or designate the competent authority or authorities responsible for the fulfilling the duties established under this Directive".

1. Legislative context

The CCS Directive establishes a legal framework for the geological storage of CO_2 and specifies that environmentally safe CO_2 geological storage means the permanent containment CO_2 in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health (CCS Directive, Article 1).

The CCS Directive considers different stages, milestones and requirements and responsibilities in the life cycle of geological storage. These stages include the assessment of the available storage capacity, characterisation and assessment of the potential storage site and complex, development, operation, closure and post-closure, and transfer of responsibility. The whole life cycle for any individual CO_2 storage project could be in the region of 50-70 years up to the final transfer of responsibility to the CA/Member State. The framework described in this guidance covers all phases in a comprehensive manner.

On the basis of the CCS Directive the competent authorities (CAs) of Member States and the operator of CO2 storage site will interact at key stages of a CO_2 storage project. These key points for interaction refer in particular to risk management.

Operators will have to interact with the CA while:

- Applying for an exploration permit;
- Applying for a storage permit, which includes proof of the technical competence of the potential operator, the characterisation of the storage site and storage complex with an assessment of its expected security, specifications related to CO_2 streams (total quantity to be injected and stored, composition, injection rates and pressures), description of preventive measures to prevent significant irregularities, a monitoring plan for the storage complex and the injection facilities, a corrective measures plan for leakages or significant irregularities, a provisional post closure plan, and proof of financial security or any other equivalent;
- Reviewing of storage permit and updating of monitoring plan;
- Reporting;
- Routine and non-routine inspections;
- Notifying the CA in the event of leakages or significant irregularities and implementing corrective measures and measures related to the protection of human health and the environment;
- Applying for closure of the storage site, including an updated post closure plan;
- Transferring the responsibility for all legal obligations after making a financial contribution available to the CA.

1.1 CO_2 Storage Safety and Risk Management

Environmentally safe geological storage of CO_2 is a fundamental goal of the CCS Directive. It states that "the purpose of environmentally safe geological storage of CO_2 is permanent containment of CO_2 in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health" (Art. 1).

The safety of storage is an ongoing theme throughout the storage life cycle. The key requirements of the CCS Directive include specific provisions at the outset (i.e. site selection), during operation and after closure:

- A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk[2] of leakage, and if no significant environmental or health risks exist.
- The requirement for the operator to immediately notify the CA in the event of leakages or significant irregularities, and to take the necessary corrective measures.
- That a key criterion for transfer of responsibility after closure is that all available evidence indicates that the stored CO_2 will be completely and permanently contained (see GD3 for details).

The CCS Directive was developed on the basis that the regulatory framework for geological storage should be based on an "integrated risk assessment for CO_2 leakage, including site selection requirements designed to minimise the risk of leakage, monitoring and reporting regimes to verify storage and adequate remediation of any damage that may occur" (Recital 7).

These requirements can be met by applying the principles of risk management to CO_2 storage projects. In this context, risk management is defined as the identification, assessment, and prioritization of the risks to secure storage, together with the application of resources to prevent, monitor, and correct leakages or significant irregularities throughout the project life cycle.

Risk management is therefore considered essential to ensuring the safety of CO_2 storage. This will require periodic and ongoing assessment of the risks relating to containment and leakage, as well as uncertainties in the geological framework, models and performance assessments. It is intended that risk management techniques will be used to identify, mitigate, and manage identified risks and uncertainties in order to ensure the safety of any CO_2 storage site.

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[2] Article 3(18) defines significant risk as a combination of a probability of occurrence of damage and a magnitude of damage that cannot be disregarded without calling into question the purpose of the CCS Directive for the storage site.

This document aims to provide guidance on the overall approach for the CAs that is consistent with the needs of the CCS Directive. More details on possible risk management procedures and methodology that may be adopted by operators are available in the CO2QUALSTORE report.

2. Life Cycle Framework for CO_2 Storage Projects

2.1 Approach

The life cycle framework for CO_2 storage presented in this guidance is based on a "stage gate" approach that is similar to the frameworks used in industry project management systems for major energy projects. This separates out major phases and milestones for the activities in project development, operations and closure, together with permitting and regulatory approvals. It is suggested that risk management is considered a central part of the processes involved in implementing CO_2 storage projects. Risk management should be a continuous and developing process throughout the project life cycle.

The terminology used here is derived from and consistent with the CCS Directive, and may therefore differ from terminology used elsewhere. The life cycle framework is intended to represent individual projects, rather than all storage activities within a region or country. The guidance is to consider what phase any specific project is at and what activities and phases are required to progress the project, and how long each phase may be.

The length and durations shown for each phase of individual projects as in the framework are generic in nature and will be project specific. Some of the early phases may not be required for some projects depending on the nature of the storage option and availability of data. For example, exploration activities may not be required for storage options in oil and gas fields.

It is also important to recognise that not all activities are sequential, and that some activities may be part of an ongoing or continuous process. For example, the assessment activities on storage capacity, as described below, are likely to be an ongoing process, as more data is accumulated over time.

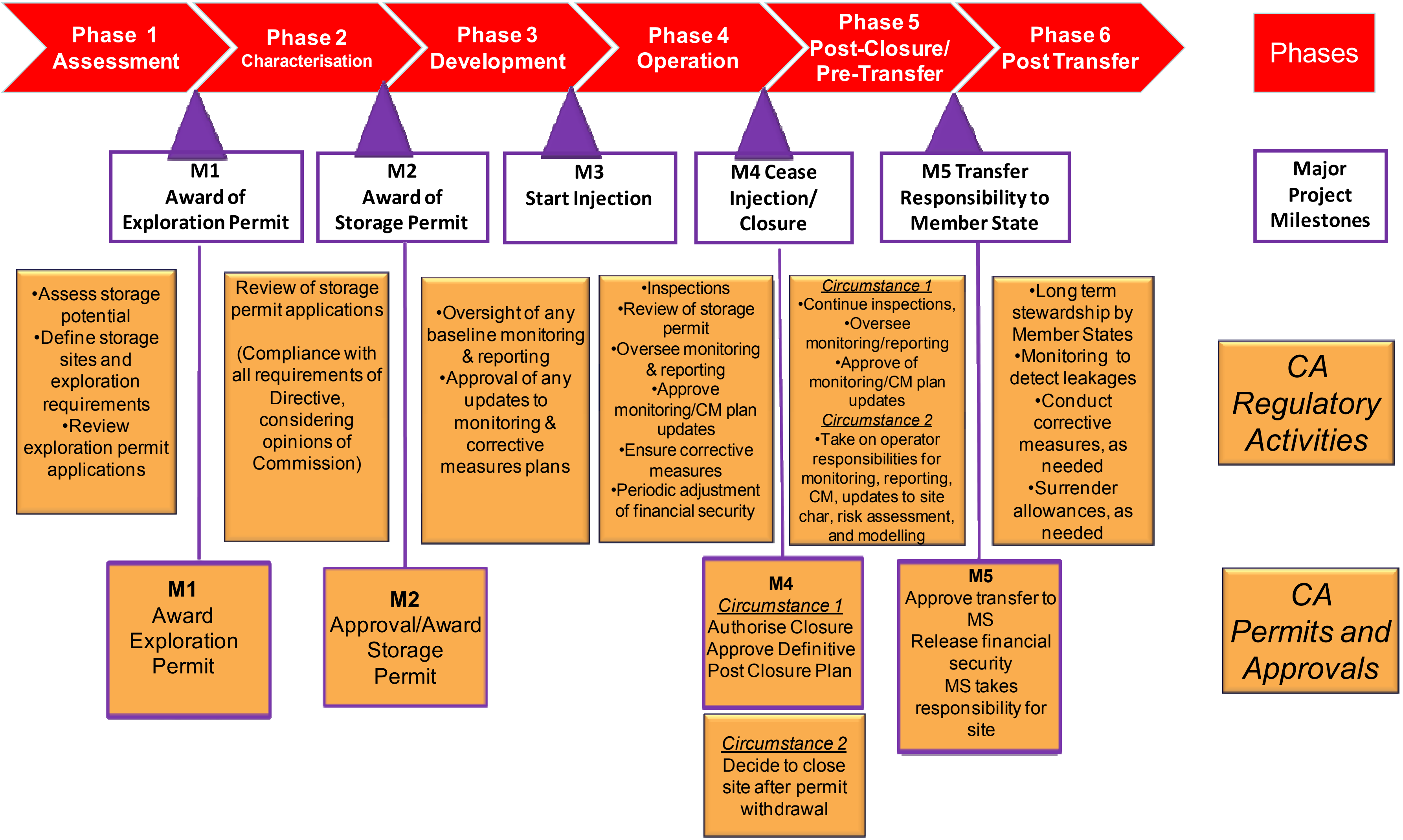
Risk management should be considered as an ongoing and iterative process throughout the storage life cycle. This will involve periodic and ongoing assessment of the risks relating to containment and leakage, as well as uncertainties in the geological framework, models and performance assessments.

Risk management techniques will be used to identify, mitigate, and manage identified risks and uncertainties through the monitoring plan, the description of preventive measures and the corrective measures plan in order to ensure the safety of any CO_2 storage site.

2.2 Phases

Based on the CCS Directive the life cycle of a CO_2 storage project can be subdivided into six main phases, separated by five major project or regulatory milestones. These are illustrated in Figure 1 and summarised in Table 1. The role of the CAs and major regulatory activities are described in section 3.3.

Figure 1: Summary of CO_2 Storage Life Cycle Phases and Milestones



Phase 1
Assessment

Phase 2
Characterisation

Phase 3
Development

Phase 4
Operation

Phase 5
Post-Closure/
Pre-Transfer

Phase 6
Post Transfer

Phases

M1
Award of Exploration Permit

M2
Award of Storage Permit

M3
Start Injection

M4 Cease Injection/ Closure

M5 Transfer Responsibility to Member State

Major Project Milestones

- Assess storage potential
- Define storage sites and exploration requirements
- Review exploration permit applications

Review of storage permit applications

(Compliance with all requirements of Directive, considering opinions of Commission)

- Oversight of any baseline monitoring & reporting
- Approval of any updates to monitoring & corrective measures plans

- Inspections
- Review of storage permit
- Oversee monitoring & reporting
- Approve monitoring/CM plan updates
- Ensure corrective measures
- Periodic adjustment of financial security

Circumstance 1
- Continue inspections,
- Oversee monitoring/reporting
- Approve of monitoring/CM plan updates

Circumstance 2
- Take on operator responsibilities for monitoring, reporting, CM, updates to site char, risk assessment, and modelling

- Long term stewardship by Member States
- Monitoring to detect leakages
- Conduct corrective measures, as needed
- Surrender allowances, as needed

CA Regulatory Activities

M1
Award Exploration Permit

M2
Approval/Award Storage Permit

M4
Circumstance 1
Authorise Closure
Approve Definitive Post Closure Plan

Circumstance 2
Decide to close site after permit withdrawal

M5
Approve transfer to MS
Release financial security
MS takes responsibility for site

CA Permits and Approvals

2.3 Activities and Roles during Life Cycle Phases

The main activities, roles and responsibilities of the CAs and the operator in accordance with the CCS Directive during different stages of the life cycle of any geological storage project are summarised below, as indicated in Table 1:

- **Phase 1: Assessment of storage capacity**

  The CCS Directive requires under Art. 4(2) that Member States which intend to allow geological storage of CO_2 in their territory should undertake an assessment of the storage capacity available in parts or in the whole of their territory. Such a capacity assessment can include a preliminary assessment of risks relating to the potential storage areas. The capacity and risk assessments could form the basis for the CA to define potential storage sites and areas where exploration is required for site selection to reduce uncertainty and risk. The assessment of available storage capacity required under Article 4(2) of the Directive can also be done by awarding exploration permits to entities possessing the necessary capacities as specified in Art. 5.

  The CA should also consider other potential uses for the subsurface and surface areas where CO_2 storage might take place and take account of competing requirements and potential synergies. These include planned or future exploration and exploitation of oil, gas or coal resources, natural gas storage, geothermal opportunities, water extraction and wind farms. The areas and volumes defined for the purposes of storage permits require specific attention to avoid future conflicts or sub-optimal use of the subsurface.

  Appropriate risk management may require a number of potential storage options to be systematically evaluated in the Assessment and Characterisation phases (i.e., Phase 1 and 2). The assessment of multiple storage options can provide a risk-diverse portfolio and can serve to mitigate geotechnical and other development risks. The intent of risk management activities is to identify at an early stage which options offer a non-significant life-cycle leakage risk, while excluding others that are unlikely to meet the requirements of the Directive.

  Specific areas and projects will progress to the next milestone and phase after the assessment phase. However, assessment activities, including storage capacity estimation, are likely to be required on an ongoing basis at the national or regional levels.

- **Milestone 1: Award Exploration Permit**

  An exploration phase may be required where further information is needed for the potential storage sites. According to the CCS Directive "exploration" is the assessment of potential storage complexes by means of activities such as drilling to obtain geological information about strata in the potential storage complex and, where appropriate, carrying out of injection tests[3] to characterise the potential storage site.

Where exploration is required, Member States would need to grant exploration permits in accordance with the CCS Directive before exploration activities take place. For storage sites authorised or used on 25 June 2009 in accordance with existing legislation, (retroactive) exploration permits are not required. In all other cases, exploration permits in line with the requirements laid out in Article 5 are necessary. Pre-existing exploration permits may be considered as long as requirements laid out in Article 5 are met.

During the validity of the exploration and storage permit (including permit procedure, pursuant to Article 6(3)), the CA shall ensure that no conflicting use of the storage complex is allowed with other uses.

- **Phase 2: Characterisation and assessment of the storage complex**

During the characterisation phase the operator will carry out a characterisation and assessment of the potential storage complex and surrounding area including, where necessary, exploration activities in order to prepare for development and submission of storage permit application for approval by the CA at the end of the phase. Chapter 2 of GD2 describes the various issues in site characterisation.

Exploration activities may be required for any type of storage option. In some cases, they may not be necessary for storage options in oil and gas fields, unless new seismic, further drilling or injection test(s) are needed to evaluate specific storage issues (see Table 4 and GD2 section 2.3.1). However exploration activities may usually be required for storage saline aquifer options[4] and other option types (see GD2 section 2.3.3). These activities should take account of identified risks and uncertainties, in order to collect new data and reduce the level of risk or uncertainty.

Detailed characterisation of the storage site and storage complex and its surrounding area is an essential and vital step ahead of the permitting of a site for storage development and injection operations. This phase involves extensive detailed studies by the operator to define the geological framework of the storage site and complex and its surrounding area, and to model it in three dimensions through initial versions of static and dynamic models. These models should consider any cross-border implications of the proposed scheme. Further drilling and injection testing activities may also be conducted as part of this phase for the purposes of risk and uncertainty reduction. Complex characterisation is also critical for assessing its monitorability, and is a starting point for developing a monitoring plan. Further guidance is provided in GD2.

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[3] Art. 5 (1) specifies "where appropriate, monitoring of injection tests may be included in the exploration permit".

[4] The CCS Directive uses the term “saline aquifer” for deep saline formations. See GD2, section 2.11 for a glossary defining and discussing “saline aquifers”

At this stage, in preparation of a storage permit application, the operator is required to conduct a detailed risk assessment, to describe measures to prevent significant irregularities and to develop monitoring, corrective measures and provisional post-closure plans. During the characterisation phase, the operator should also assess the potential types and amount of financial security or any other equivalent that would be necessary based on the risk assessment.

- **Milestone 2: Award of Storage Permit**

The "storage permit" means a written and reasoned decision or decisions by the CA authorising the geological storage of CO_2 in a storage site by the operator. This would specify the conditions under which geological storage may take place, taking account of identified risk, and would be issued by the CA pursuant to the requirements of the CCS Directive.

- **Phase 3: Site Development**

Detailed engineering design of the storage scheme, such as Front End Engineering Design (FEED) may be carried out before or after the award of the storage permit. Site development by the operator would be expected to take place when a storage permit is in place. In this phase, the operator would construct the infrastructure and facilities required for the storage site, including platforms or subsea equipment for offshore sites. New injection wells would be drilled and any remediation of existing wells or facilities would take place[5].

Baseline pre-injection monitoring of the storage complex (including drilling and collecting data from potential monitoring wells) should be conducted by the operator as part of the monitoring plan; see GD2. This would need to be reported to the CAs in accordance with monitoring guidelines as described further in GD2. The new data acquired through drilling and baseline monitoring should be used by the operator to validate and update the characterisation of the storage complex, modelling, risk assessment and monitoring and corrective measures plans.

- **Milestone 3: Start of Injection**

The commissioning of the project and start-up of CO_2 injection is a major project milestone at the start of the operations phase. It marks the commencement of actual geological storage CO_2.

The CCS Directive does not specify the start of injection as a regulatory milestone. However, it is anticipated that the CA may need to ensure that storage facilities have been constructed as planned in the storage permit prior to the start of injection.

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[5] Remediation of existing wells could take place at earlier stage if this is required to demonstrate that legacy wells can be abandoned to a level that supports secure containment and allows risk to be managed ahead of development

- **Phase 4: Operations**

The operations phase is the period when injection of CO_2 in the storage site by the operator takes place. Monitoring of the storage complex and corrective measures are key parts of the overall risk management process. The operator is required to do this in line with the CCS Directive and as described in Chapter 4 of GD2. The results of monitoring must be reported to the CA at an agreed frequency and at least once every year. A corrective measures plan is also required and corrective measures will need to be taken in the event of leakages or significant irregularities. Corrective measures would serve to manage and mitigate any leakage or irregularities as an integral part of the risk management activity. They are detailed in Chapter 5 of GD2.

Further development and drilling activities may take place during this phase. If these are undertaken the risk assessment should include consideration of their impact on site safety, as well as any particular issues where new wells are drilled into the CO_2 plume. Data from new wells and development activity should be used by the operator to verify and update the characterisation of the storage complex, modelling and risk assessment as well as the monitoring and corrective measures plan. These can also be used to reassess any cross-border issues.

During this extended period the CA must ensure that monitoring takes place in accordance with agreed plans and must approve updates to monitoring and, where appropriate, corrective measures plans (see GD2 for more details). The storage permit needs to be reviewed by the CA five years after issuing the permit and every ten years thereafter.

The CA must organise a system of routine and non-routine inspections as described below, with routine inspections taking place at least once each year.

In the event of leakages or significant irregularities (which imply the risk of leakage), the operator must immediately notify the CA, and take the necessary corrective measures. According to Article 16(3) of the CCSD, the CA may at any time require the operator to take the necessary corrective measures, as well as measures related to the protection of human health. These may be additional to or different from those laid out in the corrective measures plan. The CA may also at any time take corrective measures by itself, and shall do so if the operator fails to take the necessary corrective measures itself, and shall recover the costs incurred from the operator, including by drawing on the financial security (see GD4). Any corrective measures required in addition to the approved corrective measures plan should be proportionate to the risk associated with the leakage or significant irregularity. Additional monitoring could be needed to ensure that corrective measures are effective.

As foreseen in Article 15 of the CCS Directive, CAs are required to organise a system of routine and non-routine inspections of all storage complexes within the scope of the CCS Directive for the purposes of checking and promoting compliance with the requirements of the CCS Directive and of monitoring the effects on the environment and on human health. These should be carried out at least once a year throughout this phase of the life cycle (Article 15(3)). The CCS Directive specifies that inspections should include activities such as visits of the surface installations, including the injection facilities, assessing the injection and monitoring operations carried out by the operator, and checking all relevant records kept by the operator. They shall examine the relevant injection and monitoring facilities as well as the full range of relevant effects from the storage complex on the environment and on human health.

Non-routine inspections shall be carried out:

- if the CA has been notified or made aware of leakages or significant irregularities pursuant to Article 16(1);
- if the reports pursuant to Article 14 have shown insufficient compliance with the permit conditions;
- to investigate serious complaints related to the environment or human health;
- in other situations where the CA considers this appropriate.

Following each inspection, the CA shall prepare a report on the results of the inspection. The report shall evaluate compliance with the requirements of the CCS Directive and indicate whether or not further action is necessary. The report shall be communicated to the operator concerned and shall be publicly available in accordance with relevant EU legislation within two months of the inspection.

The operator should inform the authorities of any planned changes in the operation of the site throughout this phase, including changes concerning the operator. Where appropriate the CA shall update the storage permit or the permit conditions and the CA must ensure no substantial changes are implemented without a new or updated permit.

The CA is required to review and where necessary update, or as a last resort withdraw the storage permit in accordance with Article 11(3) of the CCS Directive:

- if the authority has been notified or made aware of any leakages or significant irregularities pursuant to Article 16(1);
- if the reports submitted pursuant to Article 14 or the inspections carried out pursuant to Article 15 show non-compliance with permit conditions or risks of leakages or significant irregularities;
- if the authority is aware of any other failure by the operator to meet the permit conditions; or
- if it appears necessary on the basis of the latest scientific findings and technological progress.
- Without reference to the above circumstances, five years after issuing the permit and every 10 years thereafter.

In the event that the CA decides to withdraw the storage permit, it may either issue a new storage permit, or decide to close the site as discussed below.

- **Milestone 4: Closure**

Article 3 of the CCS Directive defines “Closure” of a storage site as when the CO_2 injection into that storage site is definitely ceased. Article 17 specifies that a storage site shall be deemed as being closed under the following circumstances:

1. if the relevant conditions stated in the storage permit have been met;

2. if the operator has requested the site be closed and the CA has authorised the closure; or

3. the CA withdraws the storage permit under circumstances laid out in Article 11(3).

Under the first circumstance, closure will take place when site has been operated as per the storage permit and the total quantity of CO_2 authorized to be geologically stored is reached. The operator may also request the closure of the site if the operator deems that a safe limit of injection has been reached (even though the permit may allow more injection), or if continued injection becomes uneconomic. This would be subject to authorisation by the CA in accordance with the CCS Directive[6]. As discussed above, the CA may also decide, as a last resort, to withdraw the permit if the operator is unable to meet the storage permit requirements, and could either issue a new storage permit or decide to close the site.

If the closure occurs pursuant to points 1 or 2 above, then the operator will perform all post-closure obligations including post-closure monitoring according to an updated post-closure plan, approved by the CA, and then engage in transfer of responsibility. If the closure occurs pursuant to point 3 above, then the CA takes immediate responsibility for monitoring and corrective measures and to meet any requirements for surrendering allowances in case of leakages pursuant to Directive 2003/87/EC. If the CA does not issue a new storage permit, the CA will also have to perform the post-closure obligations on the basis of the updated post-closure plan. The costs for this are expected to be taken from the appropriate financial security instrument(s) provided by the operator as a condition for the storage permit (see GD4).

In practice, a series of activities are involved in the closure stage. The activities involve updating the provisional post-closure plan, cessation of injection, plugging and abandoning of selected wells, equipment removal, and on-site inspection.

The updated post-closure plan will be based on the provisional post-closure plan included in the storage permit and should have:

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[6] Article 17

1) a list of surface and subsurface facilities that will be removed once the injection has stopped;
2) plugging and abandonment plans for wells to be removed after the cessation of injection;
3) a plan for monitoring (including the needed wells and equipment) in the post-closure pre-transfer phase;
4) a list of monitoring benchmarks that will be tracked to determine when the transfer conditions are met; and
5) a plan for site sealing and reclamation.

The updated post-closure plan needs to take into consideration operational and monitoring history, best practice and technological improvements. The updated plan should also take into account the impact of any anomaly, irregularities, leakages, and corrective measures taken during the operations phase of the project.

The operator should also include relevant methods of measurement (DNV, 2010b). The updated models, including both the static geological model and the dynamic reservoir simulation models of the CO_2 plume and pressure evolution, should incorporate all information obtained during the site operation (see GD2 and GD3).

- **Phase 5: Post-Closure Pre-Transfer Monitoring Phase**

The responsibilities during this phase depend on the conditions for site closure as described above.

Where site closure is based on meeting all of the relevant conditions stated in the storage permit, the post-closure pre-transfer monitoring phase lasts from closure until the transfer of responsibility to the CA. The operator would initiate the transfer process after obtaining authorisation from the CA.

Most of the injection wells and some monitoring wells can be plugged and abandoned, based on the post-closure monitoring plans. The plugging should follow best industry practices and with best available technology and materials at the time. In order to improve monitoring, some of the injection wells may be converted to monitoring duty — and such options should be considered on the basis of risk assessments and operational history.

The primary goal in the post-closure pre-transfer monitoring is to ensure that the site reaches the conditions when the transfer of responsibility can take place, and in particular to ensure that stored CO_2 is behaving as expected without any detectable leakages based on the monitoring as determined by the updated post-closure monitoring plan. While there is greater potential for leakage during the injection period due to high and possibly increasing pressure in the injection zone, it is expected that such pressures would decrease after closure, reducing the chance of many kinds of leaks. Furthermore, if there were any leakages during the operating period and corrective measures were undertaken, it is also important to ensure that these corrective measures are still operational and the leakages do not re-occur. Therefore, this period of monitoring the stored CO_2 is critical for ensuring that there are no significant environmental or health risks.

Routine inspections should continue during this period with non-routine inspections as required. The CCS Directive, Article 15(3), requires that CA organises for routine inspections to be carried out at least once a year until three years after closure and every five years until transfer of responsibility to the CA has occurred.

The length of this phase is determined by how long it will take to meet the requirements for the transfer of responsibility conditions specified by the CA, in particular the criterion of evolution towards long term stability (see GD3).

- **Milestone 5: Transfer of Responsibility**

The Transfer of Responsibility is a key milestone in the life cycle of a storage project, covered in detail in GD3. The CCS Directive makes provision for transfer of responsibility from the operator to the CA if the following conditions are met:

- all available evidence indicates that the stored CO_2 will be completely and permanently contained;
- a minimum period, to be determined by the CA has elapsed; this period should be no shorter than 20 years, unless the first condition above is met before the end of that period;
- the financial obligations referred to in Article 20 have been fulfilled; and
- the site has been sealed and the injection facilities have been removed.

The process and activities involved are described in the detailed guidance document 3 (GD3). The operator is required to submit report and upon approval of the report make the payment for the financial obligation. Site sealing, removal of injection facilities, and transfer of relevant data will take place at this time. As discussed in GD3, site sealing could be based on existing procedures for abandonment of wells in different Member States as long as these meet the requirements of the CCS Directive.

- **Phase 6: Post-Transfer**

This is the final phase in the storage project life cycle after the transfer of responsibility. Responsibility for all legal obligations resides with the CA

CA conducted routine inspections of the site are no longer required and monitoring may be reduced to a level which allows for detection of leakages or significant irregularities. If any leakages or significant irregularities are detected, monitoring shall be intensified as required to assess the scale of the problem and the effectiveness of corrective measures which would need to be taken by the CA. CA is also responsible for the surrender of allowances in case of leakages, pursuant to Directive 2003/87/EC.

If there has been a fault on the part of the operator such as deficient data, concealment of relevant information, negligence, wilful deceit or a failure to exercise due diligence, the CA may recover additional costs (beyond the financial contribution) from the operator.

Table 1 CO_2 Storage Life Cycle Framework Summary

Phase/Milestone		**CA Activities**	**Key Operator Activities**	**Duration** [7]
Phase 1	Assessment of storage capacity	• MS intending to allow storage should assess storage capacity available in the country and/or region including by awarding exploration permits. • Define potential storage sites, and where exploration is required for site selection. • Review exploration permit application(s)	• Conduct own assessments of storage potential, sites and exploration requirements. • Prepare Exploration Permit Application(s)	0.5 – 2 Years
Milestone 1	Award of Exploration Permit	• Award exploration permit		
Phase 2	Characterisation and assessment of storage complex	• Review storage permit applications (compliance with all relevant requirements of the CCS Directive and of other relevant EU legislation, operator is financially sound and technically competent, • Permit applications and related material should be made available to the European Commission who may provide opinions to the CA. The Commission's opinion is non-binding, although the CA needs to explain the departures in the final permit decision relative to the Commission's opinions.	• Carry out exploration and appraisal seismic, drilling and injection testing activity. • Carry out site selection process • Carry out site/complex characterisation (see GD2) • Prepare project development plans and design • Submit storage permit applications (including site/complex characterisation, risk assessment, monitoring, corrective measures and provisional closure plans, quantity of CO_2, composition of CO_2, measures to prevent significant irregularities, proof of financial security, etc.)	2 – 11 Years[8]
Milestone 2	Award of Storage Permit	• Approve and award storage permit(s)	• Investment decision for Storage project development by Operator and any other partners	
Phase 3	Development	• Supervise any baseline monitoring and reporting	• Construct facilities and drill injection and monitoring wells (major capital expenditure) • Remediate pre-existing infrastructure and wells • Carry out baseline surveys and pre-injection monitoring (see GD2)	1 – 3 Years

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[7] Duration: These timeframes are indicative only, and will depend on the storage option and local circumstances.

[8] Duration of two years is possible for an oil and gas storage option not requiring exploration, and smooth and established regulatory approval system.

			• Provide updates to site characterisation, models and monitoring and corrective measures plans	
Milestone 3	Start of Operations		• Start of CO_2 injection operations and monitoring	
Phase 4	Operations[9]	• Undertake inspections • Review storage permit and, as appropriate, update corrective measures plan • Supervise monitoring and reporting • Approve any updates to monitoring • Ensure necessary corrective measures are implemented • Carry out periodical adjustment of financial security (GD4) Permit withdrawal. • The CA has authority to withdraw the storage permit. If this occurs the CA can issue a new storage permit or the site may be closed	• Perform injection operations, monitoring (GD2) • Perform reporting • Update site characterisation, models as needed • Change, review and update monitoring and corrective measures plans, based on Article 11 and Article 13(2) (ongoing) • Take necessary corrective measures in the event of leakage or significant irregularities • Surrender allowances for any emissions from the site, including leakages, pursuant to Directive 2003/87/EC, • Submit updated post-closure plan	5 - 50 Years
Milestone 4	Closure	There are two main circumstances for closure: (1) At the request of the operator and subject to approval by the CA - where permit conditions have been met, and based on an updated post-closure plan. (2) At the initiative of the CA which may decide to close the site after withdrawal of storage permit.	• End of injection operations and continuous operational monitoring of injection. • Partial reclamation of the site	
Phase 5	Post-Closure/Pre - Transfer	If closure occurs under case (1), the CA is responsible for: • Inspections • Oversight of monitoring and reporting • Approval of any updates to Monitoring and corrective measures plans • Ensure necessary corrective measures are implemented • Periodical adjustment of financial security (GD4) Under case (2), the CA takes on additional responsibilities: • Monitoring, • Reporting • Updates to, risk assessment, monitoring and corrective measures plans	• Carry out ongoing monitoring (GD2) • Perform reporting • Update, models and monitoring and corrective measures plans • Take necessary corrective measures in the event of leakage of significant irregularities • Surrender allowances for any emissions from the site, including leakages, pursuant to 2003/87/EC • Remove injection facilities • Perform site sealing	~20 Years
Milestone 5	Transfer of Responsibility	If closure occurs under case (1): • Approve or reasoned rejection of transfer of responsibility considering any opinion of the Commission. The Commission's opinion is non-binding, although the CA needs to explain the departures in the final transfer decision relative to the Commission's	• Submit transfer report • Make financial contribution available to CA (Art. 20) (GD4) • End of operator involvement	

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[9] This only covers "normal" operation and not temporary continuation of operation if CA withdraws storage permit.

		opinions. - Release financial security after fulfilment of obligations under Art. 20 - Accept the responsibility for all legal obligations on behalf of the Member State (GD3)		
Phase 6	Post-Transfer	- Long term stewardship of site by Member State - Conduct monitoring to detect leakages and take necessary corrective measures in the event of leakage or significant irregularities - Surrender allowances for any emissions from the site, including leakages, pursuant to Directive 2003/87/EC		

3. Geological Context for CO_2 Storage in Europe

3.1 Introduction

Initial assessments of geological storage potential and capacity have been completed for most countries in the European Union. The EU GeoCapacity project (Vangkilde-Pederson, T., 2009) compiles capacity estimates by storage option type for 25 European countries although a small number of EU countries were only partially or not covered (and some non-EU countries were included). The project also describes the geological setting and framework for geological storage which can be used as a reference on these matters by CAs. The "Conservative"[10] total capacity by CO_2 storage option for the countries covered is shown in Table 2.

Table 2 "Conservative" total capacity by storage option type for 25 European countries (source: EU GeoCapacity Project, Vangkilde-Pedersen, T., 2009)

Storage Option Type	Capacity $GtCO_2$	Share of Total Capacity
Saline Aquifer Formations	95.7	82 %
Hydrocarbon Fields	20.2	17 %
Coals	1.1	0.85 %
Total	**117.0**	

As discussed in section 3.3, CAs should also recognise that assessment activities, including storage capacity estimation, are likely to be required on an ongoing basis at the national or regional levels. Periodic revisions and/or updates will need to take account of new information, results on relevant activities, and changes in regulatory frameworks.

This implies that storage capacity estimates at the European level will also change in the future, however the existing figures are presented to provide a snapshot of current understanding.

The scale and nature of storage potential varies by country across Europe and different options are more or less important in different countries. Storage potential occurs in both onshore and offshore settings. Whether a site is onshore or offshore is important as it may impact some key considerations including public acceptance, risk, the type of monitoring technology deployed and the costs. Therefore the setting should be taken account of in complex characterisation documentation, risk assessment monitoring and corrective measures plans.

About 40% of the total capacity in the European GeoCapacity study is in the offshore areas in the UK and Norway, reflecting the scale of storage potential in the North Sea basins. However the other 60% of capacity is widely spread and there is at least

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[10] GeoCapacity produced storage assessments using two methods, an "Optimistic" and a "Conservative" calculation. The "Conservative" estimates areto give "the most realistic estimates [of storage capacity] for each country that can be realized in Europe." However, it is worth noting that GeoCapacity used different approaches in different states and includes variations in the resolution of published information (European Commission 2010).

1 $GtCO_2$ of capacity in eleven further countries. These occur in diverse basins and geological settings, both on- and offshore.

The geological conditions for CO_2 storage are also highly variable across Europe. The local setting should be taken account of in the storage assessment and factors such as the region's tectonic regime and seismicity should be addressed in the characterisation and risk assessment and monitoring.

3.2 CO_2 Storage Options

Apart from the exclusion of CO_2 storage in the water column[11] and the requirements set out in the Water Framework Directive 2000/60/EC[12], the CCS Directive is not prescriptive regarding the type of storage option or formation that can be used for geological storage, provided the storage safety conditions are met. The main storage options are described briefly below and on Table 3 which highlights some generic issues and risks for each option type for consideration in risk assessment. Section 2.3 of GD2 describes these options in more detail.

It is assumed that CO_2 will usually be injected and stored in dense phase at depths greater than 800m. Note that storage is also possible at shallower depths and the CCS Directive is not prescriptive about the depth of storage. Shallower storage should not be excluded, as long as phase related considerations are addressed.

And at a high level, storage opportunities will need to satisfy three principle requirements:

- Capacity – sufficient storage volume is available, or can be engineered to be available;
- Integrity – confidence that the site is secure with no significant risk of leakage;
- Injectivity – suitable reservoir properties exist allowing sustained injection at industrial supply rates into the geological formations.

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[11] According to the definition of water column, art. 3.2, CCS Directive

[12] Amended by Article 32 of the CCS Directive

Table 3 Considerations for Different Geological Options for CO_2 Storage

Favourable	Unfavourable
Enhanced Hydrocarbon Recovery (EHR) in Existing Oil and Gas Fields	
• Geological integrity demonstrated by ability to hold oil and gas for millions of years. • Have high certainty about the geological characteristics, thus, making geological analysis and site characterization relatively straightforward.	• The potential for leakage through pre-existing wells and facilities will need to be assessed, and may need to be remediated prior to commencing injection. • Cap rock integrity will have to be assessed. • EHR viability is field-specific. Offshore CO_2 Enhanced Oil Recovery (EOR) viability unproven; Enhanced Gas Recovery (EGR) technology is at the demonstration stage.
Depleted Oil and Gas Fields	
• Geological integrity demonstrated by ability to contain oil and gas for millions of years. • Moderate to high certainty about the geological characteristics and capacity, provided knowledge and data are not lost when fields are abandoned. • Potential site-specific opportunities for re-use of facilities, infrastructure, and wells.	• The potential for leakage through pre-existing wells and facilities will need to be assessed, and may need remediation prior to commencing injection • Cap rock integrity will have to be assessed. • Facilities and wells may not be suitable for conversion to CO2 storage, depending on their age and physical condition • Potential exists for extensive “lost” corporate knowledge and data which may result in the storage integrity being affected by the lack of detailed documentation associated with the engineering, operation, and characteristics of the field.
Saline Aquifers	
• Widespread, with potentially large capacities. • Present both within and outside oil and gas regions. • With significantly fewer well penetrations than other options, the risk of leakage through any pre-existing wells will be less than for storage in oil and gas fields in most cases.	• The geological characteristics proximal to the proposed storage site will be less certain than for oil and gas fields due to a lesser amount of well and seismic data. • More primary data will need to be acquired to reach the equivalent high levels of technical certainty compared with oil and gas fields. • No fluid flow data about reservoir performance will exist. Hence, significant testing of the reservoir will likely be required to estimate the long-term performance characteristics prior to final commitment to develop the site.
Coal Seams	
• Potential storage opportunities in regions without other options • Mainly located in coal bearing regions, primarily onshore • ECBM production	• Current estimates indicate capacity considered is relatively limited compared to other options, but subject to uncertainty. • Technology at pilot stage with significant scientific and technical uncertainty

Source: Modified from GCCSI CCS Ready Report, 2010

3.2.1 Oil & Gas Fields

Storage in depleted oil and gas fields provides opportunities for storage in Europe's oil and gas bearing regions. The importance of these for geological storage will depend on the scale of oil and gas reserves and storage capacity within specific countries or regions. While major storage opportunities in oil and gas fields are present in the main oil and gas regions, including the North Sea, potential is more limited in other regions where oil and gas resources are smaller.

Storage can either take place after oil and gas production ceases when fields are depleted, or during production associated with enhanced hydrocarbon recovery (EHR). EHR is not in itself included in the scope of the CCS Directive. However, where EHR is combined with geological storage of CO_2, the provisions of the CCS Directive for the environmentally safe storage of CO_2 apply.

The availability of data from oil and gas exploration and production is advantageous for the characterisation of sites for storage, provided the data and knowledge of field performance are available for the storage activities. Because of this, exploration activities or exploration permits may not be required for this type of storage option, although this should be considered on a case by case basis as additional data may need to be acquired for storage site and complex characterisation (see GD2, section 2.3.1 for details). While the existence of oil or gas accumulations provides some evidence of geological containment, the safety and integrity of all wells from the oil and gas activity, as well as caprock integrity for CO_2 storage (such as impact of pressure cycling, interactions with CO_2, etc.), need to be addressed in the risk assessment.

3.2.2 Role and Importance of Saline Aquifers

Because of their large capacity, wider distribution than oil and gas and availability, saline aquifers are an important geological storage option across much of Europe. Member States should take account of alternative uses for saline aquifers such as geothermal use when considering opportunities for permitting, along with any synergies between storage and other uses.

Currently, there is less geological and geophysical data available for saline aquifer opportunities at the outset of site and complex characterisation and project development. Consequently new data will need to be acquired in most cases, through seismic activity, drilling and injection testing. This requires exploration permits issued by the CAs

Further guidance on the geological requirements for site and complex characterisation is provided in GD2 (both for saline aquifers and other options).

3.2.3 Coal Seams

Storage in coal seams provides some potential storage opportunities in certain parts of Europe, typically in major coal-bearing basins and onshore. This may be combined with Enhanced Coal Bed Methane (ECBM) production. This storage option is at an early stage of technology development, and is discussed further in GD2.

3.2.4 Other Options

Several other types of geological formation are being considered as potential storage options. Technology for storage in these options and scientific understanding is at research stage. These include:

- Basalts,
- Salt caverns,
- Disused mines,
- Underground Coal Gasification (UCG) voids,
- Ex-situ and in-situ carbonation of ultramafic/mafic rocks (including ophiolites),
- Shales, and
- deep cool sub-surface storage as liquid CO_2 and CO_2 hydrate.

None of these are precluded by the Directive and they may become viable with further research, development and demonstration. Capacity is likely to be very limited for some of these options (salt caverns, disused mines), and specific integrity issues also need to be assessed, particularly for disused mines, UCG voids and hydrate storage.

3.3 Prospectivity and Geological uncertainty

Much of the discussion of geological storage in the public domain considers storage options in terms of these option types, generalised criteria and methodologies. While these are all essential aspects, it is vital to understand the importance of detailed understanding of the geological environment of the specific area, and of the uncertainties in the characterisation some of which may persist throughout the storage life cycle.

This is because the geology and geological attributes of the subsurface are highly variable between different countries, regions and even between sites within any region. In addition the geology provides the underlying controls on the characteristics and suitability of any potential storage site. Prospectivity assessment, explained below, is often used to address these issues and to evaluate storage sites (ICF International, 2010).

Prospectivity (IPCC, 2005, Chapter 2: Sources page 94) is a qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information and geology. It encapsulates the dynamic and evolving nature of geological assessments where conceptual ideas and uncertainty dominate.

Estimates of prospectivity are developed by examining available data and existing knowledge, applying established conceptual models and, ideally, generating new conceptual models or applying an analogue from a neighbouring basin or some other geologically similar setting.

Assessments have been done at a country or regional level to map out aspects of storage prospectivity across many parts of Europe. These assessments have involved various levels of data quality, coverage, and public availability but most have used different standards in their assessments. However, each and every region will require updating of their assessments in the future, either at more intensive scale in some regions, with new data from exploration efforts, or using improved knowledge and methodology as the science of geological storage evolves.

It is also important that the uncertainties in prospectivity assessment and the inherent geological uncertainty that underlie storage site characterisation and risk assessment are understood and taken account of. The characteristics of the local site geology will be fundamental to the characterisation of any site. This will require assessment of the structure, distribution, variability and properties of geological formations involved, and these will be used as a basis for three dimensional modelling of storage performance (see GD2) and for risk assessment.

3.4 Exploration and Appraisal Requirements

Where new data are required for site and complex characterisation or to reduce risk and uncertainties relating to the prospectivity assessment, exploration (and appraisal) activities may be required. This would require an exploration permit for CO_2 storage.

This type of activity would involve data acquisition to prove sites in a practical and technical sense, and not in theory. Depending on the particular site, it could require seismic and well-drilling activities designed specifically for CO_2 storage site evaluation, including, potentially:

- Acquisition and processing and interpretation of 2D or 3D seismic data;
- Drilling wells to acquire core, log and cutting samples to evaluate and characterise reservoir and seal sequences, supported by laboratory analysis; and
- Injection tests with CO_2 or water and testing pressure regimes in the subsurface.

For saline reservoirs, an exploration program is usually likely to be required, which could take several years (depending on the level of available data and specific geological characteristics of a site), with expenditure that may cost up to several tens of millions of Euros (depending on local drilling and seismic costs).

3.5 Technology & scientific status

While most of the technology needed to store CO_2 are mature and proven, operating experience is still at an early stage, both in Europe and the rest of the world. Extensive research pilot testing and demonstration projects are expected to be undertaken over the coming years. It is therefore important that the processes developed by CAs take account of new developments in the field

3.6 Trapping (Types)

One aspect of the geological context that is vital in relation to storage safety and risk assessment is how CO_2 will be trapped at a site. Consequently one of the first steps in assessing the geological storage prospectivity of a basin is to determine the depths of the target formations for storage in order to identify the phase of CO_2 at that temperature and pressure—hence the CO_2 density/phase under formation conditions. The prospectivity assessment can also identify if a basin is likely to trap CO_2 through either conventional structural or stratigraphic traps, or through migration assisted storage mechanisms (i.e. residual gas saturation trapping)—see Figure 2 and GD2.

The pore and reservoir scale trapping mechanisms that may secure the CO_2 over differing timescales are well understood (IPCC, 2005; Bachu, 2007): buoyancy trapping, residual saturation trapping, dissolution, mineralisation and adsorption. The first two mechanisms are most important at timescales up to 100 years, whereas dissolution and mineralisation processes will be important in very long term timeframes (1,000's -100,000+ years) and sensitive to site characteristics. The rate and proportion of reactions involved in mineralisation will depend on the formation mineralogy and may be very limited in some formations even over geological timeframes[13]. The effectiveness and timeframes for dissolution as a trapping mechanism are also uncertain; there is some concern that predictive models may overestimate dissolution because they take insufficient account of formation heterogeneity.

At the site or basin level, different trapping configurations may be present, in which the importance of different mechanisms will vary. The geological characterisation needs to describe the site level trapping configuration[14]. As existing trap configurations are typically known for specific oil and gas fields, this requirement and the following issues are primarily relevant for saline aquifer storage options:

- An important aspect is whether or not there is structural closure (at a laterally extensive sealing level above the storage reservoir).

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[13] A case study from the North Sea has shown that mineralisation may be very limited in some reservoirs even over geological timescales of millions of years (Wilkinson et al, 2009).

[14] The description of trapping configurations could be based on the systematic framework presented in the Queensland Storage atlas by Bradshaw et al (2010).

- Where structural closure is present, the main early trapping mechanism will be buoyancy trapping below sealing horizons. CO_2 traps would be close analogues to structural traps that are widespread and proven for oil and gas, but includes structures without hydrocarbons. In this case, the mapped location of the structure is of particular importance as it will determine the storage site and assessment area. Furthermore, assessing the long term integrity of any abandoned wells that may have penetrated the top seal is important.

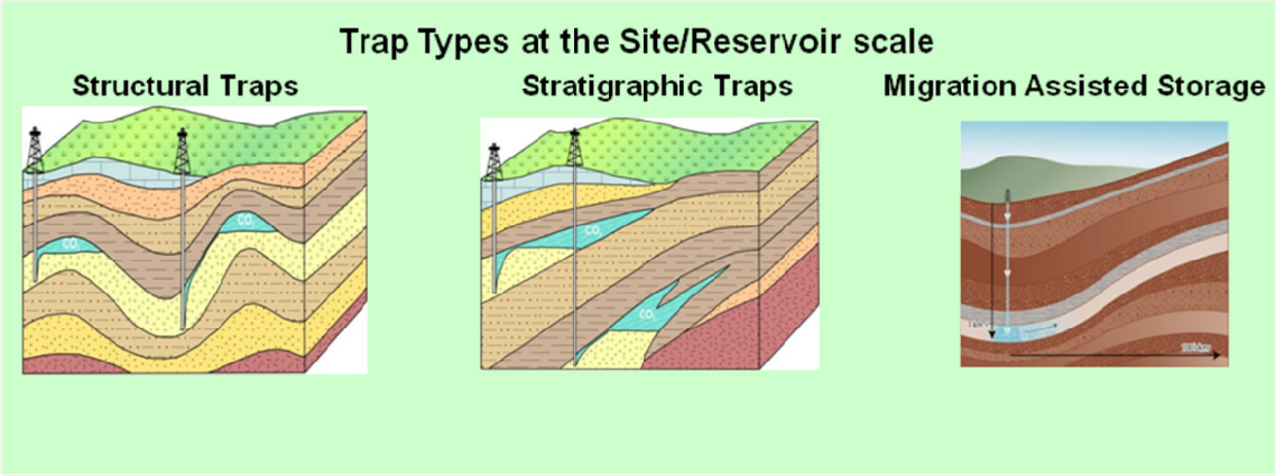
- Stratigraphic traps are another possibility for CO_2 storage sites, but higher trap risk is a concern. In oil and gas analogues these would usually carry higher trap risk, due to the additional requirements for trapping through stratigraphic controls, and lateral seals. However whereas the validity of the trap is tested by exploration drilling confirming whether hydrocarbons are trapped, this approach will not apply to storage and it may be harder to prove storage integrity ahead of injection.

- Without structural or stratigraphic closure, CO_2 trapping can still occur through residual trapping of free phase CO_2 as it moves through the formation (i.e. away from the injection site up the structure and pressure gradient). These types of traps have been referred to as Migration Assisted Storage (Bradshaw et al, 2009). Significant volumes of CO_2 can be stored if this mechanism can be established as a practical option. If injection is into an aquifer with formation water that is under-saturated with CO_2, then dissolution is an additional storage mechanism. There are analogues for this in hydrocarbon migration as oil and gas are trapped in this way as they move between generating formations and reservoirs. Assessing trapping risk and storage integrity may be more complex for these traps and there may be additional modelling and data acquisition requirements.

- Ultimately there will be additional trapping in all trap types as CO_2 dissolves in associated formation water and possibly through mineralisation. Combinations of the trap types can also occur.

- For specific aquifers another important trapping consideration is whether the aquifer is open or closed.

Figure 2: Simplified trap types for saline aquifer storage (Senior, 2010)



4. CO_2 Storage Risk

4.1 Types of Risk

According to the CCS Directive, a geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist. The definition of "leakage" is any release of CO_2 from the storage complex (but not necessarily to the atmosphere).

The safety and environmental impacts of geological storage related to the risk of release of stored CO_2 fall into two broad categories (IPCC, 2005): local environmental and safety impacts and global effects resulting from the release of stored CO_2 into the atmosphere. The local health, safety and environmental risks and hazards arise from three principal causes:

- Direct effects of elevated gas-phase CO_2 concentrations in the atmosphere above a storage complex, and in the shallow subsurface and near-surface environments;
- Effects of dissolved CO_2 or fluid movement on groundwater chemistry which could lead to water contamination, pollution and other environmental risks;
- Effects that arise from the displacement of fluids by the injected CO_2, including displacement and leakage of other formation fluids, including oil or gas, ground displacement and induced seismicity.

CCS also has global environmental impacts, in that successful storage will reduce emission from fossil fuel use and increase its potential as a greenhouse gas emissions reduction option. In contrast, high release rates from storage sites would reduce the effectiveness of CCS as an emission reduction option.

In assessing all the risks the features, processes and mechanisms are closely related to the impact and movement of injected CO_2 in the underground and the risks of CO_2 leakage out of the storage complex, either to shallower formations or to atmosphere. In addition it is important to understand how CO_2 behaviour influences the behaviour of other fluids, either through physical displacement or chemical reactions. As a final element, the impacts need to consider human safety, both from CO_2 exposure and effects, together with other potential risks (e.g. ground movement), and all possible environmental risks in the biosphere.

There has been extensive research into the issues around geological storage safety and leakage. This has been used to identify the main generic potential leakage pathways, hazards and mechanisms (i.e. types of leakage risk) by which CO_2 can be released from a storage complex. These are summarised on Table 5 which further divides the potential leakage pathways into the following categories:

- Geological leakage pathways;
- Leakage pathways associated with manmade systems and features (i.e., wells and mining activities);
- Other hazards or risks such as the mobilisation of other gases and fluids by CO_2 (e.g. methane).

As a general rule each of these generic leakage pathways should be evaluated for every site, although some may not be relevant.

4.2 Geological Leakage Pathways

The main leakage hazards and risks relating to geological pathways are in the following areas:

- Caprocks, which may be ineffective in containing CO_2, unexpectedly absent over part of the storage area, or degraded as a result of geochemical reactions and/or hydrocarbon depletion.
- Faults and fractures, with leakage through natural geological pathways, or resulting from CO_2 injection and build up in the reservoir, hydrocarbon depletion, natural or induced seismic activity.
- Structural spill out of the trap, where the reservoir is smaller than expected and/or over-filled.
- Updip leakage through high permeability intervals, of particular relevance to stratigraphic trapping or Migration Assisted Storage
- Other areas such as transport of CO_2 out of the complex which has been dissolved in formation water.

These are detailed in Table 4, which forms a checklist that could be used in risk assessment activities. The CA needs to ensure the operator has taken account of the storage option type in geological risk assessment. Table 4 is of particular relevance to saline aquifer storage options, and other non-oil and gas options. For oil and gas options, the evidence that there has been hydrocarbon containment will be favourable in relation to the geological risk assessment, although specific issues, particularly related to caprock and well integrity, for CO_2 storage in oil/gas fields need to be assessed (see GD2, section 2.3.1). The assessment should consider the impact of CO_2 with different physical and chemical properties and how it might alter sealing conditions.

Table 4 Potential Geological Leakage Pathways from Geological Storage Sites*

Type of Leakage Pathway	Potential leakage pathways/mechanisms	Notes
Caprock	• Through the pore system in low permeability caprocks if the capillary entry pressure is exceeded or the CO_2 is in solution	• Dependent on caprock characteristics, and interplay with CO_2 build-up in storage site • Relevant to all storage trap types
	• If the caprock is locally absent (includes injection features, pipes and erosion)	• Largely a function of caprock distribution and thickness, including facies change or erosion. Requires mapping using seismic and well data. • Relevant to all storage trap types • Injection features and pipes are common in some areas of North Sea and scale must be considered.
	• Through a degraded cap rock as a result of CO_2/water/rock reactions	• Depends on site specific geochemistry and potential reactions between caprock, CO_2 and water phases • Largely site specific but possible in all trap types
Caprock, fracturing	• Fracturing of the cap rock induced by injection	• Depends on fracture gradient in caprock and pressure build-up in storage reservoir. • Relevant to all storage trap types
Faulting/Fracturing	• Via natural faults and/or fractures	• Not all faults are potential pathways for leakages. Some of them are closed or sealed. • Depends on fault and fracture distribution and characteristics and geomechanics • Relevant to all storage trap types
	• Via induced faulting/fracturing resulting from seismic activity	• Depends on fault and fracture distribution and characteristics and geomechanics • Relevant to all storage trap types • Also dependant on seismicity in the region
Overfilling/Structural spill	• Via a spill point (lowest point in structure that can provide lateral closure) if the reservoir is overfilled	• Depends on site structure, capacity and storage management • Can be managed during injection stage through monitoring and operating strategy
Updip leakage	• Via high permeability zones updip	• Dependant on updip facies, rock types and permeability • Mainly applicable to stratigraphic and Migration Assisted Storage (MAS) trap types
Other	• Via dissolution of CO_2 into pore fluid and subsequent transport out of the storage complex by natural fluid flow	• Depend on dissolution rates and the hydrogeology of the storage complex and surrounding region.

***Modified version of Table in 2006 IPCC Guidelines for National Greenhouse Gas inventories – Chapter 5 Carbon Dioxide Capture, Transport and Geological Storage, Table 5.3 Potential Emissions Pathways from Geological Reservoirs**

4.3 Manmade Leakage Pathways

The main risks in this category are related to:

- Well integrity of any wells and boreholes in a CO_2 rich environment. All types of well or borehole from oil and gas, coal, mining or water exploration and exploitation activities may be relevant and must be considered. The risks relate to both pre-existing wells and wells required for the CO_2 storage activity and must take into account the geochemical environment and reactions that may result from CO_2 storage. Previously abandoned wells are a key risk in oil and gas reservoirs and regions, particularly older wells before modern abandonment practises.

- Leakage from well integrity issues could occur from the types and quality of materials used in the well and the design, management and maintenance of the well itself. Gérard et al. (2006) propose a methodology for addressing long term integrity issues for potential leakage from a well bore; this includes scenario analysis and sensitivity studies for each well component. These studies are then used to develop and support a mitigation strategy based on well completion repair and specific monitoring options. This type of approach will place emphasis on the specific issues in each well.

- Mining activity may result in leakage pathways associated with mine workings, induced subsidence or pressure cones. This is of particular relevance to storage options in coal beds, including ECBM and underground gasification.

Because all types of wells and boreholes are relevant it is important for the CA to ensure well integrity risks are considered for all options. However the risk is of particular relevance in oil and gas fields.

A list of potential man-made pathways is provided in Table 5.

Table 5: Potential Manmade Leakage Pathways (source: ICF International)

Type of Leakage Pathway	Potential emissions pathways/sources	Notes
Wells and boreholes	• Operational or abandoned wells (and boreholes)	• Main risk from all abandoned wells in and around the storage site. • Risk depends on their age and physical integrity of specific wells. • Inadequately constructed, sealed, and/or plugged wells may present the biggest potential risk for leakage. • Techniques for remediating leaking wells have been developed and should be applied if necessary.
	• Well blow-outs (uncontrolled emissions from drilling and operation of injection wells)	• Likely to be rare as established drilling and well operations practices reduces risk. • Possible source of high-flux leakage during drilling and injection operations, usually over a short period of time. • Only in areas where CO_2 storage has already taken place. • Blow-outs can be remediated.
Pathways associated with Mining activity	• Abandoned mine workings • Mining induced subsidence	• Largely related to coal bed storage. • Possible risk for other storage options underlying areas of mining activity.
	• Future mining of CO_2 storage reservoir	• Specific issue for coal bed reservoirs

4.4 Other Pathway and Risks

The intention of the risk assessment is for the operator to assess all potential risks for a storage opportunity. There are other generic risks that need to be considered on a case by case basis. These include:

- Risks relating to ground water including effects that arise directly from the effect of dissolved CO_2 in the formation water, including heavy metal mobilisation;
- Indirect effects from groundwater contamination by displaced brine;
- Oil or gas leakage or emissions that could result from the displacement of hydrocarbons in underground formations by CO_2 injection and movement. This may be of particular importance for storage in depleted oil and gas fields and coal seams;
- Any risks relating to movement of other hazardous components such as H_2S;
- Ground movement, uplift and/or subsidence;

- Natural seismicity, seismic hazards and tectonics; include exposure to earthquakes; and
- Effects from sabotage or terrorism.

5. Risk Management for Geological Storage

5.1 Introduction

The safety of storage is an ongoing imperative throughout the storage life cycle. The key requirements of the CCS Directive that relate to storage risks during the different phases are:

- Site Selection: A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist;
- Operation, Closure and Post-closure: The storage will be subject to monitoring, reporting and inspection obligations. There is a requirement for the operator to immediately notify the CA in the event of leakages or significant irregularities, and to take the necessary corrective measures;
- Transfer of Responsibility: A key criterion for transfer of responsibility after closure is that all available evidence indicates that the stored CO_2 will be completely and permanently contained.

The intention of the CCS Directive is that storage sites should only be selected, used and operated where there is no significant risk of leakage, and that the stored CO_2 should be permanently contained. Significant risk is defined in the CCS Directive as meaning “a combination of probability occurrence of damage and a magnitude of damage that cannot be disregarded without calling into question the purpose of the Directive as far as the storage site is concerned” (Article 3(18)). In this context the purpose is the permanent containment of CO_2 in geological formations in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health.

Life cycle risk management can provide an overarching framework to ensure that the selection, characterisation, operation and closure of storage site (and complex) meet these requirements. The life cycle risk management approach proposed here is broadly based on the CO2QUALSTORE report (DNV, 2010a), adapted to the needs and terminology of the CCS Directive.

The risk management approach should be integral to the project life cycle framework. The activities and deliverables in each phase would be closely related to the risk management framework, in order to reduce and manage the identified uncertainties and risks. Interaction between the operator and CAs in line with the CCS Directive would provide assurance including formal approvals at different milestones (e.g. exploration permits, storage permits, and transfer of responsibility). The philosophy and aims of the risk management approach should be adopted throughout the life cycle.

5.2 Overall Risk Management Process

The suggested overall approach to risk management subdivides the process into three steps, each of which are detailed in the following sections (sections 6.2 – 6.4). This adapts the approach described in CO2QUALSTORE Guidelines (DNV, 2010a) with the requirements of the CCS Directive to provide the following framework for risk management in geological storage:

- Risk identification and assessment: Identify and characterise risks relating to potential leakage from the storage complex, other significant environmental or health risks and associated uncertainties; The identification and assessment of risks should involve hazard identification, and the assessment of potential impacts for each identified hazard[15] (i.e. Exposure and Effects assessments as required in CCS Directive[16]);

- Risk ranking: Rank and characterise the potential significance of each risk; rank in one of the following categories: Insignificant/significant;

- Risk management measures: Identify and assess risk management measures, including monitoring activities, preventive and corrective measures that may be implemented, or planned as contingency measures, in order to reduce risks or associated uncertainties, and assess the resulting risk/uncertainty reduction and risk ranking;

The first part of the process is to identify, assess and characterise potential risks for the storage complex. The second step is to rank and categorise the identified risks based on a standard matrix of probability and severity of outcome (impacts). The next step is to describe and evaluate preventive and corrective measures that can be used to manage the risks (DNV, 2010a).

For every risk identified, the aim is to reduce both the risk and the uncertainty to acceptable levels as foreseen in the CCS Directive (Figure 3). There are limitations and gaps in current knowledge in this area, but the overall approach is to identify and mitigate any significant risks. The CA should recognize that operators must undertake site-specific approaches in their risk assessment and management.

In practice, this is a matter of identifying the options for reducing the risk and uncertainty, their costs and their consequences for risk and uncertainty reduction. As more experience with geological storage and risk assessment is gained, it is expected operators would be able to systematically accept or exclude identified storage complex options and thereby identify sites that offer no significant life-cycle risks while excluding others with a significant life-cycle risks.

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[15] A hazard is considered here as a feature, event or process that can cause leakage of CO_2 from the storage complex or other significant environmental or health risk.

[16] Annex 1

This approach will need to meet the requirements for risk assessment in Annex I of the CCS Directive which includes risk characterisation based on hazard characterisation, exposure and effects assessments.

It should be recognized that while the framework discussed here is based on a modified version of the CO2QUALSTORE guideline, operators could use their own risk management process, as long as they can demonstrate to the CA that it meets the requirements of the CCS Directive, as discussed above.

5.2.1 Risk Identification and Assessment

Identifying and assessing the potential risks is the first major step in the risk management process. The scope of activities required by the operator can be based on the guidelines proposed in the CO2QUALSTORE Report (DNV, 2010a), which forms the basis for this section, while meeting the requirements for Risk Assessment in Annex I of the CCSD.

An important requirement is to identify all significant risks of leakage or hazards that may prevent complete and permanent containment. These should be site specific, but should also take into consideration generic risks/hazards for different options and leakage pathways (as described in sections 4 and 5), which can be used as checklists by the CAs.

This exercise must evaluate environmental and human health risk and must address the hazard, exposure, and effects assessments that are required by the CCS Directive (see GD2). The storage complex location and local characteristics must be taken into account, giving due consideration to issues such as local population density, the nature of the biosphere, atmospheric dispersal and whether the site is onshore or offshore. The composition of the CO_2 stream should also be factored in (see Chapter 3 of GD2 for more discussion).

For a particular stage of the life cycle, the starting point would be to revisit any risk assessment or risk characterisation from any earlier phase of the life cycle. Next, risks should be assessed, in light of the new data and analysis results obtained through the project activities. Additional risks that were not previously identified should also be considered if the new data reveals new risks or uncertainties.

This process should start with a review of the geological framework, modelling, the numerical simulations, monitoring results and any other relevant data, and include consideration of the following questions:

- Does the available geological data and data resolution provide a sufficiently good basis for the geological model that gives an adequately correct and detailed representation of the storage site and its overburden?
- Has/have the geological model(s) been built and populated with appropriate lithological parameters with respect to the decisions to be made?

- Is the capacity estimated consistent with maximum allowed reservoir pressure levels?
- Have all possible existing or potential future leakage pathways been identified?
- What is the potential magnitude of leakage events for identified leakage pathways (flux rates)?
- Have the critical parameters affecting containment and leakage (e.g., maximum reservoir pressure, maximum injection rate, sensitivity to various assumptions in the simulation model, etc.) been duly considered?
- Have the most relevant secondary effects of the storage project that may have adverse impact on human health or the environment been considered, including effects of displaced formation fluids and release of heavy metals or other substances with the potential to contaminate vulnerable drinking water zones?
- Are there any other factors which could pose a hazard to human health or the environment (e.g., physical structures associated with the project)?

The risk identification and assessment should integrate the detailed hazard characterisation, exposure and effects assessments, which are described further below.

Hazard Characterisation

Hazard characterisation shall be undertaken by characterising the potential for leakage from the storage complex, as established through characterisation of the storage complex, dynamic modelling and security characterisation as detailed in GD2. This shall include consideration of, inter alia:

- potential leakage pathways;
- potential magnitude of leakage events for identified leakage pathways (flux rates);
- critical parameters affecting potential leakage (for example maximum reservoir pressure, maximum injection rate, temperature, sensitivity to various assumptions in the static geological Earth model(s));
- secondary effects of storage of CO_2, including displaced formation fluids and new substances created by the storing of CO_2;
- any other factors which could pose a hazard to human health or the environment (for example physical structures associated with the project).

The hazard characterisation shall cover the full range of potential operating conditions to test the security of the storage complex. The primary hazards of geological storage are described in Chapter 5 of GD1. These hazards include geological leakage pathways, manmade leakage pathways (i.e., wells and mining activities), and other hazards from the mobilisation of other gases and fluids by CO_2 (e.g. methane). Modelling and sensitivity analysis can be used to create scenarios for the different hazard mechanisms and determine the critical parameters that could result in potential leakage. Beyond the primary hazards, there are several secondary effects that are described further in Section 2.9 of GD2.

The hazard characterisation requires the estimation of the likely leakage rates and duration following various credible modes of containment failure (discussed further in GD2, chapter 2). A clear understanding of fluid/rock interactions, the impact of incidental substances on the CO_2 phase equilibrium behaviour (see GD2, chapter 3), as well the role of CO_2 hydrates during the migration process are important requirements.

It is also important for the operator to consider how the risks and risk profile will evolve through time throughout the lifecycle of the storage project. This should assist by depicting how different risks evolve (i.e., increasing/decreasing) over time, where in the storage complex and when in the life cycle they are most likely to occur, thereby providing quantitative risk assessment through time (Dodds et al, 2010). Where possible, quantitative profile of different risks may also be charted as a function of time.

Exposure Assessment

The Exposure assessment should be based on the characteristics of the environment and the distribution and activities of the human population above the storage complex, and the potential behaviour and fate of leaking CO_2 from potential pathways in the Risk Identification.

Effects Assessment

Effects assessment – based on the sensitivity of particular species, communities or habitats linked to potential leakage events associated with identified risks. Where relevant it shall include effects of exposure to elevated CO_2 concentrations in the biosphere (including soils, marine sediments and benthic waters (asphyxiation; hypercapnia) and reduced pH in those environments as a consequence of leaking CO_2). It shall also include an assessment of the effects of other substances that may be present in any leaking CO_2 streams (either impurities present in the injection stream or new substances formed through storage of CO_2). These effects shall be considered at a range of temporal and spatial scales, and linked to a range of different magnitudes of leakage events.

Discussion

The risk identification and assessment step should aim to increase understanding of both the likelihood and consequence of the identified hazards, risks and uncertainty elements. This step should therefore put focus on assessing if results from the data gathering process, as well as any modelling and simulation studies performed, provide an adequate basis for evaluating risks and uncertainties. This step may entail both qualitative and (semi-) quantitative evaluations of leakage, risk significance, and the associated uncertainties.

A variety of quantitative estimation methods may be applicable to risk assessment, including numerical models, analytical models and compartment models. All types may be performed in a deterministic or probabilistic manner and the underlying assumptions and boundary conditions must be thoroughly understood before using the results. Similar activities may be undertaken to assess risks, using one or more of the following illustrative analysis approaches:

- Scenario analysis: the process of analysing a range of possible future events by considering alternative outcomes. This may imply constructing a small number of models that satisfy and represent the observed characterization data to similar degree, and comparing the storage performance predicted by the distinct models.

- Reliability analysis: application of methods that aim to estimate the probability of failure of an engineered system given stochastic loads and uncertain characteristics of the engineered system.

- Sensitivity analysis: quantitative assessment of parameter sensitivity based on a formal mathematical relation between quantitatively described uncertain parameters and one or more performance functions. The emphasis with sensitivity analysis is usually to rigorously rank the relative importance of a set of uncertainties.

There are limitations in regard to quantitative approaches as follows:

- Research on quantification of leakage pathways and flux rates is still ongoing, and therefore these assessments are likely to be of qualitative/semi-quantitative nature, until experienced is gained. Further research studies are underway, with an aim to provide more quantitative approaches/data for such assessments.[17]

- It is recognised that current imaging technologies should be further developed to identify the existence of all relevant risks, as the scale of some risks could be less than existing surveying detection limits. Judging the likelihood and consequence of risk elements, or the associated uncertainties, both qualitatively or (semi-)quantitatively, depends in part on the reliability of the input parameters. Care should be taken that a valid body of data and experience exists for justifying the application of quantitative analysis to risk elements affecting the geological storage of CO_2.

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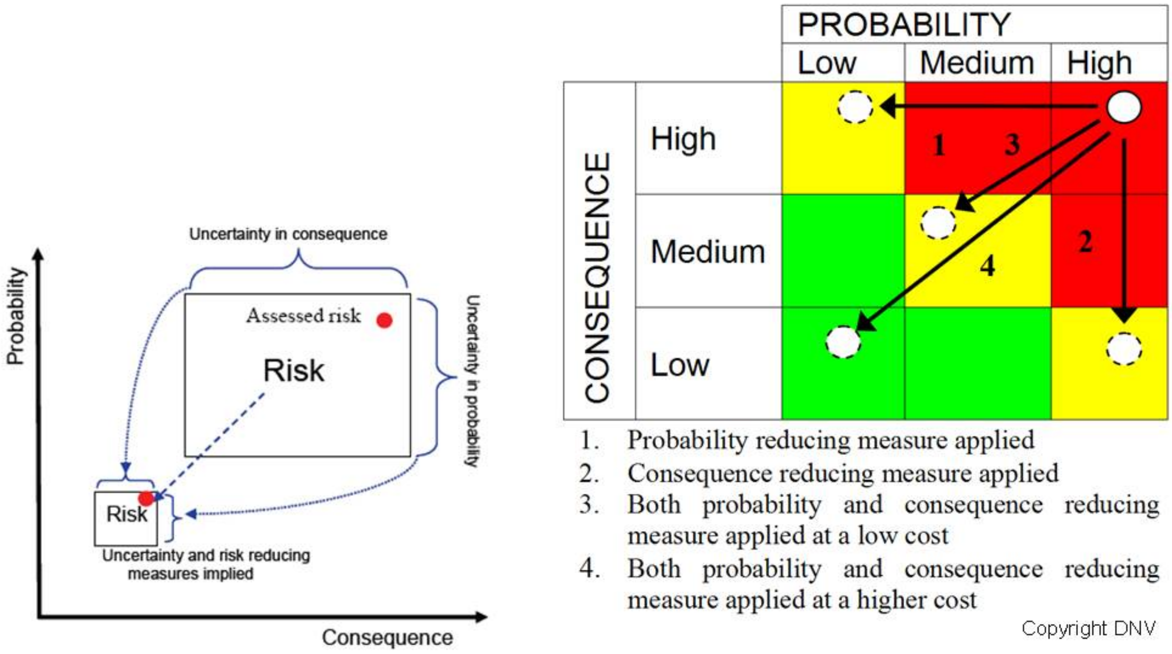
[17] See, for example, 'IEAGHG Quantification Techniques for CO2 Leakage' study and the EU FP7 RISCS project.

5.2.2 Risk Ranking

This second step is to categorise and rank the identified risks based on a standard matrix of probability and severity of outcome (impacts).

Figure 3: Risk Management Framework (Courtesy of CO2Qualstore)



1. Probability reducing measure applied
2. Consequence reducing measure applied
3. Both probability and consequence reducing measure applied at a low cost
4. Both probability and consequence reducing measure applied at a higher cost

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The initial ranking, based on the risk identification, may be supported by the analysis carried out in the risk assessment step. The aim is to characterize the potential significance of each risk. The probability and consequence of each risk should be assessed. The relative significance of each risk should then be characterized and prioritised, and placed in one of the following two risk categories:

1. Insignificant risks: risks that are broadly regarded as not posing a significant danger to human health or environment;

2. Significant risks, risks that must be reduced to insignificant through implementation of risk reducing measures in order to gain project approval, or to meet anticipated conditions for site closure*.*

Note that the result of the initial risk ranking represents the current risk level associated with the various hazards or threats with potential to have negative impact on human health or the environment. Thus, the risk ranking does not account for the effect of identified safeguards.

For many risks related to geological storage of CO_2 there may be significant uncertainty related to both probability and severity (degree of impact). To avoid underestimating risks, and thereby potentially create incidents with negative impact that could have been avoided, it is recommended that risks are ranked conservatively, e.g., by using the pessimistic end of the probability and severity scale to rank risks.

The aim is to be objective and avoid bias without exaggerating the risk unduly. Such risks would then be managed and effectively down-graded as more knowledge about the sites is acquired and uncertainties have been assessed and reduced.

In addition to modelling of risks and assessing potential impact of risks, defining how to rank identified risks could use a facilitated brainstorming session among a group of experts. This group should contain experts that have a detailed knowledge of the storage project, typically representatives from the operator, as well as experts that have no particular stakes in the associated CCS project. It might also include other stakeholders, such as representatives from the public or the local authorities that are not viewed as experts on CCS, but may evaluate certain risks differently to the operator or people with extensive knowledge about geologic storage of CO_2. Such a group exercise could reduce biases in risk assessment, focus on seeking out the weak points for each site and evaluate how these weak points could be properly tested and evaluated.

Particular attention is required to risks with high impact (consequence) including those with low probability. An expert group can assist in assessing the relative importance in such circumstances. High impact events require additional analysis in terms of risk management and mitigating actions.

5.2.3 Risk Management Measures

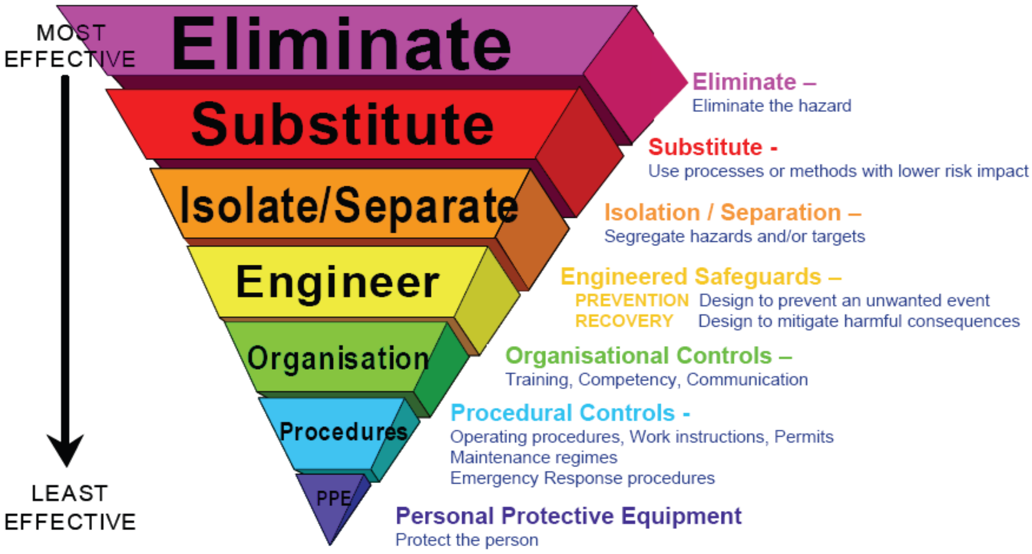
The objective of this step is to identify mitigating actions and safeguards, including monitoring, preventive and corrective measures, and other types of action, that can be used to reduce the risks and/or uncertainty for the identified risks. Contingency measures would be identified for implementation or planning at different stages of the life cycle.

Safeguards are expected to avoid the risks from developing into irregularities or leakage, or mitigate their effects. Safeguards may be preventive or corrective. Preventive safeguards can be implemented prior to the event in order to reduce the probability of an incident occurring or reduce the impact associated with an incident if it occurs. Corrective measures are safeguards that are implemented to correct significant irregularities or leakages in order to prevent or stop the release of CO_2 from the storage complex. Safeguards can be natural (inherent), engineered, or operational (procedural). These may include the consideration and use of multiple storage sites and/or storage targets within the same storage complex.

This step should evaluate what monitoring methods, preventive or corrective measures exist as options for each of the identified risks. These should be integrated with monitoring and corrective measures activities, which are essential safeguards (discussed further in Chapter 4 and 5 of GD2).

For each safeguard an assessment of the risk reduction effect of the alternative safeguards for the associated risk should be evaluated which may be either qualitative or quantitative. If the effect of the safeguard is uncertain, the uncertainty should be accounted for conservatively. The impact of the measure on the risk assessment should be assessed and can be illustrated using charts similar to Figure 3.

Figure 4: Potential Hierarchy of Control to help compare alternative safeguards for risk reduction



Source: CO2QUALSTORE 2010

Figure 4 shows a hierarchy of different types of safeguards which reflects the hierarchy of risk control mechanisms that may be applied. The top three elements of the Hierarchy of Control (i.e., Eliminate, Substitute, and Separate) bring with them “inherent safety”. It follows that these three elements of risk reduction are the most important for CCS projects, and they must be considered early.

The evaluation of more than one storage option ensures that site with poor life-cycle containment can be characterised and “eliminated” through appropriate risk assessment and a preferred site with demonstrably secure capacity can be selected. The residual risk features within that preferred site can then be isolated by physical separation (e.g. distance of injection wells from susceptible faults and below cap-rock).

CCS demonstration projects have shown that defining the lower elements of the Hierarchy of Control - is not yet “business as usual”. There is significantly more effort required to achieve robustness in these areas. Different types of safeguards will be relevant at different stages in the project life cycle. These include potential safeguards that may be incorporated in site characterisation, CO_2 composition, monitoring and corrective measures (as described in GD2).

The CA should ensure that practical and effective safeguard options are applied with due consideration of potential risks, so that the requirements of the CCS Directive are fully met.

5.3 Interaction between Operator and Competent Authorities

Within the proposed approach, the risk assessment, ranking and range of options for tackling the risk are identified by the operator and should form the basis for a dialogue with CAs to ensure that the legal requirements of the CCS Directive are met. To meet requirements of the CCS Directive, the proposed approach should therefore meet the pre-conditions for safe storage of CO_2 set out earlier (section 6.1). Given that the CCS Directive sets the risk reduction targets, the discussion between CAs and operator should focus on the best way to achieve these.

An example of the Risk Management process is given in the text Box 1 below (courtesy of DNV).

The nature of the interaction between the operator and the CAs in respect to the risk management will depend where in the life cycle the project is. Operators will have to interact with the CAs in the following circumstances, all of which should be linked to the risk management framework:

- Applying for an exploration permit;
- Applying for a storage permit, which includes proof of the technical competence of the potential operator, the characterisation of the storage site and storage complex with an assessment of its expected security, specifications related to CO_2 streams (total quantity to be injected and stored, composition, injection rates and pressures), description of preventive measures to prevent significant irregularities, a monitoring plan for the storage complex and the injection facilities, a corrective measures plan for leakages or significant irregularities, a provisional post closure plan, and proof of financial security or any other equivalent;
- Reviewing of storage permit and updating of monitoring plan;
- Reporting;
- Routine and non-routine inspections;
- Notifying the CA in the event of leakages or significant irregularities and implementing corrective measures and measures related to the protection of human health and the environment;
- Applying for closure of the storage site, including an updated post closure plan;
- Transferring the responsibility for all legal obligations after making a financial contribution available to the CA.

In all cases an ongoing and active dialogue between the operator and CA is recommended as the best practise to be adopted.

In addition to this interaction between operators and CAs, the MS and CAs will also interact with the Commission. According to Articles 10 and 18, MS shall inform the Commission of all draft storage permits and draft decisions of approval of the transfer of responsibility and any other material taken into consideration for the adoption of the draft storage permit or draft decision of approval of the transfer of responsibility. Within four months after receipt of the draft storage permit or draft decision, the Commission may issue a non-binding opinion on it. If the Commission decides not to issue an opinion, it shall inform the MS within one month of submission of the draft permit or the draft decision and state its reasons. The CA shall notify the final decision to the Commission, and where it departs from the Commission opinion it shall state its reasons.

Box 1: Risk Management Process Example, based on CO2QUALSTORE (DNV, 2010a)

This concrete example is described to clarify how this might apply in practise (example provided by DNV 2010a). Consider the following situation:

- Abandoned well within the permit area in an onshore storage project
- Plume set to intersect the well 10 years after injection
- Comprehensive well records exist from time of abandonment (1982)
- Well integrity considered to be good

The initial views of the regulator and the operator are as follows:

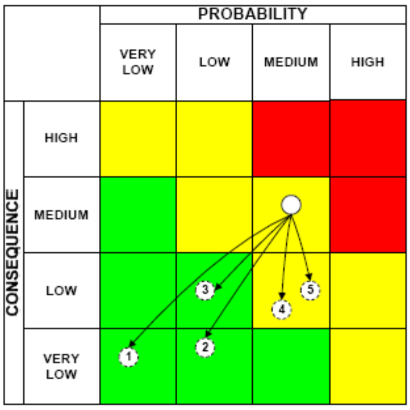
- Regulator: all abandoned wells that may come into contact with the plume must be re-abandoned.
- Operator: well will be re-abandoned if leakage occurs.

A number of options are then identified to reduce the risk, as follows:

1. Re-abandon well
2. Monitoring well for early signs of leakage – re-abandon if detected
3. Monitoring well for early signs of leakage – re-design injection strategy if detected
4. Monitoring of surface – re-abandon well if leakage
5. Monitoring surface – assess impact of leakage and redesign injection strategy. Reabandon if significant leakage

The risk reduction potential of the measures is represented in example below. A dialogue would take place between the operator and the regulator to determine which of the options should be taken in practice in order to meet the pre-conceived level of insignificant risk. Note that the result of the dialogue would normally include selection both of a monitoring strategy for this particular risk (monitoring either the well or the surface) and of a corrective measure if an adverse event occurs (redesign of injection strategy, re-abandoning of well).

Example of risk reduction options



If option 2 were taken, for instance, the performance target would be that the well is maintained secure and leak-proof; if option 5 were taken, the performance target would be that no significant leakage takes place via the well. Each of these performance targets has an associated regime of monitoring and corrective measures. Only options that satisfy the risk reduction requirements of the Directive would be eligible.

The process would be repeated for the range of risks identified, working down the ranking set out.

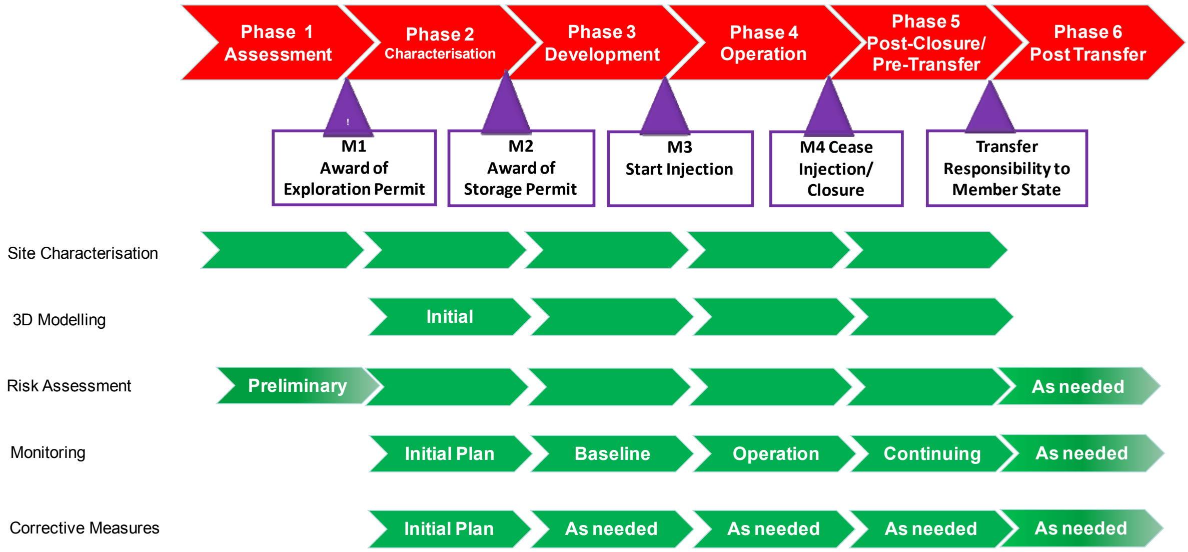
The approach is also applicable in principle to the conditions for transfer of responsibility: for instance, a range of performance targets for transfer in the above case could be elaborated (e.g. that the site had completed injection and had been monitored according to the agreed approach for a period of x years after closure and no leakage had been identified) and if the agreed target was met, the condition for transfer (in relation to that risk) would be satisfied.

5.4 Risk Management at Different Project Phases

The approach outlined above is based on identifying and assessing risks and options for tackling the risk at a given site at any phase in the project life cycle. In view of the vital importance of ensuring safe storage, the principle of risk management is relevant and applicable throughout the entire storage life cycle.

The main activities, mitigating actions and safeguards are considered for different phases below, and illustrated in Figure 5. It is important to recognise the risk identification and management process are ongoing processes through the storage life cycle, with several updates as additional data is collected about site characteristics and performance, and risk and uncertainties are better understood. The risks and uncertainty about the potential for the risk are reduced in most cases as one moves along the life cycle.

Figure 5: CO_2 Storage Life Cycle Framework - Risk Management during the Main Project Phases and Milestones



5.4.1 Phase 1: Assessment of Storage Capacity

Although there are no formal risk management requirements at this phase in the CCS Directive, initial consideration of the potential risks relating to the safety of storage should be taken account of both by the operators and the CAs in initial assessments and screening, and in identification of potential storage sites and exploration permit areas. These considerations of risks in the screening assessments may be generic or regional in nature but should give a clear idea of what further information is needed to ensure that a particular site will be suitable and safe (e.g., whether the caprock is likely to be homogenously developed across the region). These might then form the basis for the exploration permit and activities during the characterisation phase.

For operators, consideration of multiple potential storage sites may be useful in the initial assessment and screening as well as the subsequent characterisation phase. This would serve to develop a risk-diverse portfolio in order to mitigate geotechnical and other development risks. In this way, potential operators can gain a relatively high confidence that at least one site could be developed for storage. This approach is consistent in making full use of the risk mitigation potential offered by the Hierarchy of Control (see Figure 4).

5.4.2 Phase 2: Characterisation and Assessment of Storage Complex

Risk management is an essential activity during this phase in order to ensure selection of safe sites ahead of storage permitting and subsequent development.

Risk identification and assessment should be initiated at an early stage in this phase and used to determine the nature of exploration activities and evaluation work that may be required to address specific risks and uncertainties. Seismic and drilling activities can be used to reduce the uncertainties and risks relating to geological pathways. For example seismic surveys can be used to delineate the extent of caprocks and to understand the nature of faulting in a region. Wells can be drilled to confirm the suitability of different formations as caprocks and to obtain samples for detailed analysis. Engineering surveys, testing and remediation activity can be conducted to evaluate and reduce risks associated with well integrity (e.g. the status of an abandoned well that might be encountered by a CO_2 plume) and other man-made pathways.

Risk assessment is required by the CCS Directive as an integral part of the site selection, site characterisation and storage permitting. This should be based on the approach described above - further guidance on this is provided in GD2. At this phase some risks identified during the site characterisation phase can be addressed by mitigating actions and safeguards as part of the plans that are prepared and submitted with the storage permit application:

- Project design and development plans (e.g. well locations, numbers, operating and injection plans); these can be used to manage risks associated with geological pathways and parameters (e.g., by limiting pressure build-up and allowable capacity); remediative activity can be included in the development plan in event of well integrity risks associated with pre-existing wells.
- Description of measures to prevent significant irregularities;
- Monitoring plan (which must be developed to address specific risks identified in the risk assessment—see Chapter 4 of GD2);
- Corrective measures plans—see Chapter 5 of GD2;
- Provisional post-closure plan—see above.

The monitoring and corrective measures plans that are prepared at this stage as well as the description of measures to prevent significant irregularities are closely related to the Risk Assessment for the project. They must be developed to take account of and address the specific risks that are identified for the storage complex.

The CA has responsibility for approval of storage permits, and making sure that sites are suitable for CO_2 storage, with appropriate operating plans. This is in effect part of the overall risk management process and a vital aspect of ensuring that suitable sites are selected.

5.4.3 Phase 3: Development

Additional information will usually become available in this stage through development drilling and any baseline monitoring activity undertaken. The logging, coring and other measurements conducted during development drilling should be used to refine the subsurface characterisation, modelling and risk assessment conducted at the time of storage permitting.

Baseline monitoring of the storage complex should be conducted and assessed to help determine whether the monitoring results during the injection phase are irregular. This is important because it is essential to have comprehensive baseline data before CO_2 injection starts.

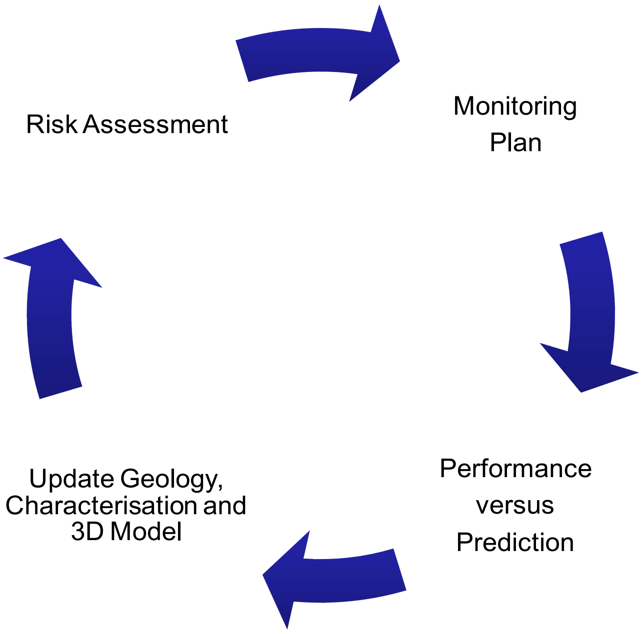
5.4.4 Phase 4: Operations

The operations phase is one of the most important periods from a risk management perspective, because large scale commercial CO_2 injection into the storage complex is initiated. This is the first phase in the life cycle when there is any actual risk of irregularities and leakage as a result of the injection project. The initial migration and movement of CO_2 may test different pathways and risks as the plume develops and expands, and pressures start to increase.

As the main phase of injection and with ongoing monitoring, there will be a continuous flow of new information and data about the project and its performance (as shown in Figure 6).

The monitoring plan and activity is an essential part of the risk management approach. The results from injection and monitoring should be used by the operator to verify, test and iterate the risk assessment, models and performance predictions on an iterative and ongoing basis. The results must also be reported to the CA in line with the CCS Directive, and the monitoring plan must be updated at least every five years (see GD2).

Figure 6: Risk Management based approach to storage project



During this phase there are a range of mitigating actions and safeguards that include:

- Operations management, procedures and practises including preventive measures;
- Monitoring activity and update of monitoring plans;
- Inspections;
- Corrective measures;
- Review of storage permit.

5.4.5 Phase 5: Post-Closure Pre-Transfer

Although CO_2 injection has stopped by this phase, the underground CO_2 plume may not have stabilised and therefore there is continued risk of irregularities and actual leakage from the storage complex.

With ongoing monitoring, there will continue to be a flow of new information and data about the project and its performance. The monitoring activity is an essential part of the risk management approach. The results from monitoring should be used by the operator to verify, test and iterate the risk assessment on an ongoing basis. This should include updates to modelling which should assess and calibrate the plume migration and migration rates, which is of particular importance for MAS storage at this phase. The results must also be reported to the CA in line with the CCS Directive.

Although the range of mitigation actions is reduced after the injection period, the mitigating actions and safeguards in this phase continue to include monitoring activity and updates of monitoring plans, as well as corrective measures and inspections.

5.4.6 Phase 6: Post-Transfer

While routine inspections by the CA will cease in this project phase, monitoring will continue, although it may be reduced to a level which allows for detection of leakages or significant irregularities. If any leakages or significant irregularities are detected, the risk assessment will need to be reviewed and monitoring will need to be intensified to assess the scale of the problem and the effectiveness of corrective measures.

6. Summary

This GD addresses the overall framework for geological storage in the CCS Directive and provides a framework for the entire life cycle of geological storage of CO_2 activities covering the phases, main activities and major regulatory milestones. It presents the high-level approach to risk assessment and management that is intended to ensure the safety and effectiveness of geological storage of CO_2.

The life cycle for any CO_2 storage project from initial assessment and characterization of a site to its transfer to the CA could be in the region of 50-70 years up to the final transfer of responsibility to the Member State/CA. The framework covers all phases in a comprehensive manner and describes the role of CAs through the life cycle, and provides guidance on the interactions with the operator at different milestones and during different phases, particularly with regard to risk management.

The scale and nature of geological storage potential for CO_2 varies by country across Europe and different options are more or less important in different countries. Major options are oil and gas fields and saline aquifers, with further potential in other storage types. CO_2 storage potential occurs in both onshore and offshore settings. The setting and type of CO_2 storage option should be taken account of in risk management.

Risk management should be used by the operator to identify, mitigate, and manage identified risks and uncertainties in order to ensure the safety of any storage through the life cycle of every CO_2 storage project. The intent of the risk assessment is for the operator to assess all potential risks for a CO_2 storage opportunity. There are a series of generic risks that need to be considered on a case by case basis. These include geological CO_2 leakage pathways, manmade CO_2 leakage pathways and a range of other risks.

The overall approach to risk management subdivides the process into three steps, each of which are detailed in the guidance. The steps are

- Risk identification and assessment: Identify and characterise risks relating to potential CO_2 leakage from the storage complex, other significant environmental or health risks and associated uncertainties; The identification and assessment of risks should involve hazard identification, and the assessment of potential impacts for each identified hazard (i.e. Exposure and Effects assessments as required in CCS Directive;
- Risk ranking: Characterise the potential significance of each risk by the probability of occurrence and consequence of the risk; the risks should then be ranked in one of the following categories: insignificant or significant;
- Risk management measures: Identify and assess risk management measures, mitigating actions and safeguards that may be implemented, or planned as contingency measures, in order to reduce risks or associated uncertainties, and assess the resulting risk/uncertainty reduction and risk ranking.

Risk management should be considered as an ongoing and iterative process throughout the CO_2 storage life cycle that aims at continual improvement of risk assessment. This will involve periodic and ongoing assessment of risks relating to containment and leakage, as well as uncertainties in the geological framework, models and performance assessments. It is also important for operators to communicate the risks to the CA and other stakeholders based on structured and publicly accepted industry methods.

Within the proposed approach, the risk assessment, ranking and range of options for tackling the risk are identified by the operator and should form the basis for a dialogue with the CA to ensure that the legal requirements of the CCS Directive are met. The nature of the interaction between the operator and the CA in respect to the risk management will depend where in the life cycle the CO_2 storage project is, what the regulatory requirements are, and whether there are specific formal approvals or milestones.

7. Acronyms

2D	Two dimensional
3D	Three dimensional
CA or CAs	Competent Authority or Competent Authorities
CCS	Carbon Dioxide Capture and Storage
CCS Directive	Directive on the Geological Storage of Carbon Dioxide (2009/31/EC)
CO_2	Carbon dioxide
DNV	Det Norske Veritas
ECBM	Enhanced Coal Bed Methane
e.g.	For example
EHR	Enhanced Hydrocarbon Recovery

EOR	Enhanced Oil Recovery
etc.	Et Cetera (Latin: And So Forth)
EU	European Union
FEED	Front End Engineering Design
FS	Financial Security
GCCSI	Global Carbon Capture and Storage Institute
GD	Guidance document
Gt	Giga tonnes
i.e.	Id est (Latin: that is)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
m	Meter
MAS	Migration Assisted Storage
pH	Potential for hydrogen ion concentration
UCG	Underground Coal Gasification
UK	United Kingdom
US	Of the United States of America
USA	United States of America

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