Guidance document 1

CO_2 storage life cycle and risk management framework

EUROPEAN COMMISSION

Directorate-General for Climate Action

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The aim of this guidance document is to contribute to a better understanding of the requirements of Directive 2009/31/EC on the geological storage of carbon dioxide. It has been prepared by the European Commission on the basis of the views and knowledge provided by stakeholders. The purpose of this guidance is explanatory and illustrative. It does not create any rights or obligations.

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1. Revision history

Key changes since the previous version
• The document was significantly shortened and re-structured with the emphasis on providing guidance on how to implement the requirements in the CCS Directive. • Tables were added to illustrate understanding of key defined and non-defined terms. • Clarifications were provided related to project phases and the associated requirements. • Additional guidance on recital 20 was provided. • A new subsection on risk evaluation criteria was introduced. Among others, it was clarified that risk assessments must evaluate three distinct consequences: leakage, damage to the environment and damage to human health.

2. Introduction

2.1. Purpose and scope of guidance documents

This guidance document (GD) forms part of a set of guidance documents as follows:

- Guidance document 1: CO_2 storage life cycle and risk management framework;
- Guidance document 2: Characterisation of the storage complex, CO_2 stream composition, monitoring and corrective measures;
- Guidance document 3: Criteria for transferring responsibility to the competent authority;
- Guidance document 4: Financial security and financial contribution.

The aim of these GDs is to improve understanding of the requirements of Directive 2009/31/EC on the geological storage of carbon dioxide (the 'CCS Directive') and give indications on how it can be implemented. They should therefore facilitate a correct and uniform application of the CCS Directive across the EU. The guidance does not represent an official position of the Commission and is not legally binding. The binding interpretation of EU legislation is the exclusive competence of the European Court of Justice that can make final judgments concerning the interpretation of the CCS Directive.

GD 1 is structured as follows. The remainder of this Section 2 describes the legislative context for CO_2 storage risk management under the CCS Directive and provides an interpretation of some of the key terms used in the CCS Directive. Section 3 provides guidance to competent authorities on the main phases of a CO_2 storage project, the associated key activities for authorities and operators, and the main points of interaction between the authorities and operators. Section 4 describes the overall approach to risk management for CO_2 storage sites, and how to demonstrate that there is no significant risk of leakage, and no significant environmental or health risks.

2.2. Legislative context

The CCS Directive establishes a legal framework for the geological storage of CO_2. It specifies that environmentally safe CO_2 geological storage means the 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 (CCS Directive, Article 1). This document provides guidance to operators and competent authorities on how to interpret and implement the obligations for risk management related to the following requirements in the CCS Directive:

- Article 4(4): 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.
- Annex I, Step 3.3: Risk assessment:
    - 3.3.1: Hazard characterisation – site-specific risk identification.

- 3.3.2: Exposure assessment – based on the hazards identified.
- 3.3.3: Effects assessment – based on the hazards identified.
- 3.3.4: Risk characterisation – based on the hazard, exposure and effects assessment.

Apart from the ban on storing CO_2 storage in the water column[1] and the requirements set out in the Water Framework Directive 2000/60/EC[2], the CCS Directive is not prescriptive regarding the type of storage option or formation that can be used for geological storage. The CCS Directive allows for storage in sedimentary and igneous aquifers, hydrocarbon fields, coal seams, and in principle other options such as salt caverns. However, the CCS Directive is prescriptive on the required characteristics of a suitable storage complex. It states that all prospective storage sites must meet the requirement in Article 4(4): under the proposed conditions of use there is no significant risk of leakage, and no significant environmental or health risks. However, from a risk perspective, knowledge from previous operations at the storage site can be leveraged to demonstrate conformance with this requirement.

There may also be circumstances where CO_2 is injected into the subsurface as part of enhanced hydrocarbon recovery (EHR) operations, or as part of geothermal operations (e.g. re-injection of produced CO_2, or using CO_2 as a geothermal working fluid). If the primary aim of such operations is the permanent and environmentally safe storage of CO_2, a risk-based approach suited for CO_2 storage projects should be used. This is also reflected in Recital 20 in the CCS Directive which states that 'the provisions of the CCS Directive should apply if EHR is combined with geological storage of CO_2' (see Box 1).

In Europe, EHR is typically permitted under the regulations governing petroleum exploration and production, which may not require compliance with all requirements of the CCS Directive. Similarly, geothermal operations are generally permitted under regulations specific to geothermal energy projects with no requirement to ensure the containment of any re-injected CO_2 or CO_2 used as working fluid. If the operators of a geothermal installation capture and reinject CO_2 underground in order to reduce GHG emissions, they will need to apply for CO_2 storage permit in accordance with Directive 2009/31/EC in addition to any other permit needed for their operation. This, however, does not apply in the cases where the CO_2 reinjection is configured in a closed cycle system, being contained within the system for the entire operation, including geothermal systems that reinject exclusively CO_2 originating from the same aquifer.

[1] According to the definition of water column, Article 3(2) of the CCS Directive.

[2] Amended by Article 32 of the CCS Directive.

Box 1: How the CCS Directive applies to enhanced hydrocarbon recovery.

Recital 20 in the CCS Directive states that 'EHR is not in itself included in the scope of this Directive. However, where EHR is combined with geological storage of CO_2, the provisions of this Directive for the environmentally safe storage of CO_2 should apply'. EHR is considered combined with geological storage of CO_2 when long-term (permanent) storage of CO_2 to contribute to the fight against climate change is a **primary objective** along with the objective to enhance hydrocarbon recovery. A general implication of being a primary objective is that the operator seeks opportunities to maximise the volume of CO_2 stored beyond what is incentivised by the economic benefit from incremental hydrocarbon production.

With this interpretation in mind, the following two types of EHR operations qualify:

1. Operations where CO_2 is injected in the aquifer support (water leg) part of a hydrocarbon-bearing formation, and the CO_2 operation is managed and monitored for the purpose of long-term storage. There may be some pressure influence that helps maintain reservoir pressure (and limit the need for water injection), but long-term storage of CO_2 and the associated economic and climate benefits is the primary driver for the CO_2 injection.

2. Operations where an EHR operator seeks to maximise the volume of CO_2 injected into the hydrocarbon field, and it can be demonstrated that the volume of CO_2 injected exceeds the life-cycle emissions of the EHR operations, including emissions generated by the combustion of incremental hydrocarbon production.

2.3. Acronyms

Table 1: List of the acronyms used in the in GDs 1 through 4.

Acronym	Meaning
2D	Two-dimensional
3D	Three-dimensional
4D	Four-dimensional
A	Area of basin or hydraulic unit
ALARP	As low as reasonably practicable
ARMA	American Rock Mechanics Association
BY	By attribution
BV	Besloten vennootschap (Dutch: private limited company)
CC	Creative Commons
CCS	Carbon capture and storage
CCSA	Carbon Capture & Storage Association
CEA	European insurance and reinsurance federation
CLIMA	Climate Action
CO_2	Carbon dioxide
DNV	Det Norske Veritas
CO2StoP	CO_2 Storage Potential in Europe
COMP	Competition
DG	Directorate-General

Acronym	Meaning
E	Storage efficiency factor
EC	European Commission
EEA	European Economic Area
EEC	European Economic Community
EED	Energy Exploration and Development
E.g.	Exempli gratia (Latin: for example)
EHR	Enhanced hydrocarbon recovery
ENER	Energy
ENV	Environment
EPA	Environmental Protection Agency
Etc.	Et cetera (Latin: and so forth)
ETS	Emission Trading Scheme
EU	Euopean Union
EUA	Emission Unit Allowance
FG	Fracture gradient
EUR	Euros (€)
GCCSI	Global Carbon Capture and Storage Institute
GD	Guidance document
GROW	Internal Market, Industry, Entrepreneurship and Small and Midsize Enterprises
h	Net thickness of the hydraulic unit
H_2	Hydrogen
H_2S	Hydrogen sulfide
H_2O	Water
Hg	Mercury
I.e.	Id est (Latin: that is)
IEAGHG	International Energy Agency Greenhouse Gas Research & Development Programme
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
JRC	Joing Research Centre
kg	Kilograms
L	Legislation
LCFS	Low Carbon Fuel Standard
LS	Legal Services
m	Meters
MARE	Maritime Affairs and Fisheries
M_{CO2}	Mass of CO_2
MRR	Monitoring and Reporting Regulation
Mt	Million tonnes
MRG	Monitoring and Reporting Guidelines
M_W	Moment magnitude
N_2	Nitrogen
N/A	Not applicable
NEAES	North-East Atlantic Environment Strategy
NO_X	Nitric oxides
n/g	Net to gross
NORSOK	Norsk Sokkels Konkurranseposisjon
NOGEPA	Netherlands Oil and Gas Exploitation and Production Association
O_2	Oxygen
OEUK	Offshore Energies UK
OGCI	Oil and Gas Climate Initiative
OJ	Official Journal
P50	50^{th} percentile (mean)
P90	90^{th} percentile

Acronym	Meaning
pH	Potential for hydrogen ion concentration
ϕ	Average effective porosity
P&A	Plugging and abandonment
ρ_{CO2}	Density of CO_2
REGIO	Regional and Urban Policy
RP	Recommended practice
RTD	Research and Innovation
S_3	Minimum total principal stress
SANTE	Health and Food Safety
SG	Secretariat-General
SO_X	Sulphur oxides
SPE	Society of Petroleum Engineers
SRMS	Storage Resources Management System
t	Tonnes
T.b.d.	To be determined
TFEU	Treaty on the Functioning of the European Union
UK	United Kingdom
URDG	Uniform Rules for Demand Guarantees
US	Of the United States of America
USA	United States of America
V_b	Bulk volume
ZEP	Zero Emissions Platform

2.4. Interpretation of main terms

Table 2: Clarification of the key defined terms used in the CCS Directive.

Term	Definition in CCS Directive	Comments
Storage site	A defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities.	The storage site should be described for each geological storage project. The subsurface component of the storage site must be contained within the storage complex. This subsurface volume should be delineated by lateral boundaries on an area map, and vertically by describing the geological stratum (or strata) into which CO_2 stream(s) are injected. These strata are often referred to as storage reservoirs. The surface and injection facilities considered to be part of the storage site should be identified. The storage site includes the injection and monitoring wells. It may also include associated infrastructure such as pipelines, CO_2 conditioning systems, storage tanks, offshore platforms and floating (storage and) injection units. Note: The boundary of the 'surface and injection facilities' is not explicitly defined in the Directive. It is generally understood that these facilities start where the transport system ends. For onshore projects, this can be at custody transfer meters for each CO_2 stream receiving line. For offshore projects, however, custody transfer meters can be onshore, prior to ship loading or injection into the offshore pipeline. It is therefore proposed to define the limits of the surface facilities to be the facilities after any custody transfer carried out within the 'surrounding area' (see definition below).

Term	Definition in CCS Directive	Comments
Storage complex	The storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations.	A storage permit application must, under Article 7(3), include a description and characterisation of the storage complex. The storage complex must be contained within the license area for the storage site, but it can have the same lateral boundaries as the license area. The storage complex must include the volume where a CO_2 plume may be present, but will often include areas of potential lateral migration outside the expected extent of any CO_2 plumes. However, elevated pressure may extend beyond the limits of the storage complex. Vertically, the storage complex will normally incorporate shallower geological formations that provide physical trapping of buoyant formation fluids, including any CO_2 plumes. The storage complex also contains the subsurface component of the storage site, which can include several geological formation(s)/stratigraphic interval(s) into which CO_2 is injected. The storage complex must include all legacy wells within the surrounding area that have the potential to provide leakage pathways. This includes all legacy wells that penetrate the caprock.
Hydraulic unit	A hydraulically connected pore space where pressure communication can be measured by technical means and which is bordered by flow barriers, such as faults, salt domes, lithological boundaries, or by the wedging out or outcropping of the formation.	The hydraulic unit containing the subsurface volume for the storage site is important for determining the expected pressure build-up from the geological storage project, which is also a key determinant for storage capacity and sustained injectivity. The hydraulic unit should therefore be mapped and described at least over an area extent where material changes in pressure can occur as a result of the CO_2 injection activities. This mapping should also describe other known activities within the hydraulic unit that may impact pressure within the storage site.
CO_2 plume	The dispersing volume of CO_2 in the geological formation.	This refers to CO_2 in free-phase[3] within the geological formation where CO_2 is being injected and must be contained. CO_2 that is fully dissolved in water, or otherwise transformed through chemical reactions is therefore not included in the CO_2 plume.

[3] Free-phase CO_2 means CO_2 in supercritical, gaseous, or liquid phase, rather than as a dissolved component in native fluid or otherwise chemically transformed or bonded.

Term	Definition in CCS Directive	Comments
Migration	Movement of CO_2 within the storage complex.	Movement of free-phase CO_2 within the storage complex.
Leakage	Any release of CO_2 from the storage complex.	This refers to CO_2 in free-phase, i.e. it does not include CO_2 that has been dissolved in water, mineralised or otherwise transformed through chemical reactions. However, the assessment and quantification of leakage must include the potential for any exsolution of CO_2 from displaced formation fluids outside the storage complex. Specifically, if CO_2 charged water is displaced to the water column, then it will be assumed that the CO_2 will eventually come out of solution and count as leakage. This is in accordance with the Monitoring and Reporting Regulations to the EU Emission Trading System (ETS), Annex IV, Section 32[4], which states that a release of CO_2 into the water column must be counted and quantified as CO_2 emissions. Note: Recital 20 of the CCS Directive covers enhanced hydrocarbon recovery (EHR) combined with geological storage of CO_2, where the provisions of the CCS Directive apply. This means that the release of quantities of CO_2 from surface installations which do not exceed what is necessary in the normal process of hydrocarbon extraction, and which do not compromise the security of the geological storage or adversely affect the surrounding environment does not represent leakage under the CCS Directive.
Significant risk	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 concerned.	The purpose of the CCS Directive is to enable environmentally safe geological storage of CO_2 where injected CO_2 is permanently contained within the storage complex while preventing and, where this is not possible, eliminating as far as possible the risk of leakage, and any risk of negative effects to the environment and human health. The risk of leakage and possible negative local effects on the environment or human health should be established for each storage site based on a project-specific assessment. Combinations of probability of occurrence and magnitude of damage that can represent a significant risk will be discussed in sections 4.2 and 4.3.

[4] https://eur-lex.europa.eu/eli/reg_impl/2018/2066/OJ.

Term	Definition in CCS Directive	Comments
Significant irregularity	Any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or human health.	A significant irregularity is a situation that can result in an event with potential for leakage or negative consequences to the environment or human health. The risk identification should identify and describe the threats that may cause significant irregularities, and the associated risk of leakage or risk to the environment or human health. **Example:** - Threats: for instance, poor cement quality, cement degradation or casing damage. - Significant irregularity: loss of well integrity. - Risk scenario: o Threat → Significant irregularity → Leakage → Negative effects. It is important to note that a significant irregularity does not necessarily imply that the level of risk for any associated risk scenario is significant.

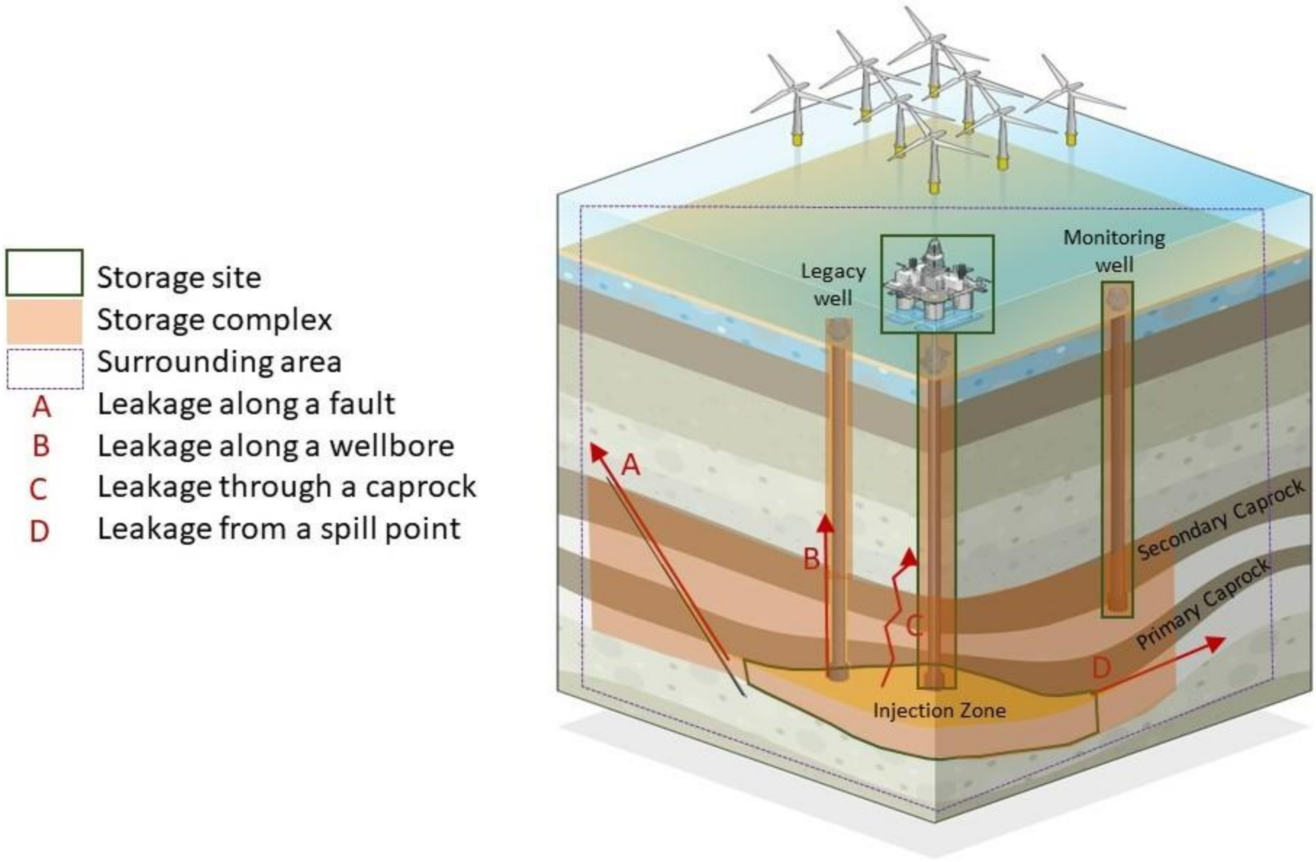


Figure 1: Illustration of a storage complex, storage site and surrounding area.

Table 3: Clarification of key non-defined terms used in the CCS Directive.

Term	Articles using terms	Comments
Surrounding area	Article 4(3) and Annex I	The term 'surrounding area' is the surface and subsurface area surrounding the storage complex where leakage or negative effects on the environment or human health are realistically possible. A risk assessment should be carried out to assess the significance of associated risks, and this should inform the design of the monitoring of the storage complex and surrounding environment under Article 13 of the CCS Directive. The storage complex and surrounding area should be specified in the site characterisation under Annex I, and together will normally encompass the monitoring area.
Caprock	Annex I	A geological formation overlying the storage reservoir that effectively restricts upward migration of free-phase CO_2. It should also restrict the upward flow of CO_2 charged formation fluids if there is potential for these fluids to create negative environmental effects or allow exsolution of CO_2. To fulfil the purpose of the CCS Directive, the caprock should have sufficiently low permeability to ensure a 'permanent containment of CO_2 and prevent negative effects and any risk to the environment and human health' in the site and project-specific circumstances. Note: Brine charged with CO_2 will generally have a higher density than the resident brine. This implies that upward movement of CO_2 charged brine requires pressure differentials sufficient to drive the flow of brine along upward, permeable pathways. By contrast, free-phase CO_2 is buoyant and can move upward along permeable paths by gravity forces.

Term	Articles using terms	Comments
Seals	Annex I (Step 2.b and 3.i)	In the context of geological storage of CO_2, the term 'seals' is often used interchangeably with caprock to mean a geological formation that restricts the upward migration of free-phase CO_2 and CO_2 charged formation fluids. In Annex I, Item 2.b it is used alongside caprock, can be understood as a secondary caprock, i.e. a geological formation overlying the (primary) caprock that can restrict the upward migration of any free-phase CO_2 that has migrated across the primary caprock. This interpretation applies to vertical seals. Annex I Item 3.i refers to 'lateral and vertical seals'. Lateral seals can refer to sealing faults, pinch-outs or other geological features that effectively restrict lateral flows and which may create compartmentalisation of the available capacity within the storage site.
Incidental associated substances from the source, capture or injection process	Article 12	Any substances that could be present in the CO_2 stream as a result of being (a) naturally in the source (i.e. coal, gas, oil, biomass, coal-biomass mixtures), (b) picked up in the capture process, or (c) incidentally entrained or intentionally added to prevent hazards during the transport and injection processes.
Permanent containment	Article 1(2) and 18(1)(a)	Permanent containment means that injected CO_2 will be effectively trapped by trapping mechanisms in perpetuity. It also means that structural, physical trapping within storage complex by caprock and seals should be effective when CO_2 is present in free-phase in the storage complex. Dissolved CO_2 should not migrate if there is potential for CO_2 exsolution prior to mineralisation or adsorption.
Overburden	Annex I, Step 2.b	The overburden is the lithostratigraphic volume of rock overlying the storage reservoir up to the surface or seabed.
Significant deviation	Annex II, 1.2	A discrepancy between observed and predicted behaviour, outside the range of uncertainty of predictive models. Though this may require taking additional monitoring and possibly preventive or corrective measures, a significant deviation does not imply that there is a significant irregularity.

Term	Articles using terms	Comments
Detectable leakage	Article 18(2)(b)	Leakage that can be detected by direct monitoring observations based on the approved monitoring plan, or which can be inferred from modelling that is in line with monitoring data.
Financial security	Article 7(10), Article 9(9), Article 11(4), Article 14(3), Article 16(5), Article 17(5), Article 19	The financial instruments or provisions created to ensure the operator is financially able to cover costs associated with site operations, closure and post-closure. The competent authority may draw on this financial security if the operator defaults or is otherwise unable to fulfil the permit obligations under the CCS Directive.
Financial mechanism	Article 20	A one-time contribution made to the competent authority prior to transfer of responsibility. Once made, the competent authority can draw on this financial mechanism to cover monitoring expenses and potentially to cover other costs related to the storage site after transfer.
Financial contribution	Article 20	A specific sum made available to the competent authority as part of the financial mechanism, which is to be calculated by the competent authority.

3. Main phases and regulatory steps

3.1. Main phases

Based on the CCS Directive, the life cycle of a CO_2 storage project can be subdivided into six main phases, culminating in five major project or regulatory milestones. Table describes the role of the competent authorities and the associated activities for regulatory authorities and operators during these phases and milestones.

Table 4: CO_2 storage life cycle framework summary.

Phase/milestone		Competent authority activities	Key operator activities	Typical duration[5]
Phase 1	Assessment of storage	• Member States intending to allow storage should	• Conduct own assessments of storage	0.5-2 years

[5] Duration: these timeframes are indicative only.

	capacity	assess the storage capacity available in the country and/or region, and promote CCS deployment, including by awarding exploration permits. • Identify the areas available for storage site exploration. • Competent authority communicates the technical requirements and evaluation criteria that operator(s) need to comply with to successfully demonstrate technical competence. • Review exploration permit application(s).	potential, sites and exploration requirements. • Outline a tentative development concept. • Perform an early risk assessment to feed into the site feasibility evaluation. This is normally done based on publicly and in-house available data and models. • Prepare exploration permit application(s).	
Milestone 1	Award of exploration permit	• Award exploration permit, if required, to meet the conditions for storage permit under Article 8(1).[6]		
Phase 2	Characterisation and assessment of storage complex	• Review storage permit applications (compliance with all requirements of the CCS Directive and of other relevant EU legislation[7]). • Storage permit applications and related material should be made available to the European Commission. The competent authority must make the draft storage permits available to the Commission, which may provide opinions to the competent authority on the draft permit. The Commission's opinion is non-binding, although the competent authority needs to explain any departures from the Commission's opinions in the final permit decision. • Provide guidance/feedback on acceptable risk levels based on risk assessment results and (preliminary)	• Carry out activities to characterise the storage complex. This includes dedicated appraisal data acquisition. • Define risk evaluation criteria (see Section 4.2) and carry out a structured risk assessment iteratively to inform characterisation activities, address the risks and underpin the permit application. • Select storage site(s) for further characterisation. • Specify the development concept and prepare project development plans and design, including plans for monitoring and corrective measures. • Carry out an environmental impact assessment in accordance with Article 5 of Directive 85/337/EEC, as replaced by Article 5 of Directive 2011/92/EU. • Submit storage permit	2-5 years

[6] An exploration permit may not be needed in all cases to compile a storage permit application under Article 7. For instance, the activities required under Annex I can sometimes be performed under an existing hydrocarbon production license in order to determine whether the hydrocarbon field can be used as a CO_2 storage site. Other cases where activities required per Annex I can be performed outside an exploration permit may be determined by competent authorities.

[7] For example, Article 5 of Directive 85/337/EEC, as replaced by Article 5 of Directive 2011/92/EU.

		project development plan, monitoring plan and corrective measures plan.	applications in accordance with Article 7 of the CCS Directive.	
Milestone 2	Award of storage permit	• Approve and award storage permit(s).	• Investment decision for storage project development.	
Phase 3	Development	• Oversee baseline monitoring in line with the approved monitoring plan.	• Construct facilities and drill required project wells. • Remediate existing infrastructure and wells if required to meet condition in Article 4(4). • Carry out baseline surveys and pre-injection monitoring. • Update site characterisation, risk assessment and plans for monitoring and corrective measures. • Front-end engineering design.	2-4 years
Milestone 3	Start of operations		• Start CO_2 injection operations and monitoring.	
Phase 4	Operations[8]	• Carry out inspections. • Approve reporting. • Approve any updates to monitoring and corrective measures plan. • Ensure necessary corrective measures are implemented. • Carry out periodical adjustment of financial security. Permit withdrawal • The competent authority has the authority to withdraw the storage permit. If this occurs, the competent authority must either issue a new storage permit (to the same operator or to another operator) or close the storage site. Permit transfer • The competent authority	• Carry out injection operations and monitoring. • Carry out reporting. • Update models as required, risk assessment and plans for monitoring and corrective measures. • 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.	10-30 years

[8] This only covers 'normal' operations and not the temporary continuation of operations if the CA withdraws the storage permit.

		may approve, at the request of the operator or following permit withdrawal, the transfer of storage permit to another operator if the new operator meets the technical and financial requirements of Article 8(1)(b), and the new operator assumes all responsibilities and obligations of the former operator in relation to the operation and/or closure of the storage site.		
Milestone 4	Closure	Authorisation of closure following request from the operator under Article 17(1)(b) (Case 1) or a decision to withdraw the storage permit under Article 11(3) and to close the site under Article 17(1)(c) (Case 2).	• End of injection operations and continuous operational monitoring of injection. • Partial reclamation of the site.	
Phase 5	Post-closure/pre-transfer	Case 1: When a site is closed following a request from the operator, the competent authority is responsible for: • inspections; • oversight of monitoring and reporting; • approval of any updates to monitoring and corrective measures plans; • ensuring the necessary corrective measures are implemented; • making periodic adjustments to the financial security. Case 2: When a site is closed following the withdrawal of a storage permit, the competent authority must take on the Phase 5 operator activities in addition to the competent authority activities for Phase 5.	• Carry out ongoing monitoring. • Carry out reporting. • Update risk assessments, models and plans for monitoring and corrective measures. • Take necessary corrective measures in the event of a leakage or significant irregularities. • Surrender allowances for any emissions from the site, including leakages, under Directive 2003/87/EC. • Remove injection facilities. • Perform site sealing.	5-20 years
Milestone 5	Transfer of responsibility	• Approve or provide a reasoned rejection of the request to transfer responsibility, considering any opinion issued by the Commission. The Commission's opinion is non-binding but the competent authority must explain any departures from the Commission's opinion in the final transfer decision. • Release remaining financial security after	• Submit transfer report. • Make financial contribution available to the competent authority (Article 20). • End of operator involvement.	

		fulfilling the obligations under Article 20. • Accept the responsibility for all legal obligations under Article 18(1) on behalf of the Member State, and release the operator from liability related to these obligations.		
Phase 6	Post-transfer	• Long-term stewardship of the site by Member State. • Conduct monitoring to detect leakages and take necessary corrective measures in the event of a leakage or significant irregularities. • Surrender allowances for any emissions from the site, including leakages, under Directive 2003/87/EC.		5-30 years

3.2. Interaction between operators and competent authorities

Interactions between operators and competent authorities on risk management will depend on the stage of the project life cycle. Operators must interact with the competent authorities in the following circumstances, all of which should be linked to the risk management framework:

- applying for an exploration permit under Article 5;
- applying for a storage permit under Articles 6-9;
- reviewing the storage permit under Article 11;
- acceptance and control of the CO_2 stream composition under Article 12;
- compiling and updating the monitoring plan under Article 13;
- reporting under Article 14;
- routine and non-routine inspections under Article 15;
- notifying the competent authority in the event of a leakage or significant irregularities and implementing corrective measures under Article 16;
- applying for closure of the storage site and updating the post-closure plan under Article 17; and
- transferring responsibility to the competent authority under Article 18.

In all cases, an ongoing and active dialogue between the operator and competent authority is recommended as the best practice to adopt, including for projects that are outside the scope of the CCS Directive as per Article 2. The nature and timing of interactions related to these activities are likely to vary across jurisdictions and project-specific aspects.

To provide predictability to operators, the Member States are encouraged to develop specific guidance on their expectations to operators on the level of interaction for each of the above circumstances. This includes expectations to the timing and frequency of interactions, and the extent of written inputs required. Guidance can include providing a standardised report structure for reports under Article 14, detailing the content to be included.

4. Risk management approach

4.1. Key principles

In the context of the CCS Directive, risk management should demonstrate that geological storage of CO_2 within a designated storage complex can be or is done safely in accordance with Article 1(2) and Article 4(4). Risk management should be an ongoing and iterative process throughout the CO_2 storage life cycle with the aim of continual improvement of the risk assessment process. This will involve regular and ongoing assessments of the risks and uncertainties in the geological framework, models and performance assessments.

Risk assessments should be documented in a traceable and transparent manner, with the aim to build trust with the competent authorities and other stakeholders that the risk assessments have been comprehensive and that results are underpinned by scientifically robust analysis. The competent authority can consult risk management guidance in relevant standards (such as ISO 27914:2017 Clause 6 or DNV-RP-J203 Section 6) for guidance on how to evaluate the comprehensiveness and robustness of risk assessments. However, competent authorities should be fully transparent on the requirements that potential operator(s) need to meet. It is therefore recommended that competent authorities publish a detailed list of essential requirements and evaluation criteria that they will use to review risk assessments, referring to the relevant standards.

This GD 1 covers risks related to scenarios that may lead to a failure to achieve the purpose of Article 1(2) of the CCS Directive. This means that it covers only consequences with a potential impact on permanent containment, on human health or on the environment. The impacts of geological storage on human health or the environment fall into two broad categories:

1. local impacts to human health or the environment, and
2. global effects from avoided release of CO_2 into the atmosphere.

A key principle of risk management is that the level of risk is reduced as low as reasonably practicable (ALARP). This implies that some risks may be assessed as contingent acceptable or tolerable if the cost or effort associated with reducing the risk is disproportionate to the level of risk, and the risk can be maintained at an insignificant level (see Section 4.3.4).

One important consideration for an ALARP demonstration and the determination of risk significance is the principle that the risk of negative impacts should not outweigh the positive effects. For CO_2 geological storage activities, this implies that the risk of negative impacts of a project to human health or the environment should not outweigh the expected benefits to the social good, including from the emission reductions obtained. Guidance on how to compare positive and negative effects is provided in Section 4.2.5.

At a high level, storage sites will need to satisfy three main requirements:

- capacity: sufficient storage volume is available or can be engineered to be available[9];
- integrity: confidence that the site is secure with no significant risk of leakage or material adverse impacts from induced seismicity, ground motion or earth deformation; and
- injectivity: the site has suitable reservoir properties that allow for sustained injection at required rates into the geological formations without having a negative impact on the integrity of the storage site.

A core part of risk management for CO_2 storage projects is to identify and rank risk scenarios against these three requirements and to develop and implement risk and uncertainty management strategies to address and manage these risk scenarios.

4.2. Risk evaluation criteria

In line with ISO 27914:2017, risk evaluation criteria provide the terms of reference against which the significance of risk is evaluated. For geological storage of CO_2, these criteria must be set on the basis of site-specific information and context.

This section outlines guidance on how to draw up risk evaluation criteria for individual storage projects, with an emphasis on the risk of not achieving the purpose set out in Article 1(2) of the CCS Directive, i.e. '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'. The focus is exclusively on the consequences related to leakage, the environment and human health. It does not cover commercial impacts for the operator, or reputational impacts to either the operator or the competent authority.

Consequences related to the volume of leakage are generally evaluated indirectly against any subsequent impacts on the environment or human health. This should be done using site-specific considerations. Impacts of leakage on the global environment (less emission reductions) should also be evaluated, but these are normally of lower

[9] The capacity of prospective areas for geological storage of CO_2 within storage sites that use structural trapping can be assessed using the CO_2 Storage Resources Management System (SRMS) methodology developed by SPE. In mineralisation projects, the capacity is assessed by the reactivity of the rock (over time) and the ability of the operation to avoid CO_2 exsolution prior to mineralisation without causing a negative environmental impact. From a project perspective, the emphasis is generally on verifying sufficient capacity for project volumes, rather than on estimating the total available capacity of the selected storage site. This also entails evaluating the capacity for sustained injectivity, i.e. injection rates that can be sustained over the planned timeframe for injection.

significance than the potential subsequent impacts to human health or the local environmental impacts. In the European Economic Area (EEA), these impacts are also covered by the EU ETS (Directive 2003/87/EC), since all storage sites are ETS facilities.

4.2.1. Categories of likelihood

The criteria for assessing the probability or frequency of an undesirable event are often established by specifying different categories of likelihood[10]. For each category, the likelihood is often conveyed in terms of different descriptors. The descriptors may include quantitative probability or frequency bands, such as between 0.01 and 0.001 probability that the event will occur in a single year. The descriptors are often supplemented with more qualitative descriptors to help project developers factor in industry experience and statistics.

4.2.2. Categories of consequence – human health

Similarly, the criteria for assessing potential damage to human health as a result of an undesirable event are often expressed as categories of impact. The impact is often described in terms of the severity of injuries and the number of potential fatalities, and associated impact on life quality and work performance, e.g. illness, disability or lost worktime. It can often be useful to describe, for each impact category, a situation that has the potential to cause the associated impacts. For instance, 'a moderate CO_2 release at well site or topside with exposure to fewer than five people, causing respiratory or temperature-related health effects requiring short-term medical treatment'.

Given the focus on potential for induced seismicity (and associated ground motion), it is recommended that operators develop one impact example for leakage events and one impact example for induced seismicity. The latter has the potential to cause annoyance and possible damage to buildings and infrastructure, which can have knock-on damages to human health. Fault slip, which leads to induced seismicity, is also a containment risk. However, the impacts of this should be evaluated by assessing the possible damage from any leakage and induced seismicity separately, and classifying the resulting impact by the most severe damage expected to occur from leakage and ground motion.

4.2.3. Categories of consequence – environment

The severity of environmental impact depends on the size of the area impacted, the magnitude of the damage to the environment in the area (flora and fauna) and the vulnerability of the flora and fauna that are affected. The impact categories tend to include descriptors related to each of the above (e.g. an exposure radius with respect to the size of the area impacted), as well as the timeframe needed for ecological restoration to return the environment back to its original, pre-event condition, if return is feasible.

[10] ISO 27914:2017 defines 'likelihood' as 'chance of something happening, expressed qualitatively or quantitatively and described using general terms or mathematically, e.g. by specifying a probability or frequency of occurrence over a given period'.

As for human health impact, it is often useful to provide descriptors to aid the impact evaluation process. This can include how judgements should be made between impact severity for, e.g. medium flux-rate and short-duration leakage events, compared to low flux-rate, long-duration leakage events. The descriptors should assist the evaluation of environmental effects from each of the main effects to cover in the hazard characterisation (see Section 4.3.2), i.e. effects from CO_2 leakage, intrusion of CO_2 charged fluids and mobilised elements, displaced formation fluids, subsurface compaction and seismicity.

4.2.4. Assessing the level of insignificant risk

The aim of this section is to provide guidance on when a combination of a probability of damage occurring and the magnitude of damage represents a significant risk. It is common practice in the maturation of CO_2 geological storage projects to visualise risk significance using a risk matrix, where each cell in the matrix represents a degree of likelihood and consequence. Cells in the matrix are normally coloured to indicate the level of significance of risk scenarios placed in that cell, with red often used to indicate unacceptable risk.

The operator should propose a risk matrix indicating their view of which cells represent significant and insignificant risk for the project. The operator must then discuss and calibrate this proposal with the competent authority. To this end, for each likelihood range, the operator and competent authority should discuss and agree on the consequence of each severity level (corresponding cells in risk matrix) for human health and environment that constitute a 'significant risk'. This should include assessing the nature of the damage to human health or the environment, the risk acceptance criteria for such damage in applicable regulations and corporate policies, and the benefits of the CO_2 storage activity.

Following a 'project-specific risk assessment', operators and competent authorities will also need to decide whether the aggregate risk profile of the project from all project risk scenarios is acceptable or insignificant. This also implies that the aggregate risk profile for the project does not outweigh the project benefits. Section 4.2.5 below provides an example of how to reach this decision. Once the aggregate risk profile has been finalised and agreed on between the operator and the authority, the operator should develop and implement an integrated plan for communicating these risks to the communities directly impacted.

4.2.5. Example: how to compare the aggregate risk profile with the expected benefits of the project

Many risk scenarios for CO_2 storage projects have a very low likelihood of occurring. For this reason, it is recommended to compare the risks and benefits by looking at a portfolio of 'identical' or comparable projects as follows:

1. carry out a project-specific risk assessment;
2. draw up the overall risk profile for the project in terms of the risk of leakage and potential consequences to human health and the environment;

3. identify the overall benefit of the project in terms of human health and the environment, including the benefits in reducing global CO_2 emissions;
4. assume that there is a portfolio of, for example, 100 identical or comparable projects;
5. assume that each risk scenario identified for the project occurs at the assessed frequency in each individual project, and that the assessed impact occurs;
6. evaluate the cumulative damage and cumulative benefit from the portfolio of identical or comparable projects;
7. assess whether the potential damage outweighs the benefit or vice versa.

Case: An offshore CO_2 storage project is planning to inject 3 million tonnes (Mt) a year over 25 years, storing a total of 75 Mt CO_2. The likelihood that leakage will occur along each injection well over the lifetime of the project is assessed to be 1%. If leakage occurs, the cumulative leakage will be less than 500 tonnes per well. The environmental impact related to such a release is assessed to be low. No impacts to human health.

In a portfolio of 100 identical or comparable projects, the cumulative planned annual storage is 300 Mt and the cumulative total storage is 7 500 Mt. This is the key benefit of the project. The cumulative leakage from the injection wells will be 1 500 tonnes, and the cumulative environmental impact will be low. This is the key negative impact to human health and the environment.

Clearly, in this case, the cumulative benefit of the portfolio outweighs the cumulative negative impacts. In a real case, one would also need to include an assessment of the negative impacts of all risk scenarios, not just the risk of leakage from the injection wells. Nonetheless, this example illustrates how risk and benefits from a particular project can be made more tangible and understandable for stakeholders by taking the portfolio approach, i.e. comparing the risks and benefits against a portfolio of identical or comparable projects.

4.3. Risk assessment

4.3.1. General guidance

This section provides guidance on how to interpret and implement the requirements to carry out risk assessments as laid out in Step 3.3 of Annex I to the CCS Directive. This entails characterising the hazards (Section 4.3.2), assessing exposure and potential effects (Section 4.3.3) and characterising the risk (Section 4.3.4).

The risk assessment for geological storage of CO_2 should be site-specific. This means it should take into consideration the site-specific context and geological conditions, including local population density, the nature of the local biosphere and hydrosphere, the nature and magnitude of any scenarios involving dispersal of CO_2 to atmosphere or water column, and whether the site is onshore or offshore. The composition of the CO_2 stream should also be factored in.

For each stage of the life cycle, the starting point would be to review any risk assessment carried out in an earlier phase of the life cycle. Next, the risks should be assessed in light of new data and an analysis of the results obtained through the project activities. Any additional risks that were not previously identified should be considered if the new data reveals new risks or uncertainties. This process should include a review of the geological framework, modelling, the numerical simulations, monitoring results and any other relevant data. It should also include consideration of the following questions:

- Does the available geological data and data resolution provide a sufficient basis for the geological model that gives an adequately correct and detailed representation of the storage site and its overburden?
- Are the geological model(s) built and populated with appropriate lithological parameters with respect to the decisions to be made?
- Have the dynamic models been properly history-matched and aligned with monitoring data?
- Is the current list of possible leakage pathways comprehensive?
- What is the potential magnitude of leakage events for the leakage risk scenarios identified?
- Have the critical parameters affecting containment and leakage been duly considered?
- Have the most relevant secondary effects of the storage project that may have an adverse impact on human health or the environment been considered (see Items 2-5 in Section 4.3.2)?
- Are there any other factors that could pose a hazard to human health or the environment (e.g. physical structures associated with the project)?

4.3.2. Hazard characterisation

Hazard characterisation under Annex I, Step 3.3.1 of the CCS Directive, is synonymous with risk identification, covered in Clause 6.7.2 of ISO 27914:2017 and Section 6.3.2 of DNV-RP-J203. Users of this GD 1 are encouraged to also consult these standards for a best practice approach to identifying the risks of projects that involve the geological storage of CO_2. The hazard characterisation required by the CCS Directive (Box 2), however, focuses exclusively on leakage and 'other factors which could pose a hazard to human health or the environment'.

Box 2: CCS Directive requirements to hazard characterisation.

Hazard characterisation must be undertaken by characterising the potential for leakage from the storage complex […]. This must include consideration of:

a) potential leakage pathways;

b) the potential magnitude of leakage events for identified leakage pathways (flux rates);

c) the critical parameters affecting potential leakage […];

d) secondary effects of storage of CO_2, including displaced formation fluids and new substances created by storing CO_2;

e) any other factors that could pose a hazard to human health or the environment […].

The process of hazard characterisation must cover the full range of potential operating conditions to test the security of the storage complex.

Local hazards to human health or the environment arise from five principal effects:

1. Direct effects of leakage, resulting in elevated concentration of CO_2 and impurities in the CO_2 stream composition in the overburden, in the atmosphere or in the water column above a storage complex[11]. In this section, leakage pathways are divided into two main categories: geological pathways (Table 5) and manmade systems (Table 6).
2. Effects of intrusion of CO_2 charged fluids and mobilised elements into groundwater or other environmental receptors in the biosphere[12].
3. Effects from the displacement of formation fluids and mobilised elements by the injected CO_2, including brine (for aquifer storage) and hydrocarbons (for storage within or below hydrocarbon fields).

[11] Anomalies with CO_2 release to seabed or atmosphere can arise from other origins than the CO_2 storage site, such as biogenic sources in the overburden.

[12] ISO 27914:2017 defines the biosphere as the 'realm of living organisms including the atmosphere, on the ground surface and in soils, in oceans and seas, in surface waters such as rivers and lakes, and in the subsurface above the storage complex'.

4. Effects of subsurface compaction and corresponding ground displacement (uplift or subsidence).

5. Effects of natural or induced seismicity and associated knock-on events, such as damage to wells and to the built infrastructure.

The leakage pathways specified in Table 5 and Table 6 are also relevant to the process of identifying risk scenarios for effects 2 and 3 in this list.

The risk identification process should identify threats that can cause any of these effects to occur, and describe the associated risk scenario, i.e. the threat-event-consequence sequence. The requirement to characterise each hazard implies that the associated risk scenarios must also be characterised. Modelling and sensitivity analysis can be used to identify the risk scenarios and the critical parameters that could result in leakage, or any of the other principle effects.

For leakage-related risk scenarios, the hazard characterisation requires estimating the potential magnitude of a leakage (i.e. leakage rates and duration) following various credible modes of containment failure. While industry statistics may be able to support characterisation of leakage rates and durations for some risk scenarios (e.g. active wells), it is likely that the estimation of leakage magnitude for many scenarios will need to be based on qualitative judgements.

In both cases, it is recommended that the operator estimates the expected or most likely magnitude in the event of the associated risk scenario. A worst-case estimate of both rate and duration will generally lead to undue exaggeration of the leakage magnitude. To capture both the down- and up-side cases and properly reflect the degree of uncertainty in the estimated magnitude of a leakage, operators are advised to estimate the uncertainty range for both rate and duration, and to communicate these uncertainty ranges.

If the geological formation(s) used for geological storage of CO_2 is within a hydraulic unit that is or has been used for other activities, e.g. neighbouring CO_2 storage activities, hydrocarbon field developments or geothermal operations, then the operator should consult with the competent authority to ascertain the nature, extent and duration of such activities, and consider the pressure influence from these activities when identifying risk scenarios. Such influences may impact CO_2 storage capacity and associated subsurface compaction can also impact well and seal integrity. To achieve safe storage in a multi-site hydraulic unit, it is important to reach a common understanding of the impact of pressurisation on critical points in entire hydraulic units, including wells and faults.

The competent authority should therefore enable, and put forward requirements for, sharing related information between operators, and to maintain records of pressure influence from previous operations. When acreage for CO_2 storage is made available in hydraulic units that extend across national borders, the competent authority should ensure that there is adequate sharing of information between the authorities in the respective countries to inform operational constraints on pressurisation.

Table 5: Potential geological leakage pathways from geological storage sites.

Leakage pathway	Potential leakage mechanisms	Notes
Vertical leakage through caprock[13] **(Relevant for storage options that rely on structural trapping)**	Through the pore system in the caprock if the capillary entry pressure is exceeded, or through existing (high) permeable paths in the caprock.	Dependent on caprock characteristics, and interplay with CO_2 plume build-up in storage site.
	Caprock is locally absent or more permeable.	Depends on caprock distribution and thickness, including changes to the facies or erosion. Requires mapping using seismic and well data.
	Geochemical degradation of caprock quality, including any alteration of permeability along fault zones.	Depends on site-specific geochemistry and potential reactions between caprock, CO_2 stream constituents and formation fluids.
Vertical leakage along faults or fractures **(Relevant for storage options that rely on structural trapping)**	Fracturing of the caprock induced by injection.	Depends on minimum principal stress in caprock and pressure build-up in storage reservoir. Fracturing induces (micro-)seismicity.
	Via faults and/or fractures in caprock or seals (prior to initiation of CO_2 injection).	Not all faults are potential pathways for leakages. Some are closed or sealed. Geomechanical or geochemical effects can create or enhance fault transmissibility. Depends on fault and fracture distribution and characteristics, and the pressure history of the storage site.
	Via faults that have been reactivated.	Depends on fault and fracture distribution, characteristics and geomechanics. Fault reactivation may induce seismicity. Fault reactivation can occur due to injection-induced changes in reservoir pressure and temperate or due to natural seismicity.
Structural spill	Via a spill point (lowest point in structure that can provide lateral closure) if the reservoir is overfilled, and subsequent vertical or lateral leakage.	Depends on site structure, capacity and storage management. Can be managed by implementing the monitoring and operating strategy. Relevant for storage options that rely on structural trapping.
Lateral leakage	Movement of CO_2 outside the lateral boundary of the storage complex, e.g. via up-dip migration.	Depends on up-dip facies, rock types and permeability. Mainly relevant to storage sites that rely on structural trapping, but without structural closure. Particularly relevant for sites that rely on residual saturation trapping.
CO_2 exsolution	Failure of dissolution trapping prior to mineralisation.	Relevant to sites that lack seals capable of providing structural trapping of free-phase CO_2, i.e. sites where containment relies on effective trapping by other trapping mechanisms.

[13] See interpretation of term 'caprock' in Section 2.4.

		The reservoir pressure needs to be maintained above bubble-point pressure to avoid exsolution of CO_2.

Table 6: Potential manmade leakage pathways.

Leakage pathway	Type of pathway/mechanism	Notes
Wells and boreholes	• Operational or abandoned wells (and boreholes).	• Risk depends on the characteristics of each well, including age, status (active, suspended, abandoned), use (injection, production, monitoring), construction and abandonment. • Risk also depends on the ability to implement remediation options to (re-)establish well integrity in a CO_2 storage environment. • Well integrity is required for all storage sites, but the specific requirements to achieve integrity may depend on storage site options and local circumstances, e.g. sites where CO_2 plumes will exist and sites where all injected CO_2 will be dissolved during the injection process. • See GD 2 for further information on evaluating legacy wells for leakage risk.
	• Well blow-outs (uncontrolled emissions from drilling and operation of injection wells).	• Likely to be rare as established drilling and well operations practices reduce risk. • Possible source of high-flux leakage during drilling and injection operations, usually over a short period of time. • Blow-outs can be remediated.
Pathways associated with mining activity within or below storage complex	• Abandoned mine workings. • Mining-induced subsidence.	• Largely related to CO_2 storage in coal beds. • Compaction and subsidence may impact wells and the built infrastructure overlying areas of mining activity, and loss of well integrity or fault reactivation can create CO_2 leakage.
	• Future mining of CO_2 storage reservoir.	• Specific issue for coal bed reservoirs.

4.3.3. Exposure and effects assessment

The exposure and effects assessment under Annex I, Step 3.3.2 and 3.3.3 of the CCS Directive (Box 3) are elements of risk analysis. The requirements to risk analysis are covered in Clause 6.7.3 of ISO 27914:2017 and Section 6.3.3 of DNV-RP-J203. Users of this GD 1 are encouraged to consult these standards for a best practice approach to risk analysis for projects involving the geological storage of CO_2.

Box 3: CCS Directive requirements to exposure and effects 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 identified leakage risk scenarios.

The 'effects assessment' should be based on the sensitivity of particular species, communities or habitats linked to identified leakage risk scenarios. Where relevant, it must include the effects of exposure to elevated CO_2 concentrations in the biosphere (including soil, marine sediments and benthic waters (asphyxiation; hypercapnia) and reduced pH in those environments as a consequence of leaked CO_2). It must also include an assessment of the effects of other substances that may be present in leaked CO_2 streams (either impurities in the injection stream or new substances formed by storing CO_2). These effects must be considered at a range of temporal and spatial scales, and linked to a range of different magnitudes of leakage events.

Box 3 focuses on the effects of a leakage. The exposure and effects assessment should, however, also include an analysis of the exposure and the effects of the other principal effects listed in Section 4.3.2.

The risk analysis process aims to provide the information required to estimate the level of risk, i.e. the likelihood that a certain risk scenario can occur, and the magnitude of damage that could result if the risk scenario occurs. This step should therefore focus on assessing whether the results from the data collection process and any modelling and simulation studies performed provide an adequate basis for evaluating the risks and uncertainties. The risk analysis process also involves the deliberation of possible risk treatment options for mitigating the risk, and whether this can be justified given the additional cost, time required, and other practical aspects involved in mitigating the risk.

The risk analysis process may entail evaluating both the qualitative and quantitative aspects of leakage, risk significance, and the associated uncertainties. Quantitative or semi-quantitative risk analysis approaches should be applied to risk scenarios where it is possible to obtain the relevant data for quantification, e.g. available empirical data, statistics or scientific reasoning. The latter can involve dedicated modelling studies and evaluating the sensitivity to key parameters. An example where quantitative approaches may be appropriate are well-leakage scenarios. If data to support a quantitative risk analysis approach cannot easily be obtained, then the level of risk for associated risk scenarios should be calibrated by the judgement of experts qualified in terms of their applicable professional expertise and project knowledge.

A variety of quantitative estimation methods may be applicable to risk analysis, including numerical models and analytical models. All methods can be carried out in a deterministic or probabilistic manner and the underlying assumptions and boundary conditions must be thoroughly understood before using the results. Similar methods may be used to assess risks using the following illustrative analysis approaches:

- Scenario analysis: the process of analysing a range of possible future events by assessing alternative outcomes. This may involve constructing a few models that satisfy and represent the observed characterisation data to a similar degree and then comparing the storage performance predicted by each model.
- Reliability analysis: using 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: a quantitative assessment of parameter sensitivity based on modelling the impact of parameter variations of key uncertain parameters to one or more performance functions. The emphasis is usually on rigorously ranking the relative importance of a set of uncertainties.

Judging the likelihood and consequence of risk elements, or the associated uncertainties, both qualitatively or (semi-)quantitatively, depends on the reliability of the input parameters. Care should be taken to use a valid body of data and experience to justify the application of quantitative analysis to risk elements affecting the geological storage of CO_2.

4.3.4. Risk characterisation

Risk characterisation under Annex I, Step 3.3.4 of the CCS Directive (Box 3) is often called risk evaluation. It involves categorising and ranking identified risks using risk evaluation criteria. Risk evaluation is covered in Clause 6.7.4 of ISO 27914:2017 and Section 6.3.4 of DNV-RP-J203. Users of this GD 1 are encouraged to consult these standards for a best practice approach to risk evaluation for projects involving the geological storage of CO_2.

The risk evaluation process is supported by the risk analysis (Section 4.3.3). Risk evaluation compares the results of a risk analysis against the risk evaluation criteria to ascertain whether the risk is significant. The aim of the risk evaluation process is to characterise the potential significance of each risk by assessing the likelihood that risk scenarios can occur and the severity of the consequences that could arise if they occur. The significance of each risk should then be characterised and placed in one of the following two risk categories:

- insignificant risks: risks that do not call into question the purpose of the CCS Directive for the storage site concerned; and
- significant risks: risks that must be reduced to insignificant by taking risk-reducing measures in order to meet Article 4(4) and subsequently achieve compliance with the conditions for transfer of responsibility (to meet Article 18(1)(a)).

Under ISO 27914:2017, the result of the risk evaluation before mitigation sets the performance requirements for the corresponding strategy for mitigating the risk[14], i.e. the level of risk that needs to be achieved to be 'insignificant'. It is considered best practice to document both the level of risk before implementing risk treatments aimed at mitigating the risk, the target level of risk to be achieved after the risk mitigation actions are taken, and to justify why the selected risk controls will be effective in mitigating the risk. The uncertainty attached to the predicted effectiveness of planned risk mitigation action should also be evaluated and documented. See Box 4 for guidance on the selection of risk controls.

Box 4: CCS Directive requirements to the risk evaluation process.

Risk evaluation must comprise an assessment of the safety and integrity of the site in the short and long term, including an assessment of the risk of leakage under the proposed conditions of use, and of the worst-case environment and health impacts. The risk evaluation must be conducted based on the hazard, exposure and effects assessment. It must include an assessment of the sources of uncertainty identified during the steps of characterisation and assessment of storage site and when feasible, a description of the options to reduce uncertainty.

For many risk scenarios related to the geological storage of CO_2, there may be significant uncertainty related to both probability and severity. This also applies to the risk reduction effect of the alternative safeguards. The CCS Directive requires consideration of worst-case impacts (Box 3). This can be done by assessing the worst plausible consequences that can follow from the risk scenarios. Alternatively, the level of risk can be communicated using the best estimate, along with the associated uncertainty, for example by giving a range of possible outcomes. The aim is to be objective and avoid bias without unduly exaggerating the risk. The risks would then be managed and effectively downgraded as more knowledge about the sites is acquired and uncertainties are assessed and reduced.

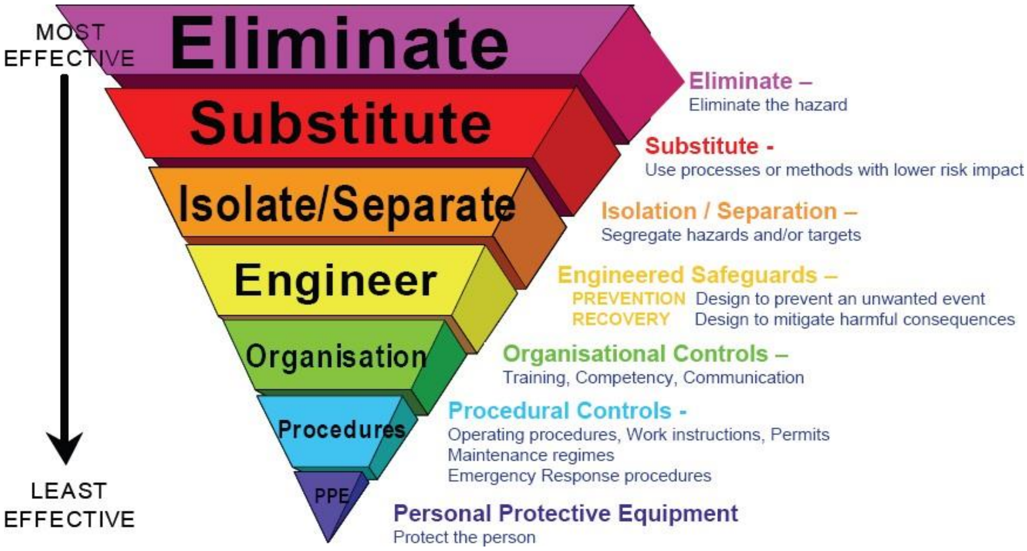
[14] Risk treatment refers to the process of implementing risk controls (safeguards). In line with ISO 31000:2018, risk controls are measures that maintain and/or modify risk.

Box 5: Guidance on the selection of risk controls.

Risk controls (safeguards) may be preventive or corrective. Preventive controls can be implemented to reduce the probability of an incident carrying risk from occurring or reduce the impact associated with an incident if it occurs. Corrective measures are safeguards implemented to reduce the consequences from risk scenarios after they have occurred. The CCS Directive definition is 'measures taken to correct significant irregularities or to close 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). They may include the consideration and use of multiple storage sites and/or storage targets within the same storage complex. Figure 2 shows a hierarchy of different types of safeguards reflecting the hierarchy of risk control mechanisms that may be applied. The top three elements of the hierarchy of risk control (eliminate, substitute and isolate/separate) lead to 'inherent safety'. It follows that these three elements of risk reduction are the most important for CCS projects, and they must be assessed at an early stage.

Figure 2: Potential hierarchy of control to help compare alternative safeguards to reduce risk.



The evaluation of more than one storage option ensures that a site with poor life-cycle containment is characterised and 'eliminated' following a proper risk assessment, and instead a preferred site with a demonstrably secure capacity is selected. The residual risk features within that preferred site can then be isolated by physical separation (e.g. by creating a distance between the injection wells from any susceptible faults and below the caprock).

In addition to a qualitative or quantitative risk ranking based on a risk analysis, the risk evaluation may involve facilitated sessions with a group of experts that have detailed knowledge of the storage project. However, experts are biased by their experience. To reduce bias in risk evaluations, it is important to select a broad group that includes both representatives from the operator and experts that have no particular stake in the CCS project. It might also include representatives from the public or the local authorities that may evaluate certain risks differently to the operator or people with knowledge about the geologic storage of CO_2. One of the aims of stakeholder participation in the risk evaluation is to enhance transparency around the risks and risk management amongst groups exposed to risk.

The process of evaluating the risk and selecting risk treatment should form the basis for a dialogue with the competent authorities to ensure that the legal requirements of the CCS Directive are met. Deciding what constitutes a significant risk versus insignificant risk is, however, ultimately subjective, and it depends on the risk appetite of the entities exposed to risk or will bear responsibility for managing the risk.

Therefore, to reach an agreement between the operator and competent authority that a storage site meets Article 4(4) – under the proposed conditions of use there is no significant risk of leakage, and no significant environmental or health risks exist – it is recommended that the operator is transparent about the risk controls considered and why the chosen risk controls were selected. The operator can then also be requested to explain why certain risk controls were not selected or considered necessary to reduce the risk to an insignificant level. Box 5 provides an example of how an operator could set the stage for a dialogue with a regulator to agree on risk controls to be implemented to establish that the risk of leakage along an abandoned well is insignificant.

In the process of assessing significant versus insignificant levels of risk, it should be highlighted that such determinations are not necessarily transferable between sites. For instance, a risk scenario with the same likelihood for leakage to occur, and the same potential magnitude of leakage, may be found to be insignificant risk at one site and significant risk at another site. This is due to differences in negative effects of the leakage to human health or the environment. Such effects can, for instance, be quite different for an offshore site compared to an onshore site. Similarly, the significance of an 'identical' risk scenario related to any of the other effects listed in Section 4.3.2 can be evaluated differently for different sites.

It is also important for the operator to consider how the risks and risk profile will evolve throughout the lifecycle of the storage project. This should include evaluating how the aggregate risk profile from all leakage risk is expected to evolve over time, and the corresponding effect of risk treatment actions.

Box 6: Example of how an operator set the stage for a dialogue with competent authority to agree on level of insignificant risk.

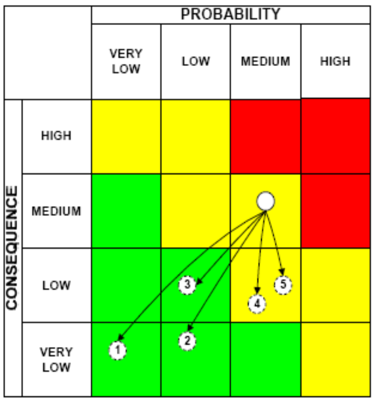
Consider the following situation:

1. Abandoned well within the permit area in an onshore storage project.
2. Plume set to intersect the well 10 years after injection.
3. Comprehensive well records exist from time of abandonment (1982).
4. Well integrity considered to be good.
5. The initial views of the regulator and the operator are as follows:
6. Regulator: all abandoned wells that may be in contact with the plume must be re-abandoned.
7. 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. Monitor well for early signs of leakage – re-abandon if detected.
3. Monitor well for early signs of leakage – re-design injection strategy if detected.
4. Monitor for leakage at surface – re-abandon well if leakage is detected.
5. Monitor for leakage at surface – assess impact of leakage and redesign injection strategy. Re-abandon if significant leakage.

Figure 3: Potential risk reduction resulting from the 5 identified options illustrated using a risk matrix.



The risk reduction potential of the measures is represented in the matrix above. 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). The process would be repeated for all risks that are not ranked as insignificant pre-mitigation.

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