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Guidance document 2

Characterisation of the storage complex, CO_2 stream composition, monitoring and corrective measures

EUROPEAN COMMISSION

Directorate-General for Climate Action

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E-mail: *CLIMA-CCS-DIRECTIVE@ec.europa.eu*

European Commission
B-1049 Brussels

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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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Contents

1. Revision history

Key changes since the previous version
• Broadened description of a more balanced site-specific and risk-based approach to ensure containment through validation of effective trapping mechanisms. • More detailed section on geomechanical characterisation. • More emphasis on legacy wells as part of the process to assess site suitability. • New subsection on evaluating legacy wells as part of site characterisation. • Sensitivity case dynamic modelling included to feed into the range of uncertainty. • Additional guidance on interpretation of Article 12 on CO_2 stream composition, including statement that water co-injected with the CO_2 should not be considered part of the CO_2 stream. • More balanced discussion of monitoring technologies and risk-based monitoring plan. • Additional guidance specific to depleted field storage. • Additional guidance related to considerations around induced seismicity. • New section on evaluating storage capacity in Member States in line with Article 4(2) of the CCS Directive.

2. 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 transfer of 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 2 provides guidance on:

- site selection;
- the composition of the CO_2 stream;
- monitoring; and
- corrective measures.

Note: See GD 1, Section 2.4, for interpretations of the main defined and non-defined terms used in the CCS Directive.

3. Characterising the storage complex and surrounding area

The goal of the process to characterise the storage site, storage complex and surrounding area is to assess the containment, capacity[1], injectivity and monitorability, and also to demonstrate that storage activities pose no significant risk to human health or the environment. The risk assessment process (see GD 1) provides the foundation for data collection, site characterisation and site selection. Site-specific risks will be identified and evaluated through several steps, such as data analysis, 3D static geologic modelling, dynamic modelling and sensitivity characterisation.

The CCS Directive allows for many CO_2 storage settings and trapping mechanisms, provided they meet the requirements of the CCS Directive. Saline aquifers, depleted hydrocarbon fields, CO_2 mineralisation, coal seams and other settings, such as still active hydrocarbon fields, in case of EHR, or geothermal systems, in the case where the objective is to reduce GHG emissions, may all apply under the CCS Directive. The process to characterise the storage site, the storage complex and the surrounding area will vary depending on the storage type of the site, data availability from previous activities, and site-specific conditions.

3.1. Legislative context

This section provides guidance to operators and competent authorities on how to interpret and meet the obligations stipulated by Article 4(2) and Article 4(3) in the CCS Directive. Article 4(2) states that Member States that intend to allow geological storage of CO_2 in their territory must assess the storage capacity available in parts or in the whole of their territory. Article 4(3) states that ‘the suitability of a geological formation for use as a storage site must be determined through a characterisation and assessment of the potential storage complex and surrounding area pursuant to the criteria specified in Annex I’.

Annex I to the CCS Directive sets out the specific criteria to be met in order to characterise and assess the potential storage complex and surrounding area. It requires operators to complete the assessment according to best practice at the time of the assessment. Best practice may vary depending on site-specific considerations. The steps to carry out during the site characterisation process in Annex I include:

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[1] Capacity of prospective areas for geological storage of CO_2 within storage sites relying on buoyancy/structural trapping can be assessed using the CO_2 Storage Resources Management System (SRMS) methodology developed by SPE. In mineralisation projects, the capacity is determined 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 estimating the overall available capacity of the selected storage site.

1. Data collection.
   - Sufficient data must be collected to construct a volumetric and three-dimensional static (3D)-earth model for the storage site and storage complex, including the caprock, the surrounding area and hydraulically connected areas.
2. Three-dimensional (3D) static geological modelling.
   - Using the data collected in Step 1, a three-dimensional static geological earth model, or a set of such models, of the candidate storage complex, including the caprock and the hydraulically connected area and fluids must be built using computer reservoir simulators.
3. Characterising storage dynamic behaviour, sensitivity and risk assessment.
   - The process to characterise storage dynamic behaviour must be based on dynamic modelling. It must comprise multiple time-step simulations of CO_2 injection into the storage site using the three-dimensional static geological earth model(s) in the computerised storage complex simulator constructed.
   - Multiple simulations must be carried out to identify the sensitivity of the assessment to assumptions made about particular parameters. The simulations must be based on altering parameters in the static geological earth model(s) and changing rate functions and assumptions in the dynamic modelling exercise. The risk assessment must factor in any significant sensitivity.
   - The risk assessment must include the following steps:
     - hazard characterisation
     - exposure assessment
     - effects assessment
     - risk characterisation.

3.2. Evaluating storage capacity in the Member States

To meet the Member States' obligations under Article 4(2), the competent authority should carry out or commission work to develop a storage atlas for the areas in their national territory considered to be potentially suitable for the geological storage of CO_2. The storage atlas should be made available as a digital, searchable database. Examples of storage atlas' developed for this purpose include the CO_2 storage atlas for the Norwegian Continental Shelf[2], the storage atlas developed for the UK[3], the North

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[2] https://www.npd.no/en/whats-new/publications/co2-atlases/co2-atlas-for-the-norwegian-continental-shelf/.

[3] https://www.co2stored.co.uk/home/index.

American Storage Atlas[4] and the OGCI storage resource catalogue[5]. A European CO_2 storage database was also developed by the CO2StoP project (CO_2 Storage Potential in Europe)[6]. The work to develop the storage atlas should factor in considerations that may exclude certain areas for geological storage, such as protected nature areas, or other socioeconomic aspects, such as human settlements, even though the subsurface in the area may be technically suitable for geological storage.

To carry out an initial high-level evaluation of the capacity available in those areas of the Member State's territory, a dual approach is often taken.

Depleted fields

Depleted hydrocarbon fields are those fields for which it has been demonstrated that hydrocarbon reserves have been depleted (either fully or partially) or the remaining resources may no longer be recovered/developed economically. For depleted fields, the capacity is often estimated based on the volume of hydrocarbons – at reservoir conditions – that have been produced, and the equivalent volume of CO_2 that will occupy the same reservoir volume. This requires access to production data and an evaluation of CO_2 density at reservoir conditions.

A discount factor (i.e. storage efficiency factor) is typically applied since the injected CO_2 may not be able to access the full reservoir volume, and geomechanical effects of depletion and reinflation may not permit re-pressurisation to initial reservoir pressure. This may also be necessary if reinflation could lead to higher reservoir pressures than virgin pressure if the full equivalent volume is injected. A storage efficiency factor of 50% may be considered conservative and used to compare different projects, but the value for a given reservoir should be scrutinised on a case-by-case basis. For instance, the storage efficiency factor will vary depending on the nature of the reservoir and corresponding connected aquifer (i.e. the hydraulic unit), where a field with strong aquifer pressure support (i.e. production from water drive resulting in pressure recharge) would have a lower storage efficiency factor and lower estimated CO_2 capacity compared to a field lacking aquifer pressure support (i.e. little to no production from water drive or pressure recharge).

Aquifer sites

Aquifer sites are often not depleted and CO_2 injection operations generally increase pressure significantly above virgin pressure (unless active pressure management is carried out using brine production). The storage capacity for such sites is constrained by allowable pressure build-up without fracturing the rock, or causing activation of faults, as well as by constraints on CO_2 migration to achieve long-term containment. High-level (e.g. basin-wide) capacity estimates are, however, generally derived without considering

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[4] https://www.netl.doe.gov/sites/default/files/2018-10/ATLAS-V-2015.pdf.

[5] https://www.ogci.com/ccus/co2-storage-catalogue.

[6] https://setis.ec.europa.eu/european-co2-storage-database_en hosted by the Energy and Industry Geography Lab (https://energy-industry-geolab.jrc.ec.europa.eu), platform developed by the Joint Research Centre.

migration. Instead, estimates are typically derived by using rough estimates of mass that can be injected without over-pressurising the storage system.

The typical method to derive initial high-level capacity estimates for aquifer sites links capacity to the volume that can be made available by water displacement and compressibility using the following formula:

$M_{CO2} = V_b \times \phi \times n/g \times \rho_{CO2} \times E$

Where:

- M_{CO2} = mass of CO_2 (kg);
- V_b = bulk volume (m^3);
- ϕ = average effective porosity (% or ratio);
- n/g = net to gross ratio (or %);
- ρ_{CO2} = density of CO_2 at reservoir conditions (kg/m^3); and
- E = storage efficiency factor.

As it is conventional to represent CO_2 capacity in tonnes (t) or million tonnes (Mt), M_{CO2} in kilograms (kg) must be multiplied by 1000 or 1.0×10^9, respectively. Here the bulk volume (V_b) is sometimes expressed as $V_b = A \times h$, where A is the area of the basin or hydraulic unit being considered, and h is the net thickness of the hydraulic unit. Hydraulic units may have been mapped by national geological surveys, and the net thickness can be derived from well logs of wells that penetrate the hydraulic unit. Similarly, porosity and n/g can be derived from analysing cores from the hydraulic unit.

For entire hydraulic units, it is reasonable to assume that the unit is a closed system. The storage efficiency factor depends on the window to maximum allowable pressure constraints, generally estimated using evaluations of hydraulic systems around the world. For instance, the storage efficiency factor has been estimated for four closed systems (Mount Simon (USA), Basal Cambrian (Canada), and Bunter and Rotliegend in the North Sea) in Sylvain Thibeau et al. (2014). These estimates range from 0.62 for the Basal Cambrian to 0.92 for Mount Simon. Without specific knowledge about allowable pressure constraints and specific modelling for the hydraulic unit, it is recommended that the competent authorities use a conservative value for E, e.g. E = 0.5.

Note that this volumetric approach can also be used to derive initial high-level capacity estimates for individual storage sites. However, at site level, capacity depends on the extent of the hydraulic unit containing the aquifer used for geological storage (allowing pressure dissipation) relative to the volume of the aquifer in the storage complex. If a storage site (the aquifer proposed for geological storage) is part of a large hydraulic unit, then the storage efficiency factor may be much higher. Such assessments at the scale of individual sites are not expected to be carried out by the Member State.

3.3. Data collection

Data collection is an important component of site characterisation and modelling. Data collection plans should be developed that are specific to the type of storage site, trapping mechanisms, environmental and human health risks, and subsurface complexities.

In some cases, access to existing data from oil and gas exploration, geothermal operations, or other subsurface activities will facilitate a reliable characterisation and assessment of the potential storage complex and surrounding area. If access to these data is available in a region nearby to a proposed storage site with a similar geology, then a storage operator may be able to make considerable progress in proving the existence of a viable storage site.

3.3.1. Geology and geophysics

The primary objectives of the geology and geophysical data collection are to describe and characterise the storage site, storage complex, surrounding area, and hydraulically connected areas with enough detail to build the 3D geological static model and underpin the monitoring plan. The data must cover at least the intrinsic characteristics of the storage complex discussed in the following subsections. The data must be taken from multiple sources including well logs, well cuttings analyses, core samples and analyses, fluid samples, injection and production tests, outcrop studies, seismic/geophysical surveys and/or remote sensing surveys. The level of detail required for each component will depend on the trapping mechanism(s) and the key risks identified for the CCS project.

Additional subsurface characterisation data may be required to provide a complete understanding of site conditions over time as part of monitoring (see Section 5). For example, accurate 4D seismic monitoring requires calibration to core measurements, petrophysical data, rock physics information and/or saturation models. These data may be required to accurately predict the seismic response to injected CO_2 in hydrocarbon fields, and to monitor the movement of CO_2 in the subsurface over time.

In both saline aquifers and depleted hydrocarbon fields, the volume and area of the storage site may be defined by the maximum extent of the injected CO_2 stream in the reservoir throughout the project lifecycle. In depleted hydrocarbon fields, the vertical and lateral boundaries will be defined based on the natural limits and characteristics of the field, such as trap geometry, spill points, lithology or facies changes, or bounding faults. Both saline aquifers and depleted hydrocarbon field sites are likely to involve a porous and permeable injection zone comprised of sandstone or carbonate. In sites which leverage predominantly CO_2 dissolution or mineralisation trapping, the volume-area may be defined by the maximum extent of the injected CO_2 stream, factoring in natural limits such as lithology, facies changes or non-transmissible faults. The injection zone is likely to consist of mafic or ultramafic rocks, such as basalt or peridotite with permeable facies and distributed fractures or faults.

Competent authorities and operators are encouraged to be involved at an early stage to achieve consensus on the vertical and lateral extent of the defined storage complex.

The description of the storage complex will include any caprocks or seals, faults, facies changes or other geologic features that would impact the containment of the injected stream (see Figure 1). A storage complex may consist of multiple injection zones, each with applicable trapping mechanisms and natural limits.

For mineralisation projects, a storage site will include the geological stratum (or strata) into which the CO_2 stream is injected (referred to as the storage reservoir) as well as surface and injection facilities. The vertical extent of the storage site will be determined by the vertical extent of the storage reservoir(s). The lateral extent should include the domain where CO_2 may exist in free-phase and should be contained within the storage complex.

Additional guidance on the infrastructure to be included in the storage site definition is provided in GD 1, Table 1: Clarification of the key defined terms used in CCS Directive. The definition of the storage complex should include the subsurface component of the storage site. It is recommended that protected groundwater is clearly identified and excluded from the definition of the storage complex. Caprocks and seals are not required components of the mineralisation storage complex definition if it is demonstrated that they are not critical to ensure the containment of injected CO_2 within the storage complex (see Section 3.4 Box 1).

The description of the surrounding area should include the area surrounding the storage complex where negative effects to the environment or human health are possible (see Figure 1). Member States may also include specific requirements or descriptions to consider in the surrounding area. The surrounding area will be determined on a site-specific basis, and will be based on a risk assessment. The recommended geologic considerations for the surrounding area include areas of increased pressure, horizons containing groundwater consumable to humans, or areas with a risk of natural or induced seismicity. Additional considerations are included in Section 3.3.8.

Geologic data should be collected to characterise the following areas, as appropriate:

1. Storage site:
    - a diagram indicating the vertical and lateral extent of the storage site, indicating the vertical and lateral extent of key horizons within the site;
    - properties of the injection zone rock such as lithology, thickness, mineralogy, porosity, permeability, facies types and distributions;
    - properties of the caprock, where applicable, such as lithology, thickness, mineralogy, porosity, permeability, facies types and distributions;
    - faults and fractures: location, orientation, fault throw, transmissibility, fracture distribution (also see Section 3.3.5);
    - capacity estimates.

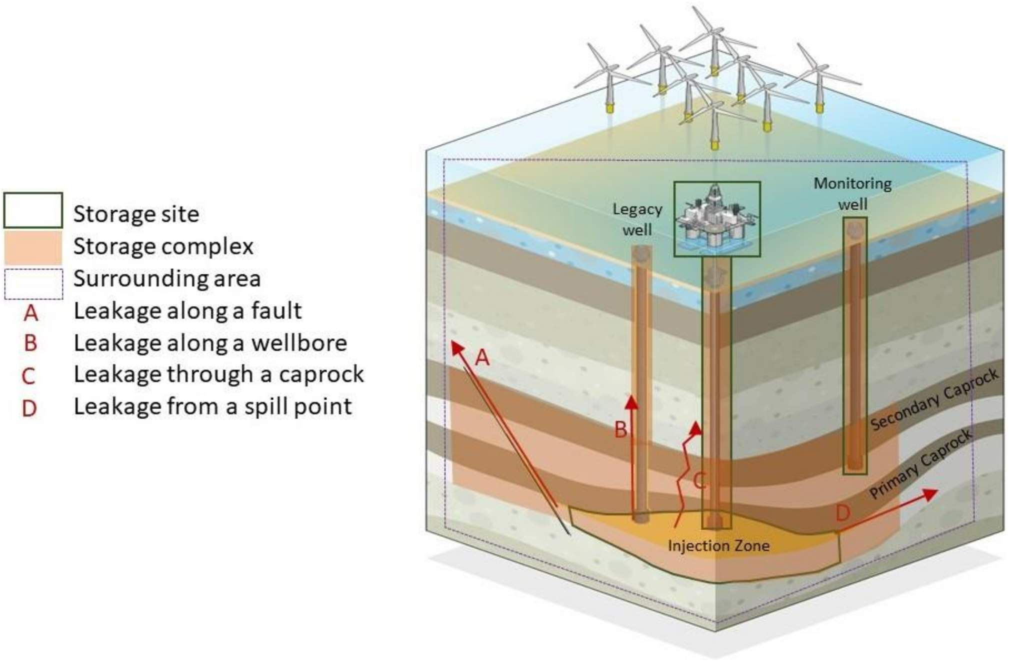

Figure 1. Illustrative example of the storage site, storage complex, surrounding area and leakage pathway in a saline aquifer or depleted oil and gas field.

2. Storage complex:
    - a diagram indicating the vertical and lateral extent of the storage complex, including the vertical and lateral extent of all horizons in the storage complex;
    - rock properties for key horizons: lithology, porosity, permeability, thickness, facies types and distributions;
    - faults and fractures: location, orientation, fault throw, transmissibility, fracture distribution (also see Section 3.3.5);
    - leakage pathways: faults, fractures, permeable zones in caprock, capillary pressure estimates (for more details, see Section 3.3.8);
    - paleogeography, depositional history, structural evolution and nearby petroleum systems (if present).

3.3.2. Hydrogeology

The primary goals of the hydrogeology characterisation process are to identify the groundwater[7] intended for human consumption[8], or necessary to avoid impacts on health or the environment within the storage complex and surrounding area, and to prevent it from becoming contaminated by CO_2 leakage. The additional goals are to provide information on the movement and interaction of fluids within the groundwater as they link to modelling of the pressure and temperature gradients and groundwater salinity, which in turn link to the evaluation of containment, capacity and hydrodynamics.

Groundwater may contain CO_2 in solution due to the natural generation of CO_2 from the subsurface during volcanic activity, mantle degassing, diagenesis, and geochemical alterations of the rock formations over time. Baseline monitoring (see Chapter 4) can be used to characterise the chemical composition of groundwater prior to injection.

Some storage sites may propose CO_2 injection into aquifers. which require demonstration that the site would pose no significant risk to human health or the environment, and that groundwater intended for human consumption is protected, with no CO_2 injection being performed in such aquifers (also see Section 3.3.10). In these cases, it is recommended that groundwater intended for human consumption is clearly differentiated from groundwater that is not intended for human consumption and that a geologic barrier or system is in place preventing mixing of these components.

It may also be crucial to carry out detailed monitoring of both these components to ensure that early corrective action can be taken if groundwater intended for human consumption is threatened (see Section 5). Injection into aquifers, however, may be subject to other local regulation. It is recommended that operators refer to local

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[7] 'Groundwater' is defined as all water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil (ref. Article 2, Directive 2000/60/EC Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, retrieved from: https://eur-lex.europa.eu/eli/dir/2000/60/oj).

[8] Water intended for human consumption is defined as (ref. Article 2, Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption, retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31998L0083):

(a) all water either in its original state or after treatment, intended for drinking, cooking, food preparation or other domestic purposes, regardless of its origin and whether it is supplied from a distribution network, from a tanker, or in bottles or containers;

(b) all water used in any food-production undertaking for the manufacture, processing, preservation or marketing of products or substances intended for human consumption unless the competent national authorities are satisfied that the quality of the water cannot affect the wholesomeness of the foodstuff in its finished form.

groundwater protection regulation for other applicable definitions as these may vary by jurisdiction.

3.3.3. Reservoir engineering and petrophysics

Reservoir engineering is the study of the characteristics and movement of fluids within a subsurface porous medium (reservoir or injection zone). Reservoir engineering is closely linked to the dynamic modelling step of the site characterisation process. Information on reservoir engineering is used to evaluate the capacity, containment and injectivity of a storage site. It can also be used to monitor the movement of injected fluids (see Section 5). Key data types will include chemical compositions of reservoir fluids, pressure and temperature profiles, and the relative permeability of reservoir fluid to the injected fluid.

A description of the hydraulic unit[9] will also be a component of the reservoir engineering characterisation. For shared hydraulic units, it is the responsibility of the operator, as part of the storage permit, to identify and characterise activities around the storage site, including characterisation of the hydraulic unit (Article 9, Annex I to the CCS Directive). The competent authority must ensure that ‘potential pressure interactions are such that both sites can simultaneously meet the requirements of the directive’ (Article 8). If the storage complex spans across national boundaries, multiple competent authorities will need to collaborate to ensure the requirements are met.

Petrophysics is the study of rock and pore-fluid properties from physical samples (i.e. core and cuttings) and digital measurements (well logs). It includes studying the physical and chemical properties of the rock and its petrological (mineral composition) characteristics and how these elements impact upon the development of and interaction of fluids in a subsurface formation. Petrophysical data and evaluation are critical inputs into the 3D static geological model (see Section 3.3.3) and will feed into the evaluation of capacity, containment, injectivity and likely monitorability of storage sites. Key petrophysical data types include porosity and permeability evaluations, fluid properties, wettability of the rock and capillary pressure measurements.

In sites with a history of operations, such as depleted hydrocarbon field sites and geothermal fields, there may be plentiful reservoir engineering and petrophysical data due to exploration and production activity. However, it is recommended to ensure that data available are representative of the ‘current’ site conditions, and not of the initial condition or production condition. Production can impact porosity, permeability and fluid

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[9] ‘Hydraulic unit’ is defined as 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. This mapping should also describe other known activities within the hydraulic unit that may impact pressure within the storage site.

characteristics leading to misrepresentation of geologic conditions in 3D static and dynamic models if older data are used.

3.3.4. Geochemistry

Geochemistry is the study of the chemical constituents of rocks and the fluids they contain at the elemental and mineralogical level and identifies the conditions in which minerals are likely to precipitate or dissolve. These processes have implications for assessing capacity, containment, injectivity and for monitoring the injected CO_2 stream.

A geochemical analysis may identify the likelihood for minerals in a storage zone or caprock to dissolve, which can potentially result in leakage. In some cases, geochemical analysis can identify the propensity for mineralisation reactions to take place, leading to mineral storage of CO_2. It may also identify the propensity of a geochemical system to result in precipitation of solids, which may be another indicator of mineral trapping, or lead to a reduction in injectivity. A geochemical analysis may identify the likelihood of mobilisation of other elements that could have site-specific environmental or health implications in the event of leakage.

Geochemical investigations may also be used to assess interactions between the contents in the CO_2 stream and wellbore cement to identify potential leakage pathways. Geochemical analysis and modelling will also help to identify capacity in systems that rely on geochemical interactions, such as mineralisation projects.

The extent and nature of any geochemical changes that could occur will be site-specific, and therefore appropriate sampling and assessment will need to be completed for each storage complex. Geochemical sampling from appropriate and key intervals (e.g. the water leg of a petroleum field or the injection zone of a mineralisation site) may be important in producing representative results for storage complex characterisation.

A geochemical analysis may include reactive transport modelling, reservoir simulation of pressure and temperature conditions, as well as chemical and mineralogical sampling of rock, reservoir fluids and injected fluids.

3.3.5. Geomechanics

Geomechanics is the study of forces (stresses) and deformation in the subsurface and the evaluation of potential failure (breaking) of rock fabric, which is one of the root causes of the creation of permeable pathways that can result in leakage. Knowledge of the stress condition in the subsurface (which is the force per unit of area) is essential because rock failure is described by stress-based criteria.

Changing the pore pressure during oil and gas production and again during geological storage of CO_2 changes the stress condition in the subsurface both within and outside the reservoir. A changing temperature also impacts the stress condition in the subsurface. Geomechanical analyses assess how the stress conditions change due to prior oil and gas production in depleted field sites and planned geological storage of CO_2; identifying where in the subsurface critical stress condition and rock failure may occur. Geomechanical analyses also provide information about expected deformations such as subsidence and heave at surface or seabed, and compaction and extension along new and/or legacy well trajectories.

Geomechanical analyses impact evaluations of containment (e.g. through induced fracturing of the top-seal and reactivation of fractures and faults), capacity (as prescribed pressure gradients and/or and thresholds for rock fracture gradients or minimum total principal stress may be required by the competent authority), and injectivity (as geomechanical considerations constrain injection rates, pressure and temperature). It is closely linked with thermal modelling (temperature changes can result in fractures) and geochemical analysis (for example, dissolution can weaken rock and precipitation can strengthen rock). Operators are recommended to consider taking an integrated approach to these subjects.

Geomechanics analyses require characterisation of the geological structure (geometry of the storage and sealing formations, faults), the mechanical (elastic and failure) properties and the initial conditions in terms of stress, pore pressure and temperature. The geomechanical characterisation is dependent on data from petrophysical logging (such as density, porosity and sonic velocity logs), drilling experience (observations of bore hole instability and losses), well testing (e.g. extended leak-off test and step-rate test), core analyses and various rock mechanical testing, and seismic interpretation of formations, faults, salt bodies etc.

It is important to collect data to characterise the current stress regime within the injection zone, caprock, and/or surrounding geologic environment, as well as data to characterise changes in the stress as injection proceeds, because previous production and planned storage operation impact an area much larger than the reservoir formations.

Geomechanical impacts and considerations will differ depending on the geologic setting, past and present stress regime, and the risks or issues associated with the type of geological storage. All sites are recommended to evaluate the store and overburden to identify faults (location, geometry, extent, orientation, throw) extending through the store or caprock, establish the initial conditions (stress, temperature) and induced changes (compaction, pressure, temperature). They should also evaluate the natural or induced seismicity risk (see Section 3.3.6), and consider the impact of injection operations on changes in the geomechanical setting.

Additional considerations may be relevant to different sites and settings. For mineralisation projects, for example, the geomechanical characterisation may include identification of fracture sets to assess storage capacity (mineralisation reactions may be more likely to occur in permeable fractured zones) and the reactivation of critically stressed pre-existing faults to identify induced seismicity potential and other considerations.

For depleted oil and gas reservoirs, geomechanical analyses are critical to identify stress changes and compaction impacts to the current stress state to ensure that leakage pathways are identified during the site screening and that no new pathways are created through injection. The stress condition will change from the production phase to the injection phase in these projects, but a return to the pre-production stress state is unlikely. New data will likely need to be collected to properly evaluate these settings.

The operator should assess the injection pressure limits based on minimum total principal stress (S_3), the fracture gradient (FG), and geomechanical constraints. The term FG stems from drilling engineering to generally indicate the mud weight at which the bore hole begins to lose drilling fluid into the formation due to the nucleation and/or growth of a fracture. The FG requires a reference depth to obtain the absolute stress value, which can be lost or misinterpreted from reports. The S_3 is a more accurate value to use to assess injection pressure limits as it is not biased by near-wellbore stress variations and wellbore orientation and is a better measure of in-situ stress in the reservoir.

Lower injection pressure limits will result in a lower capacity and lower sustainable injection rates for individual wells. The operator should communicate clearly to the competent authority the basis used to assess the injection pressure limits, including reference depths as applicable and expected safety margins. Site-specific geomechanical assessments, testing and modelling should be used to assess the appropriate thresholds for the site.

There are a range of thresholds and approaches proposed (for example, in US EPA Class VI regulations, Offshore Norge ARMA 22-559 and ARMA 2016-887, California LCFS and others). Any injection pressure limits established must ensure there are no significant risks to human health and the environment.

3.3.6. Seismicity

Seismicity is an important consideration for CO_2 storage sites due to associated leakage risk, the potential impact on health, safety, the environment and damage to infrastructure. Earthquakes are caused when two structural blocks abruptly slip past one another along faults, generating seismic waves that propagate through the earth. Blocks may also slip slowly past one another, without generating seismic waves. This is referred to as an a-seismic slip. It is assumed that an a-seismic slip precedes an abrupt seismic slip. Seismic and a-seismic slips may both create leakage pathways along fault planes and occur when the fault plane is critically stressed.

Seismicity can be broken down into three categories: natural, induced and triggered seismicity.

- **Natural seismicity** refers to earthquake activity that occurs due to natural geologic (tectonic) processes. It means that the critical stress condition along fault planes is dominated by natural processes and that storage site operations have a minor or negligible contribution.
- **Induced seismicity** refers to earthquakes that are directly caused by human activities, typically associated with industrial operations such as mining, hydraulic fracturing (fracking), geothermal energy extraction and reservoir-induced seismicity from large water impoundments. These earthquakes occur as a result of changing the stress conditions within the Earth's crust. The seismic events are directly linked to human interventions and would not have occurred naturally in the absence of such activities.
- **Triggered seismicity** refers to earthquakes that are indirectly influenced by human activities but are primarily caused by natural stress conditions in the Earth's crust. These earthquakes occur when pre-existing faults or stresses in

the Earth's crust are affected by external factors, such as seismic waves from large distant earthquakes, volcanic activity or changes in fluid pressure due to activities like reservoir filling or fluid extraction. In this case, human activities act as a trigger that initiates the earthquake, but the underlying cause is the release of stress accumulated naturally over time.

Fault movement and seismic waves can be initiated due to increased subsurface pressure or sometimes due to geochemical processes or subsurface temperature changes. Triggered seismicity may be more likely to occur in areas of natural seismicity and where existing faults are further stressed.

Evaluations of natural, induced or triggered seismicity risk are important components and operators are recommended to include this work in the site risk assessment (see GD 1) and in the site characterisation process. This evaluation will require information about i) the presence, extent and orientation of pre-existing faults systems, which may be inferred by studying 2D and 3D seismic reflection data and assessed using earthquake catalogues available for the area. This will include i) historical data ii) the stress condition in the subsurface, iii) the fault strength (before it starts to slip), and iv) the change in pore pressure and temperature induced by previous oil & gas production and planned CO_2 storage operations. The seismicity evaluation may use data from geomechanical modelling (see Section 3.3.6), and it may have an influence on site suitability decisions, well placement and injection operation plans (i.e. allowable injection and reservoir pressure and temperature).

Some faults may not be able to be identified through site characterisation tools and techniques. Seismicity may occur also on invisible faults (e.g. faults with little throw that are not visible on seismic data). This scenario may be tackled through uncertainty management and included in monitoring plans (see Section 5).

Seismicity can be generated at multiple scales: at grain level causing micro-seismicity with a very small moment magnitude ($M_w<<0$) not felt by humans, or at a very large level resulting in a safety and environmental hazard. Moment magnitude is, by definition, related to the seismic slip area on the fault plane.

The larger the moment magnitude, the larger the size of the seismic slip patch. So, larger earthquakes may increase permeability over a larger area and create permeable pathways across larger/thicker sealing formations. Seismic activity accumulating along a fault line and migrating upwards, even at relatively low levels (magnitude less than 3) may result in the generation of leakage pathways (faults or fractures) out of the storage complex (Willacy et al 2019). Larger events may impact nearby infrastructure and pose a safety hazard that increases with increasing moment magnitude. Operators are recommended to review materials standards to identify the relevant thresholds.

Not every seismic event will result in a leakage pathway; in some cases seismic activity may result in the sealing of existing leakage pathways or faults. The risks associated with the seismic hazard depend on the potential damage, which is expected to be different for onshore and for offshore geological storage sites for CO_2. Site characterisation is recommended to include an assessment of seismic risks and related impacts.

Seismicity can also be measured and monitored at multiple scales, providing different forms of insight to feed into the site characterisation process. Permanent networks of seismic monitoring stations supported by geologic surveys can identify large-moment magnitude earthquakes that impact broad areas and pose a hazard to communities and infrastructure. Additional measurement and monitoring systems are often required to be installed at CO_2 storage sites to identify smaller-scale seismic activity that can jeopardise containment. More precise measurement, for example using wellbore geophysical monitoring and/or site-specific measurement arrays, is also often required to uniquely identify responsible faults in the storage complex to assess potential leakage. Higher resolution measurement may enable injection operations to be modified when low-level seismicity thresholds are reached, potentially avoiding inducing a larger earthquake.

Under GD 1, the thresholds for acceptable level of seismicity should be based on a site-specific, risk-based approach (see Zhang et al 2016; Porter et al 2019). These thresholds should factor in the level of completeness[10] of the seismicity monitoring network in the monitoring area and should be set in concert with the competent authority and the operator. Seismic monitoring is recommended to begin as early as feasible before CO_2 injection starts. Some approaches to date have included a traffic light system indicating increasingly stringent operational constraints as seismic activity increases. This can be based on multiple factors including ground motion, duration or frequency of seismic events, local building codes or offshore platform structural limitations (Grigoli et al 2017; Zoback 2012; Thorsteinsson and Gunnarsson 2014).

3.3.7. Presence and condition of natural and man-made pathways

Predicting the presence of leakage pathways for the potential migration of CO_2 out of the targeted storage formations is a vital component of the characterisation process. It is included explicitly in the containment evaluation and it links to risk assessment, site characterisation, CO_2 composition, monitoring and corrective action.

The project's description of the storage complex will form the basis and context for this evaluation, and will need to factor in the trapping mechanism(s). All leakage scenarios that have the potential to pose a significant risk to human health and the environment should be considered.

Natural pathways

Natural pathways include geological features that can provide either a conduit to overlying and adjacent geological formations outside the targeted storage formation, or a conduit to the surface. The risk associated with some natural pathways will differ by trapping mechanism and geologic setting. It may include, for example, faults, variation in the caprock quality or a lack of adequate side seals.

For sedimentary basin storage sites, additional considerations may include delineation of the structural trap (e.g. height of a spill point or characteristics of a migration pathway), and may extend to geochemical risks associated with the injection of acidic fluids (i.e. dissolution of caprock or seals).

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[10] The level of completeness refers to the minimum magnitude above which all pertinent earthquakes in a certain area are reliably identified. This value may vary in time and space.

For mineralisation sites, pressure changes in the subsurface may lead to CO_2 exsolving from solution before the minerals are formed. Or there may be geochemical considerations related to acidic fluids mobilising previously formed carbon-bearing minerals. Depleted field storage sites may have additional caprock risks related to compaction due to previous production activities (see Section 3.3.5).

Human-made pathways

Human-made pathways include wellbores and boreholes. As part of the characterisation of the storage complex, data should be collected to inform the status and condition of all existing wells within the storage complex, as well as all wells outside the storage complex that may represent conduits for formation fluids from the hydraulic unit. This data should be evaluated in a risk assessment context to assess the risk of leakage along legacy wells and the risk of movement of formation fluids and CO_2 charged fluids to environmental or economic receptors (risk related to principal effects 1-3 in GD 1).

The risk assessment of relevant legacy wells within and outside the storage complex should be based on available data on the status and condition of all wells. It should follow the guidance provided in applicable regulations, guidelines or standards. Relevant guidance is provided in the following sources:

- ISO 27914:2017 *Carbon dioxide capture, transportation and geological storage* – Geological storage Clause 7.6 – Evaluation of wells, and Clause 7.8 – Abandonment of wells;
- DNV-RP-J203 *Geological storage of carbon dioxide*, Section 7 – Well qualification, 2021; and
- OEUK *Guidelines: Well Decommissioning for CO_2 storage*, 2022[11].

Guidance issued by the Petroleum Safety Authority Norway recommends using ISO 27914:2017 Clause 7.6 and DNV-RP-J203 (2021) Section 7 to evaluate well barriers in existing (legacy) wells[12]. All the above guidance documents describe a risk-based approach to assess the need for risk mitigation, including monitoring, intervention and remediation. Neither document is prescriptive regarding the materials or well abandonment design, for example.

Allowing a risk-based, non-prescriptive approach is particularly important to enable cost-effective storage in depleted hydrocarbon fields. Depleted hydrocarbon fields may have many legacy wells within the storage complex and surrounding area. While all wells will need to be thoroughly assessed on a case-by-case basis, the need to perform monitoring, intervention or remediation should be determined by the risk assessment process and the evaluated performance of the well barriers in terms of zonal isolation.

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[11] Additional guidance can be found in standards developed for hydrocarbon recovery activities, such as NORSOK D-010:2021, *Well integrity in drilling and well operations*, ISO 16530-1:2017, *Petroleum and natural gas industries - Well integrity* - Part 1: Life cycle governance; and NOGEPA ST045, *Decommissioning of Wells*.

[12] https://www.ptil.no/contentassets/272a208eb9a94b1f833737d378dd58d4/veiledning-til-forskrift-om-sikkerhet-og-arbeidsmiljo-ved-transport-og-injeksjon-av-co2-04.12.19.pdf.

The evaluation of well barriers should also factor in the exposure of the wells to CO_2, other buoyant fluids or elevated pressure[13]. Taking a risk-based approach also enables operators to factor in different geological contexts and the reliance on physical trapping by well barriers. For instance, if a well can be demonstrated to not be exposed to free-phase CO_2 or other buoyant fluids, e.g. if all injected CO_2 is fully dissolved in the storage site, then the number of potential mechanisms which could lead to fluid migration along the well are limited (e.g. if pressure is elevated) and the related risks may be reduced.

The key considerations for evaluating well barrier performance are requirements to the following elements:

- barrier materials
- number of barriers
- length of barriers
- position and placement of barriers.

Guidance on each of these elements is provided in the OEUK *Guidelines: Well Decommissioning for CO_2 storage*, 2022, Section 3. Regulations may also stipulate requirements for each of these elements.

For CO_2 storage projects, specific considerations should be given to the chemical and mechanical impact that CO_2 and CO_2 charged fluids and elevated pressure may have on the long-term performance of the well barrier. For instance, the guidance in ISO 27914:2017 states that geochemical modelling should be carried out to:

- ‘evaluate the response of wells to geochemical reactions, including cement and/or casing degradation, which may lead to potential flow of CO_2 or CO_2-saturated formation fluid’; and
- ‘evaluate the predicted pH and chemical composition of the fluids in contact with the cement sheath in order to select suitable cements and tubular metallurgy for new wells, or remedial materials for legacy wells, to resist chemical degradation'.

Similarly, the guidance provided in ISO 27914:2017 states that geomechanical modelling should be carried out to evaluate the mechanical aspects of well integrity.

A particular consideration related to the potential chemical or mechanical degradation of casing and cement is the potential for debonding of casing and cement, or corrosion of casing by CO_2-charged fluids contained in the annulus. To mitigate this risk and limit possible leak-paths in the wellbore zone, it is sometimes recommended that wells in CO_2 storage projects are decommissioned which may utilise equipment, such as ‘bridge’ or ‘pancake’ plugs. This involves removing the casing along a section of the wellbore and placing cement to cover the exposed formations with a cement-to-rock contact across the borehole.

While this decommissioning procedure may reduce the risk of well leakage, it is not required by any of the CO_2 storage-specific standards listed above. The need to carry

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[13] Pressure sufficient to cause the flow of formation fluids along permeable conduits into environmental or economic resources above the storage complex.

out an intervention to place a bridge plug in existing wells based on a risk assessment of existing well barriers in the well, however, may be considered recommended practice for wells that are accessible or are to be decommissioned during the CO_2 storage project. This risk assessment should factor in the potential long-term exposure to reactive chemistries that can degrade casing and cement, and predicted changes to matrix stress and compaction or elongation strains along the wellbore.

The 2022 OEUK *Guidelines: Well Decommissioning for CO_2 storage* state that the storage site should be separated from the seabed or surface by two independent well barriers. However, it also indicates that wells without two well barriers may be accepted (without the requirement to perform well intervention or remediation) if a risk assessment concludes that the well leakage risk is insignificant, or it is demonstrated that a single well barrier 'is as effective and reliable as the two barriers and is an appropriate method to achieve the objectives that two barriers would otherwise have provided'.

If the risk assessment concludes that a storage site is suitable for CO_2 storage (per Article 4(4) of CCS Directive) contingent on the remediation of certain wells, then it is important that the storage operator can demonstrate a high chance of success of the remediation operation (see Section 7.5 of DNV-RP-J203 (2021)). Section 7.7 of ISO 27914:2017 provides guidance on (recompletion and) workover of wells. Workover operations can represent a very substantial cost and will therefore normally be done following the issuance of the storage permit and financial investment decision. The storage permit may be granted contingent on the successful execution of the workover operation.

The holder of a storage permit is responsible for ensuring adequate integrity of all wells during the life of the project until responsibility is transferred to the Member State, or the competent authority withdraws the storage permit. Following transfer or storage permit withdrawal, the competent authority is responsible for ensuring well integrity, including any risk mitigation (e.g. monitoring or well remediation). Competent authorities and storage operators should define and agree before the start of injection how any liability not transferred to the competent authority under Article 18(1) of the CCS Directive is dealt with for decommissioned wells.

3.3.8. Domains surrounding the storage complex that may be affected

Annex I (Step 1 (h)) to the CCS Directive indicates that the domains surrounding the storage complex that may be affected by the storage of CO_2 in the storage site must be documented. The domains include the deep geosphere, the shallow geosphere, (marine or surface) biosphere, and the atmosphere (see Table 1). Subsurface modelling and other evaluation may be used to determine which domains may be affected.

The impacts may include CO_2 migration into oil and gas reservoirs, contamination of groundwater consumable to humans, pressure interactions with nearby operations, or potential impacts to geothermal operations. The documentation should include site-specific characteristics and location, such as the location of the storage site, onshore or offshore. Additional groundwater and hydraulic connectivity considerations are outlined in Section 3.3.2, Hydrogeology.

Table 1: Definition of domains surrounding the storage complex.

Domain	**Definition**
Atmosphere	On the surface, the compilation of gases that make up the environment surrounding the storage complex.
(Marine) biosphere	The seawater column and the seabed for offshore projects, or the surface of the Earth including plant and animal life for onshore projects.
Shallow geosphere	Shallow subsurface down to the formation above the ultimate or secondary caprock. Includes groundwater zones above the injection zone.
Deep geosphere	Includes the injection zone, caprock(s), seal(s), and geologic formations below the storage complex.

3.3.9. Population distribution

The location and concentration of populated areas above and adjacent to the storage site will be an important aspect to consider, particularly during the risk assessment and uncertainty analysis. The competent authority will need to consider the likelihood of leakage combined with the potential impact prior to approval of a site.

The local terrain (e.g. flat-lying, or low-lying valleys adjacent to storage sites) should be factored into the considerations of impact in the event of a leakage, and whether there is a likelihood for leaking CO_2 to disperse or concentrate. The impact of potential contamination of groundwater from CO_2 leakage should also be considered. This should be evaluated using hydrogeological studies (see Section 3.3.2).

There will be a need to examine data in the assessment that identify land holdings, tenure and potentially site access.

3.3.10. Proximity to valuable natural resources

Operators must document the proximity of a storage complex to valuable surface and subsurface natural resources, such as Natura 2000 areas (under Council Directive 79/409/EEC of 2 April 1979 on the conservation of wild birds[14] and Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora[15]), groundwater and hydrocarbons).

The purpose of this documentation is to identify risks related to the exposure of natural resources to CO_2 leakage. These considerations should be included in the risk assessment (see GD 1), including potential exposure to leakage in the monitoring plan (see Chapter 5).

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[14] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32009L0147.

[15] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31992L0043.

3.3.11. Activities around the storage complex and possible interactions

There are a range of potential competing activities around the storage complex that must be considered. Competition can arise from surface uses, pore space being used for other purposes, and the fact that potential leakage of CO_2 may affect the usability of other subsurface resources.

Site conditions can be impacted by other activities surrounding the storage complex, which are important to factor into the characterisation workflows. For example, pressure, temperature and chemical changes in the subsurface due to nearby operations can impact storage site conditions, characterisation outcomes, injection thresholds and monitoring requirements. It is recommended that the competent authorities require, and establish efficient mechanisms for, information sharing amongst operators of nearby activities to improve the characterisation process and risk management effectiveness:

- Groundwater.
    - CO_2 could contaminate groundwater resources.
- Geothermal.
    - CO_2 could impact the facilities both at the surface and in the subsurface thus increasing costs to the operators as they would have to strip off CO_2 and allow for changes in the materials of the infrastructure at a facility.
    - CO_2 injection could increase regional reservoir pressure and benefit geothermal production operations.
- Other CO_2 storage sites.
    - CO_2 injection could lead to an increase in pressure in other storage sites, either through hydraulic connections or through leakage into other hydraulic units, reducing the capacity and injectivity of those sites.
- Other storage applications.
    - This includes natural gas storage, hydrogen storage, compressed air storage, and other subsurface energy storage applications. CO_2 could reduce the pore space available for energy storage applications that may be used in conjunction with wind farms and other power generation.
- Offshore wind farms.
    - Wind farms may provide access constraints for monitoring, maintenance and corrective action activities required at the storage site.
- Fishing.
    - Fishing activities may lead to access constraints for monitoring, maintenance and corrective action activities required at the storage site.
- Subsea cables and pipelines.

    - Subsea cables and pipelines may result in access constraints for monitoring, maintenance and corrective action activities required at the storage site.
- Salt mining and brine mining.
    - CO_2 could impact or halt mining operations by creating unsafe mining conditions.
- Oil and gas field development.
    - The CO_2 plume could contaminate the production of hydrocarbons, thus increasing costs to the operators as they would have to strip off CO_2 and allow for changes to the infrastructure at a facility.
    - Conversely, CO_2 injection could increase regional reservoir pressure and actually benefit oil and gas production.
    - The CO_2 plume could reduce the pore space available for natural gas storage reservoirs.
- Coal bed methane production.
    - The CO_2 plume could contaminate the production of hydrocarbons, thus increasing costs to the operators as they would have to strip off CO_2 and allow for changes to the infrastructure at a facility.
    - CO_2 injection could increase regional reservoir pressure and decrease production as methane can only be produced by producing the formation water to allow it to desorb off the coal.
- Coal mining.
    - CO_2 could have an impact on or halt coal mining operations and create unsafe mining conditions.
- Underground coal gasification.
    - CO_2 could extinguish underground coal gasification processes or limit the development of such operations.
- Energy/waste storage.
    - CO_2 injection could increase regional reservoir pressure, reducing the injectivity of water or waste injection wells.
    - Injecting CO_2 or other fluid streams (such as wastewater disposal) can alter the geochemical makeup of reservoir fluids, resulting in dissolution or precipitation of minerals and changes to fluid movement in the reservoir.
    - CO_2 injection could increase regional reservoir pressure, introducing leakage pathways that compromise energy storage or waste storage sites.

The competent authority should provide the operator with timely guidance on which of the items listed above are relevant to the specific storage complex at the time of the permit application. It will be in the final phases of the complex characterisation analysis that any possible interactions can be identified, and an assessment can be made to determine whether there is any likelihood that they pose a conflict of use.

It is recommended that the assessment focus on known possible interactions at the time of the assessment, and not future activities that may take place at the site. The operator should document any such conflicts and include this documentation in the storage permit application sent to the competent authority.

It is also recommended to maintain dialogue with the competent authority on any known planned activities surrounding the storage complex that could result in a conflict of use.

There are monitoring practices and best practices to follow to reduce the likelihood of such conflicts. The most effective way to do so will be at the discretion of the authority that grants the permits to carry out subsurface and related activities in close proximity to each other, and/or to insist on agreements between operators of the various industries on how they conduct their activities and share information and planning.

3.3.12. Proximity to the potential CO_2 source(s)

Annex I (step 1 (l)) to the CCS Directive indicates that the proximity of the CO_2 source to the storage site must be documented, including estimates of the total potential mass of CO_2 economically available for storage, and adequate transport networks. Site selection for geological storage of CO_2 depends on the likely geologic storage volume and supply rates being identified at a very early stage in the selection process. Some sites may be commercially and technically viable at low rates of injection; others at high rates. Some sites will have large storage capacity; others only small.

CO_2 supply issues will be an important factor in the size and nature of the trapping mechanisms envisaged at any site and can impact the safety and containment of CO_2. The geological characteristics will determine whether a site is compatible with injection requirements. Reservoir properties and modelling activities will determine the CO_2 specification, numbers of wells, and be a factor in the commerciality of the storage site.

Transport networks are an important consideration to ensure CO_2 is safely delivered to the storage site in a condition that is compatible with the geological conditions (including, for example, the fluid phase, the chemical makeup, pressure and temperature). Transport methods can have significant implications on site development, impacting injection infrastructure, capital requirements and project economics.

Changing the CO_2 supply conditions during a site characterisation process may affect the outcome of the process. While subsurface suitability of a storage site may have been proven, it may not be possible to technically or commercially meet the CO_2 supply volumes and injection rates required. It is therefore recommended to ensure that limits have been tested and a range of CO_2 supply conditions given as part of the site characterisation process.

3.4. Building the three-dimensional static geological Earth model

Building three-dimensional static geologic Earth model(s) is included in Step 2 in Annex 1 to the CCS Directive. Step 2 consists of using the data collected in Step 1 to construct one or more three-dimensional static geological Earth models of the potential storage complex, including the caprock (where relevant, see Box 1) and the hydraulically connected areas and fluids. This should be done using numerical reservoir modelling software to characterise the complex in terms of the:

1. geological structure of the physical trap;
2. geomechanical, geochemical and flow properties of the reservoir overburden (caprock, seals, porous and permeable horizons) and surrounding formations;
3. fracture system characterisation and presence of any human-made pathways;
4. areal and vertical extent of the storage complex;
5. pore space volume (including porosity distribution);
6. baseline fluid distribution;
7. any other relevant characteristics.

Box 1: Modelling the caprock.

Annex I makes specific reference to a 'caprock' as a component in the 3D geological model. This term refers to a geological formation overlying the injection zone that effectively restricts the upward migration of free-phase CO_2. For in the context of the purpose of the CCS Directive, the caprock should have sufficiently low permeability to deliver '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.

Free-phase CO_2 is buoyant and tends to migrate upward, making the presence of a caprock an important component of containment of the injected fluid. Conversely, dissolved CO_2 in water (solubility trapping) is dense and usually sinks relative to native reservoir fluids. Mineralised CO_2 is solid and does not migrate.

In sites that rely on trapping mechanisms where the CO_2 does not exist in a free-phase, such as solubility trapping and mineralisation, our interpretation is that a caprock is not an explicitly necessary component of the storage complex and the 3D model.

In these cases, the model(s) would need to provide sufficient evidence to demonstrate that the injected CO_2 remains in a non-free phase for the duration of the injection, closure, and post-closure periods and that pressures associated with the injection of CO_2 does not drive CO_2-bearing fluids to the atmosphere, the water column or to domains where negative effects to the environment may occur.

A risk management approach is recommended during the construction of the 3D geologic model(s) (e.g. ISO 27914:2017, DNV-RP-J203). Scenarios that reduce uncertainty and risk should be evaluated and considered, including sensitivities for input variables. Many modelling approaches may be used (i.e. deterministic, probabilistic), and the selected methodology should be completed according to best practices at the time of model construction.

The operator may need to consider models at different scales, such as basin/regional, subregional, or local (storage complex) level to adequately manage the address site risks adequately. Multiple models may also be required to assess different processes, such as a geochemical and geomechanical models, and should be integrated into a cohesive interpretation of the subsurface.

Multiple data sources, as discussed in Section 3.3, will be used as input into the construction of the geological models. The model(s) should contain sufficient detail to determine the geologic and fluid properties related to fluid flow, phase changes, geochemical impacts and differences in capacity, injectivity and containment. The error associated with interpretations should also be assessed, such as the error involved in upscaling, contouring or averaging. For instance, a probability range for the storage volume and closure area could be given based on uncertainties in the reservoir parameters and in the seismic velocity model used. Geostatistical methods are recommended to be used to populate rock and fluid properties away from control points, and calibrated to measured data. The use of analogue data is recommended to supplement or validate measured data, where available and appropriate. Where fractures are a significant consideration related to capacity, containment, injectivity or a monitoring plan, it will also be necessary to build a fracture distribution model that includes an assessment of multiple possible distributions and properties of the fractures.

During the various stages of appraisal and development of a storage site, new and more reliable data will be acquired that affect critical matters associated with storage complex characterisation. There will be a need to iteratively update and review the geological and reservoir simulation modelling throughout the process of both the characterisation of a storage complex and during its operational phases. It will also be necessary to maintain and manage data to be able to compare iterations of the site characterisation as it evolves over the lifespan of the storage site.

3.5. Dynamic modelling

3.5.1. Characterisation of the storage dynamic behaviour

When building the dynamic model(s) (e.g. ISO 27914 or DNV-RP-J203), it is recommended that operators take a risk management approach. Scenarios that reduce uncertainty and risk should be evaluated and considered, including sensitivities for input variables. Many modelling approaches may be used, including deterministic and probabilistic approaches. The selected methodology should follow best practice at the time of model construction. The operator may need to consider models at different scales, such as basin/regional, subregional, or local (storage complex) level to adequately address site risks. The dynamic model(s) will be used to demonstrate that injection operations pose no significant risk to human health and the environment.

Annex I, Step 3.1 specifies the requirements for storage dynamic modelling (see Table 2). The modelling scenarios should integrate evaluations of capacity, containment, injectivity, well placement and design, and monitorability. Additional factors may also be considered depending on the geologic setting, trapping mechanism(s) and best practices. For example, it may be important to model the elevated pressure region over time when assessing the nature of CO_2 flow in the reservoir, phase behaviour, the risk of fracturing the storage formation and caprock, and possibly the monitoring area. It may be important to model the extent of the CO_2 to identify the storage complex and the monitoring area.

Dynamic models may include a suite of approaches and methodologies, such as fluid transport and pressure evolution, thermodynamic modelling, reaction kinetics, and geochemical fate and reactive transport models. It will also be important to model pressures within and around the storage complex. For example, where solubility trapping is a primary containment mechanism, pressure modelling will be important to ensure the site conditions are suitable for long-term storage. Relative permeability is an important component to consider in the dynamic behaviour of a storage site as it has a significant impact on the distribution of CO_2 in the subsurface. In all cases, the modelling must factor in geologic heterogeneity and account for a range of possible scenarios (geologic uncertainty). Several iterations of modelling may be required to refine the models and to understand geologic uncertainty, which may incorporate outcomes of dynamic modelling into updated static models, and then revising dynamic outputs accordingly.

History matching workflows are recommended to calibrate CO_2 injection model results, where data are available. Sources of these data may include production/injection test data, CO_2 injection history, or fluid production histories from depleted field sites.

Table 2: Characterisation of the storage dynamic behaviour.

Factors listed in Annex 1, Step 3.1, of CCS Directive: Characterisation of the storage dynamic behaviour
At least the following factors must be considered:
− possible injection rates and CO_2 stream properties;
− the efficacy of coupled process modelling (how different individual effects in the simulator(s)) interact, such as interactions between plume migration, geomechanics, and geochemistry);
− reactive processes (how the injected CO_2 reacts with in-situ minerals feedback in the model);
− the reservoir simulator used (multiple simulations may be required in order to verify certain findings);
− short and long-term simulations (to establish CO_2 fate and behaviour over decades and millennia, including the rate of dissolution of CO_2 in water).
The dynamic modelling process must provide insight into:
− pressure and temperature of the storage formation as a function of the injection rate and the accumulative volume of injection over time;
− areal and vertical extent of injected CO_2 stream and the elevated pressure zone, vs time;

− the nature of CO_2 flow in the reservoir, including phase behaviour;
− CO_2 trapping mechanisms and rates (including spill points and lateral and vertical seals);
− secondary containment systems in the overall storage complex;
− storage capacity and pressure gradients in the storage site;
− the risk of fracturing the storage formation(s) and caprock;
− the risk of CO_2 entry into the caprock;
− the risk of leakage from the storage site (for example, through abandoned or inadequately sealed wells);
− the rate of migration (in open-ended reservoirs);
− fracture sealing rates;
− changes in formation(s) fluid chemistry and subsequent reactions (for example, pH change, mineral formation) and inclusion of reactive modelling (kinetics, reactive transport, thermodynamics) to assess affects;
− displacement of formation fluids;
− increased seismicity and elevation at surface level.

3.5.2. Sensitivity characterisation

Annex I Step 3.2 states that ‘multiple scenarios should be modelled to identify the sensitivity of the assessment of assumptions made about particular parameters. Significant sensitivities shall be taken into account in the risk assessment’.

Any assumptions about a specific parameter that could create a risk of leakage and affect human health or the environment should be considered a significant sensitivity. Assumptions or interpretations of parameters that impact estimates of capacity, injectivity, or monitorability may also be considered significant sensitivities.

Sensitivity characterisation workflows may include tornado plots showing the sensitivity of different parameter alterations on key metrics of interest, scenario evaluations, probabilistic assessments that evaluate which scenarios or assumptions are reasonable, as well as the likelihood of those assumptions occurring.

3.5.3. Risk assessment

The process to characterise the storage site, including 3D static geological modelling and dynamic modelling, is closely tied to the risk assessment process as these components aid in the identification and sensitivity analysis of leakage pathways, secondary effects of CO_2 storage, and risks to human health and the environment.

Guidance document 1 provides detailed guidance on carrying out risk assessments in accordance with the requirements of Step 3.3 in Annex I to the CCS Directive. This is without prejudice of compliance with other EU regulations, for instance the Environmental Impact Assessment Directive or the Nature Directive.

4. CO_2 composition

4.1. Legislative context

Recital (27) in the CCS Directive states that ‘it is necessary to impose on the composition of the CO_2 stream constraints that are consistent with the primary purpose of geological storage, which is to isolate CO_2 emissions from the atmosphere, and that are based on the risks that contamination may pose to the safety and security of the transport and storage network and to the environment and human health’.

Article 12 of the CCS Directive, which covers the criteria for CO_2 streams for geological storage, sets out the requirements operators must follow with the aim of ensuring that the above objective will be met. It sets three requirements.

1. A CO_2 stream must consist ‘overwhelmingly of carbon dioxide’.
2. No ‘waste or other matter’ may be added to the CO_2 stream for the purpose of disposing this waste or other matter underground.
3. In addition to CO_2, the CO_2 stream may contain:
    a. incidental substances associated with the (CO_2 emission) source (this is dependent on the used feedstock and the industrial process), the capture process; or injection process; and
    b. trace substances that may be added to assist in monitoring and verification of CO_2 migration.

Concentrations of such incidental and added substances must, however, be below levels that would:

- adversely affect the integrity of the storage site or the relevant transport infrastructure provided the CO_2 composition is acceptable to all stakeholders;
- pose a significant risk to the environment or human health; or
- breach the requirements of applicable EU legislation.

Member States must ensure that operators accept CO_2 streams for storage only if their composition is analysed, including an analysis of the presence of corrosive substances, and a risk assessment has been carried out indicating that the levels of incidental and trace substances in the CO_2 stream are acceptable, as defined above. In addition, Member States must keep a register of the quantities and properties of the CO_2 streams delivered and injected, including the composition of these streams.

Several references provide information on the impact of enhanced CO_2 concentrations in ambient air on human health and environment (e.g. Benson et al., 2002).

4.2. CO_2 stream consists overwhelmingly of carbon dioxide

The 'CO_2 stream' is a flow of substances that results from CO_2 capture processes. The actual CO_2 concentration is only one of several factors that may contribute to risk to human health or the environment. Streams with, for instance, 70% CO_2 and 30% N_2 may have certain risk considerations, whereas streams with similar or lower percentages of H_2S could have more significant risk implications.

Therefore, competent authorities must assess the trade-off between the cost of additional CO_2 stream purification, and the cost of managing risks to human health, the environment, storage sites and transport infrastructure. The requirements to manage acceptable levels of concentrations of 'non-CO_2 constituents' align with this objective and will be further discussed in Section 4.4.

4.3. No waste or other matter may be added for the purpose of disposal

The intent of this requirement is to clarify that it is not permitted to co-inject 'waste or other matter' with the CO_2 stream that can create an additional risk to human health or the environment. Here 'waste' means the substances defined as waste in Article 3(1) of Directive 2008/98/EC.

The co-injection of 'other matter' can be allowed if this is necessary to deliver safe geological storage of carbon dioxide under Article 1 and the following requirements are met:

- the CO_2 stream is overwhelmingly carbon dioxide; and
- the concentrations of added substances, as defined in the relevant storage permit, are below levels that would adversely affect the integrity of the storage site or the relevant transport infrastructure, pose a significant risk to the environment or human health, or breach the requirements of applicable EU legislation.

Additional substances may be necessary for operational and monitoring purposes. They may include, for example, tracers added to monitor the behaviour of the injected stream, substances added to condition the CO_2 stream (e.g. to treat or inhibit scale), or substances added to alter the properties of the CO_2 stream in the reservoir (e.g. to alter viscosity or density). These substances are permissible if they are added for the purposes of ensuring the safe and effective injection of CO_2, and provided they meet the requirements of Article 12 of the CCS Directive (see Section 4.4).

Mineralisation projects have demonstrated that CO_2 can be stored safely provided all injected CO_2 is fully dissolved in water and maintained in dissolved form until CO_2 is mineralised through geochemical reactions with the host reservoir rock. This typically involves injecting approximately 25 parts water per part CO_2 injected[16]. 'Mineralisation' CO_2 storage operations are also permissible under the CCS Directive since the water injected is not considered to be part of the CO_2 stream.

4.4. Acceptable concentrations of incidental and added substances

Article 12 of the CCS Directive covers the acceptable level of non-CO_2 constituents in the CO_2 stream, i.e. constituents that stem from the 'source, capture or injection process' or substances added to help monitor and verify CO_2 migration. Concentrations of such incidental or added substances are permitted if the requirements of Article 12(1)(a-c) are met.

The requirements under Article 12(1)(c) mean that the concentration of pollutants regulated under the Integrated Pollution Prevention and Control Directive, the Large Combustion Plants Directive or the Industrial Emissions Directive must comply with the limit values and other requirements of those Directives, including the use of best available techniques.

To ensure compliance with Article 12(1)(a-b) and Article 12(3)(a), competent authorities must ensure that each operator carries out an analysis of the composition of the CO_2 stream and a risk assessment of potential impacts of the CO_2 stream (including incidental or added substances) to 'the integrity of the storage site or the relevant transport infrastructure' or the 'environment or human health'. The risk assessment should include assessment of the potential for CO_2 stream compositions outside nominal specifications. Variations in CO_2 compositions may occur in multiple situations, including:

- transient composition variations due to start-up or shut-down of capture facilities;
- mixing of CO_2 streams from multiple sources, in transport vessels or infrastructure, or prior to injection;
- CO_2 shipping with boil-off or different cargo during ship operations.

This also implies that the location and frequency of measurement of CO_2 composition should consider the potential for such variations.

The CCS Directive does not lay down specific requirements regarding the locations of CO_2 stream measurement, nor the frequency of measurements. It is recommended that the locations and frequency of measurements of the CO_2 stream are informed by the risk assessment, to ensure that the CO_2 stream composition is within safe operational limits based on system design. This also implies that there may be a trade-off between more frequent measurements or for instance measurements on each wellhead and a more robust system design or other risk controls to manage the risk to storage integrity, transport infrastructure, the environment and human health.

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[16] Snæbjörnsdóttir, S.Ó., Sigfússon, B., Marieni, C. et al. (2020), 'Carbon dioxide storage through mineral carbonation'., Nature Reviews Earth Environ 1, 90-102.

Constituents in the CO_2 stream can generally be divided into three categories:

1. constituents that can have an impact on corrosion, such as O_2, H_2O, NO_X, SO_X, Glycol, and H_2 (can cause embrittlement);
2. constituents that can pose a concern for human safety, including CO, H_2S, NO_X, SO_X, and Hg;
3. constituents that could affect the physical properties of the CO_2 stream, including:
    - H_2O – the risk of hydrates;
    - inert gases - impact on vapour pressure during the liquid phase and impact on critical pressure during the dense phase;
    - non-corrosive constituents that could precipitate as solids – leading to flow assurance problems;
    - non-corrosive constituents that could freeze and cause blockage issues.

Therefore, the risk assessments to address Article 12(1) (a) and (b) of the CCS Directive should factor in each of the constituents and their potential to affect the integrity of the storage site and transport infrastructure or represent a significant risk to the environment or to human health. Various references describe issues related to components or impurities of a CO_2 stream (DNV-RP-F104; ISO 27921; ZEP and CCSA 2022, and others).

Operators also need to keep a register of the quantities and properties of the CO_2 stream delivered and injected, including the composition of those streams. While pipeline operators are likely to impose CO_2 stream composition standards to protect the physical integrity and flow characteristics of the pipes, the competent authority must approve the composition of the CO_2 stream as it affects pipeline integrity and storage integrity as part of the storage permit.

In determining an acceptable composition of the CO_2 stream, operators and competent authorities could consider optimising the composition across the integrated capture, transport and storage chain. Overall optimisation involves examining the trade-off between reducing components in a CO_2 stream across the value chain, the cost of removal of components, designing the infrastructure to tolerate the composition of the stream and ensuring the integrity of the storage site is not adversely affected.

In the event of significant irregularities in the CO_2 stream composition during operation, corrective measures would have to be taken on a case-by-case basis. This would include an analysis of the causes of the irregularity and the impact of the injection of the inappropriate stream into the storage site.

5. Monitoring

This section provides guidance on the allocation of monitoring responsibilities. While the operator is responsible for monitoring the storage site operations and surrounding environment under Article 13(1) of the CCS Directive, the competent authorities in all relevant Member States will carry joint responsibility for transboundary monitoring. Data sharing is encouraged to ensure that adjacent storage sites are accurately characterised and monitored, especially across borders.

One of the aims of monitoring is to demonstrate that the injected CO_2 is contained in the storage site. Monitoring activities will need to take place within the storage site as well as within the storage complex to identify any early warning signs of a potential leakage. Monitoring may also need to take place in the surrounding area to prevent negative effects to the environment or human health.

A risk assessment should be carried out to determine the significance of associated risks. The results should then feed into the design of the monitoring of the storage complex and surrounding environment under Article 13 of the CCS Directive.

5.1. Legislative context

Monitoring is required by Article 13 of the CCS Directive to ensure the safety of geological storage. The requirements are as follows.

- *Article 13(1): Member States shall ensure that the operator carries out monitoring of the injection facilities, the storage complex (including where possible the CO_2 plume), and where appropriate the surrounding environment for the purpose of:*
    - *a) comparison between the actual and modelled behaviour of CO_2 and formation water, in the storage site;*
    - *b) detecting significant irregularities;*
    - *c) detecting migration of CO_2;*
    - *d) detecting leakage of CO_2;*
    - *e) detecting significant adverse effects for the surrounding environment, including in particular on drinking water, for human populations, or for users of the surrounding biosphere;*
    - *f) assessing the effectiveness of any corrective measures taken pursuant to Article 16;*
    - *g) updating the assessment of the safety and integrity of the storage complex in the short- and long-term, including the assessment of whether the stored CO_2 will be completely and permanently contained.*
- *Article 13(2). The monitoring shall be based on a monitoring plan designed by the operator pursuant to the requirements laid down in Annex II, including details on the monitoring in accordance with the guidelines established pursuant to Article 14 and Article 23(2) of Directive 2003/87/EC, submitted to and approved*

> *by the competent authority pursuant to point 6 of Article 7 and point 5 of Article 9 of this Directive. The plan shall be updated pursuant to the requirements laid down in Annex II and in any case every five years to take account of changes to the assessed risk of leakage, changes to the assessed risks to the environment and human health, new scientific knowledge, and improvements in best available technology. Updated plans shall be re-submitted for approval to the competent authority.*

Annex II sets out the criteria for establishing and updating the monitoring plan and for post-closure monitoring. Directive 2003/87/EC is the EU ETS Directive establishing a scheme for greenhouse gas emission allowance trading within the EU. Article 14(1) of the EU ETS Directive sets out that the Commission must adopt guidelines that describe detailed arrangements concerning the monitoring and reporting of emissions for activities included in Annex I to the Directive. These rules are set out in the Monitoring and Reporting Regulation (MRR) 2018/2066/EU, Annex IV, Section 23. Article 14(2) of the CCS Directive sets out that Member States must ensure the emissions are reported in accordance with the guidelines.

The aim of this section is to provide operators and competent authorities with guidance on interpreting the requirements for the monitoring plan under Annex II, and on the requirements for monitoring and reporting in accordance with the MRR.

5.2. Establishing the monitoring plan

5.2.1. Approach

The initial monitoring plan must be part of the storage permit approved by the competent authority. The competent authority is obliged to ensure that the operator monitors the injection facilities, the storage complex (including where possible the injected CO_2 stream and its migration), and where appropriate the surrounding environment during the operational phase and after closure until transfer of responsibility. If any leakages or significant irregularities are detected, monitoring must be intensified as required to assess the attribution/origin of the CO_2, the scale of the problem and the effectiveness of corrective measures.

The main objectives and purpose of monitoring are to confirm containment of CO_2, to alert of any increased leakage risk, to identify any leakage if it occurs and significant irregularities, and to verify the behaviour of the injected CO_2. The competent authority should ensure that all monitoring activities are based on site-specific plans that have been agreed and approved by it as part of the storage permit and following the requirements laid down in Annex II to the CCS Directive. The monitoring plan must be updated regularly and at least every five years.

Monitoring and associated monitoring plans are recommended to:

- be risk-based, linked to the risks identified in the site characterisation process and the overall risk assessment;
- be specific to the storage site, storage complex, and trapping mechanism(s);

- be sufficiently extensive to cover the storage complex (including where possible the CO_2 plume), migration and behaviour of formation fluids and where appropriate the surrounding environment;
- ensure that monitoring is linked to preventive and corrective measures;
- use technology based on the best available at the time of design;
- include regular and routine reporting of monitoring data and interpretations of results;
- be regularly updated to take account of changes to the assessed risks to the environment and human health, new scientific knowledge, and improvements in best available technology;
- set detection limits such that significant irregularities and leakages can be identified and corrected before they lead to negative impacts on human health and the environment, including consideration for uncertainties;
- be ready to be operational on or before the first day of injection;
- include redundancies and/or contingency plans for high-risk scenarios.

The starting point for developing and updating any monitoring plan is an adequate characterisation and risk assessment. Guidance on both risk assessment and site characterisation are covered in GD 1 and Section 3 of this document. Following the CO_2 storage lifecycle risk framework, the risk assessment will result in site-specific criteria for monitoring requirements. It may include threshold values for adopting a range of preventive or corrective measures, some of which will include monitoring plans.

The CCS Directive requires that competent authorities ensure that the injection facilities, storage complex and surrounding environment are monitored for the purposes listed in Article 13(1) (see Section 5.1). Annex II to the Directive also specifies that the monitoring plan must in any case include continuous or intermittent monitoring of the following items, considered mandatory:

- fugitive emissions of CO_2 at the injection facility;
- CO_2 volumetric flow at injection wellheads;
- CO_2 pressure and temperature at injection wellheads (to determine mass flow);
- chemical analysis of the injected material;
- reservoir temperature and pressure (to determine CO_2 phase behaviour and state).

In addition to the above list, continuous or intermittent monitoring of the pressure in the injection wellbore annulus is recommended.

The Directive does not specify the measurement methods or technologies that should be considered or used for monitoring. It does, however, provide some general guidance on the technologies to consider and use as appropriate (see Annex II to CCS Directive):

- technologies that can detect the presence, location and migration paths of CO_2 in the subsurface and at surface;

- technologies that provide information about pressure-volume behaviour and areal/vertical distribution of the injected CO_2 fluid to refine numerical 3D simulation to the 3D geological models of the storage formation;
- technologies that can provide a wide areal spread in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond, in the event of significant irregularities or migration of CO_2 out of the storage complex.

This can be achieved either by measuring the absence of any leakage through direct detection methods, or by verifying indirectly that the CO_2 is behaving as expected in the reservoir based on static and dynamic modelling and updating, corroborated by monitoring data. The main challenge for measuring the absence of any leakage consists of spatial and temporal coverage of the monitoring method, i.e. 'Where and when do we need to monitor in order to be sure that no leakage occurs'. The strategy should therefore be based on the risks identified.

For indirect model-based monitoring, the emphasis is more on scenario confirmation. As long as predictive models behave in line with the monitoring data, the understanding of both the processes occurring and the behaviour of the storage complex can be considered sufficient. If there are deviations, the causes of the deviations must be found. If there is a significant deviation between observed and predicted behaviour, the 3D model must be recalibrated to reflect the observed behaviour as described in Chapter 2 of this GD and in GD 3. If, however, the deviations fall well beyond the uncertainty ranges of the predictive models, then additional monitoring and possibly preventive or corrective measures may need to be taken.

It is also important to check the methods and techniques against the main objectives and different elements of the storage system and monitoring plan at the specific site. Figure 2 provides an overview of the possible components of a monitoring plan but it is not prescriptive. The plan's elements, objectives and technologies should be site-specific and risk-based; they are also likely to vary through the project life cycle.

At present, there is no technical measurement that provides a full quantitative analysis of CO_2 leakage. Therefore, a portfolio of methods is likely to be required to adapt to each specific storage complex. The methods and plan should also cover the formation waters and brine within the storage complex and in surrounding units that may be impacted by injection or leakage.

Figure 2: Monitoring plan components.

Operational	Plume	Pathways	Environmental (leakage)
• Injection well control • Pressure & temperature • Composition • Quantification	• Calibrate models • Migration • Kinetics • Trapping mechanisms • Trapping efficiency • Pressure • Water behaviour	• Caprocks • Faults & fractures • Wells • Aquifers	• Detection of suspected leak or anomaly • Attribution of anomaly • Leak quantification • Emissions/ ETS impact • Safety & environmental impacts

The above components can be factored into the plan in terms of:

- operational monitoring (which must meet the mandatory requirements);
- monitoring the plume, including:
    - tracking the injected CO$_2$ and its movement;
    - water/brine behaviour, properties and movement resulting from CO$_2$ injection;
- monitoring pathways for potential leakage identified by risk assessment, i.e.:
    - caprocks;
    - faults and fractures;
    - wells (and well integrity);
    - overlying aquifers.
- environmental monitoring for leaks out of the storage complex towards, at or near the surface, on land or offshore:
    - detection of suspected leakage anomaly;
    - attribution of leakage anomaly;
    - quantification of leakage;
    - accounting and quantifying emissions from the storage complex for surrender of emissions trading allowances for any leaked emissions under EU ETS Directive 2003/87/EC;
    - safety and environmental impacts.

Although the CCS Directive does not specify the well design requirements, Member States are recommended to define design requirements based on industry best practice.

Well design best practices have been established to limit the risk of leakages, blow-outs, and to protect fresh waters.

There are also special considerations to be made when selecting materials in CCS wells tied to the acidic nature of CO_2 in the presence of water, and to the phase behaviour of CO_2 streams in different pressure and temperature systems (IEAGHG 2018, Iyer et al 2022, US EPA 2012).

5.2.1.1. Monitoring technology & scientific status

Operators and competent authorities should take account of the state of development of the technologies considered and whether it is proven commercial technology, developmental or at the research stage. This should also factor in whether the method and specific technique is proven for use in CO_2 storage and/or other relevant applications (e.g. oil and gas, hydrogeology, environmental monitoring, geothermal and mining).

The design of monitoring plans at the time of the storage permit should reflect current best practice and the state of technology. When the monitoring plan is reviewed at a later stage, it should incorporate any learning and experience from actual storage projects, new scientific knowledge, and improvements in best available technology.

5.2.1.2. Overall monitoring limitations

Each monitoring method has limitations to its potential application, sensitivity and use in CO_2 storage, and there may be limitations in the applicability of specific methods at any given site. Monitoring methods and technologies should be demonstrated to be suited to the site-specific conditions and monitoring goals through analogue examples and/or site-specific testing.

The additional considerations are relevant to operators and competent authorities as part of any monitoring strategy:

- Which methods are relevant for the specific site?
- What is the resolution of monitoring in detecting leakage?
- How accurately can leakage be quantified?
- What volumes of CO_2 can be resolved in the plume or geosphere?
- If continuous monitoring is considered, what is the operational lifespan of the system?
- Does the monitoring system provide data in real time, accessible and usable also by third parties (e.g. researchers, citizens)?
- Does the monitoring system allow early warning?

5.2.2. Scope and format of monitoring plans

5.2.2.1. Storage complex summary

The starting point for developing the monitoring plan is the site characterisation, modelling and risk assessment. The general requirements for both site characterisation and risk assessment are given in the other chapters of this GD. The monitoring plan, in turn, must be related to the corrective measures plan.

The storage complex may be described differently depending on the trapping mechanism(s) used and the storage type. See Section 3.3.1 for a discussion on the site-specific considerations for the storage complex.

The site-specific information in the monitoring plan should include:

- location and geographical considerations (e.g. onshore/offshore, local considerations, population centres, land use and potable aquifers);
- overview of site/complex location and geological characterisation, including reservoir, trapping mechanism(s); summary of identified risks, including pathways and potential impacts;
- expected plume behaviour over time from simulation modelling;
- identification of leakage pathways in relation to the plume migration;
- justification for selecting each technology or methodology to tackle the specific risks.

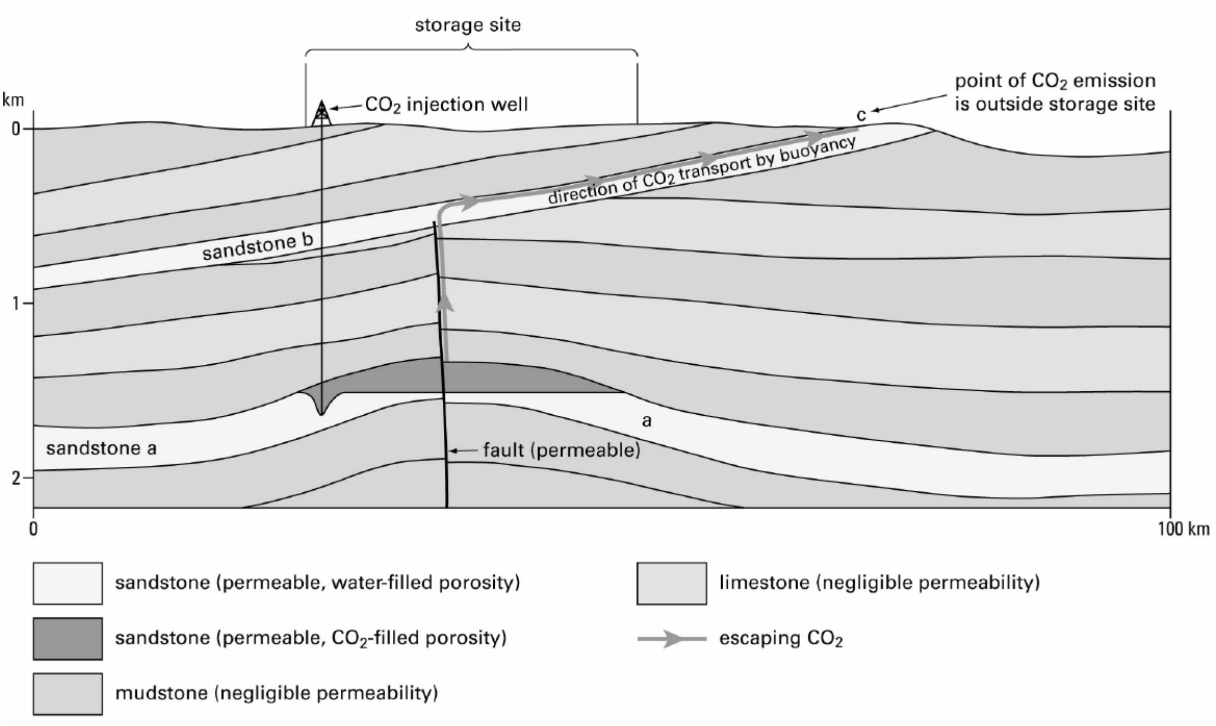
5.2.2.2. Defining the monitoring area

The storage complex and the surrounding area combined will normally encompass the monitoring area (see definition for surrounding area in GD 1). The monitoring area should be sufficiently extensive to cover possible routes to the surface through identified potential pathways for the specific sites, as these may be offset from the storage site (Figure 3). This may include areas in hydraulic communication (the hydraulic unit) where negative impacts can occur, even if located at a distance outside the storage complex.

If CO_2 migrates from a storage reservoir (a) via an undetected fault into porous and permeable reservoir rock (b), it may be transported by buoyancy towards the ground surface at point (c). This may result in the emission of CO_2 at the ground surface several kilometres from the site itself at an unknown time in the future.

Modelling should be used to project the extent of potential impacts of CO_2 storage in saline aquifers, such as pressure increases and formation water displacement so that monitoring plans can be designed to tackle these impacts as necessary. Monitoring should also be considered to detect CO_2 movement into aquifer formations between the main storage reservoir and the surface, especially for the protection of drinking water.

Figure 3: Illustration of potential leakage from a storage site (IPCC).



In some cases, different operators working in proximity may have overlapping monitoring footprints or alternative uses of the subsurface. This overlap in monitoring footprints should not, however, extend to the areas where CO_2 plumes can be expected to occur. Where this occurs, the operators and competent authorities should work together to ensure the monitoring plan can be effectively implemented.

5.2.2.3. Plan description

A monitoring plan drawn up by the operator must meet the following requirements under the CCS Directive.

The monitoring plan must detail the monitoring to be carried out at the main stages of the project, including baseline, operational and post-closure monitoring.

The following must be specified for each phase:

- the parameters monitored;
- the monitoring technology employed and justification for technology choice;
- monitoring locations and spatial sampling rationale; and
- the frequency of application and temporal sampling rationale.

At a minimum, the plan must include continuous or intermittent monitoring of the following items, under Annex II:

- fugitive emissions of CO_2 at the injection facility;

- CO_2 volumetric flow at injection wellheads;
- CO_2 pressure and temperature at injection wellheads (to determine mass flow);
- chemical analysis of the injected material;
- reservoir temperature and pressure (to determine CO_2 phase behaviour and state).

Additional parameters are likely to be needed in the monitoring plan, depending on the storage type, the trapping mechanism and site-specific risks. Mineralisation sites, for example, may require geochemical sampling and geochemical modelling to accurately evaluate containment and conformance. Box 2 provides additional considerations for monitoring plans related to mineralisation sites.

These measurements and related triggers or thresholds are very important in providing early indications of any anomalous behaviour and enable preventive measures to be taken before any leakage occurs.

The choice of monitoring technology must be based on the best practice available at the time of design. The following options should be considered and used as appropriate (Annex II):

- technologies that can detect the presence, location and migration paths of CO_2 in the subsurface and at the surface;
- technologies that provide information about pressure-volume behaviour and areal/vertical distribution of the CO_2 plume to refine numerical 3D simulation of the 3D geological models of the storage formation established under Article 4 and Annex I to the CCS Directive;
- technologies that can provide a wide areal spread in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond, in the event of significant irregularities or migration of CO_2 out of the storage complex.

In addition to the technology considerations highlighted in the CCS Directive, techniques for water sampling and analysis are also recommended. Saline water from the injection zone, reacting to higher pressures and imperfections in the caprock or well cement, can breach the caprock endangering shallower drinking water sources and indicating a pathway whereby the CO_2 plume might later escape.

Therefore, it may also be appropriate to monitor for relevant chemical changes, such as the salinity (resistivity), pressure and temperature of fluids above the caprock to detect such fluid movements. Water sampling and analysis may also need to be monitored and factored into geochemical modelling.

Different categories of monitoring can be set out:

- Mandatory monitoring (for all sites). Some parameters to be monitored are mandatory in the CCS Directive. These parameters are important for operational monitoring, and will provide some important and continuous measurements relating to plume behaviour and potential leakage pathways (e.g. formation pressure data).

- Required (site-specific) monitoring. Site-specific monitoring activity is designed to collect evidence for containment in the reservoir and to demonstrate the integrity of seal, fault and wells at the specific site. This will build on the risk assessment during site characterisation in order to manage site-specific risks and uncertainties.
- Optional contingency monitoring. Contingency monitoring systems are only used in the event of irregularities or system failures. Under the CCS Directive, a ‘significant irregularity’ is defined as ‘…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’.

Box 2: Monitoring plan description for mineralisation sites.

Mineralisation sites may initially rely on solubility trapping initially, as it can may take two years or more for the injected CO_2 to fully mineralise. Ensuring the CO_2 remains dissolved in water is therefore essential to demonstrating containment. Pressure and temperature monitoring of the injection zone is recommended to be a significant component of monitoring at mineralisation sites to ensure the CO_2 remains trapped in solution, unless a secondary (i.e. structural) trapping mechanism is also present.

5.2.2.4. Baseline surveys

The scope of baseline surveys will depend on the availability and type of data over the specific site, storage complex and surrounding area, including data acquired before and during site characterisation and as part of any environmental impact assessment.

Baseline measurements may be considered as follows:

- formation gas and fluid characteristics in the storage reservoir, surrounding complex and formations that might be affected by potential leakage, including aquifers;
- background CO_2 emissions at surface or sea floor;
- surface and near-surface environmental surveys;
- seabed, surface or near-surface baseline surveys to define any pre-existing leakage indicators;
- ground surface surveying, e.g. where ground movement monitoring is expected to be beneficial and/or in areas of ground movement risk;
- natural seismic activity (earthquakes).

The extent of sampling for a baseline measurement will depend on the risk to be considered and site-specific conditions. For example, there may be seasonal variability in CO_2 concentrations at the surface or sea floor, and baseline surveys may want to consider sampling in all seasons and various types of attribution monitoring (see Box 3). The characterisation of natural seismic activity in a site or region may require data collection over a longer timeframe.

Depleted hydrocarbon fields may require data acquisition to demonstrate a 'new' baseline after production operations cease. Such data acquisition needs to be managed as described in Section 3.3.

Box 3: Attribution monitoring.

The aim of attribution monitoring is to differentiate naturally occurring CO_2 from CO_2 that originated from storage operations. Natural processes, such as the decay of organic matter, dolomitisation, volcanic activity/migration of magmatic CO_2 through dikes and sills, wildfires or other process can generate CO_2. This is a key consideration in baseline monitoring to distinguish natural CO_2 from leaked CO_2. Geochemical monitoring methods including tracers can sometimes be used to attribute CO_2 to its source (Zero Emissions Platform 2022 and Dixon et al 2015).

5.2.2.5. Detailed plan format

A template for a monitoring plan is proposed in Table 3. The plan should include the following.

- Parameters to be monitored (e.g. Column 1). These parameters follow both from the mandatory monitoring obligations as stipulated by the CCS Directive and from the risk assessment. The latter parameters will be highly site-dependent.
- The technique that will be used to measure the parameter (Column 2), with a more detailed description of the technique provided outside the table. Site-specific issues especially need to be clarified in an accompanying text. For example, the description would encompass the acquisition parameters.
- The category of monitoring: mandatory, required, contingency (Column 3).
- Frequency of measurement (Column 4).
- Spatial coverage (Column 5) of the data acquisition planned in each phase of the project (pre-injection, injection and post-injection including long-term stewardship after transfer of responsibility). The rationale behind the monitoring strategy should be described in an accompanying text.
- The expected accuracy of the monitoring method and of expected values that indicate normal behaviour (Column 6).
- Threshold alert values where predicted normal behaviour stops and where potentially anomalous measurements occur (Column 7). The assessment of threshold alert values is closely linked to the outcomes of the site characterisation and risk assessment should follow storage permit award, as well as execution and synthesis of baseline monitoring. As long as the measured values remain below the threshold values (Threshold 1), no actions are required (green column). If the values exceed the threshold values, specific preventive actions may be defined and adopted when the alert value is exceeded. This stage is considered as an increased alert phase, where behaviour starts to deviate from expectations. For example, it could lead to recalibration of the models and to more stringent measures if the behaviour persists. The triggering of alerts might also be

dependent on how measurements taken at different locations and times corroborate or contradict each other.

- Contingency values and actions (Column 8). If the monitoring measurements values exceed the identified threshold coloured red, which would indicate either a significant irregularity or leakage, the highest alert phase starts and immediate actions (or corrective measures) are required, as specified in the second sub-column.

Table 3 provides an indicative example, not a minimum requirement for monitoring all sites, as monitoring plans should be site-specific and tied to the risk assessment. The example provided shows several parameters in the template such as injection rate, injected gas composition and fault integrity. Note that more than one monitoring method may be selected for each parameter. At the operator’s discretion, the table can be further subdivided to describe the different risks and elements to be monitored (for example operations, caprock, well leakage pathway, plume). Monitoring techniques and frequency should be established in accordance with best practice at the time of drafting the monitoring plan or update.

The operator should also connect the chosen monitoring methods to the risks identified in the risk assessment and provide a rationale for the choice of method. It should list the risks identified in the risk assessment analysis. It should relate the chosen monitoring method to the risks they address, recognising that one method can cover more than one risk and that a single risk may require more than one method. It should describe why each method is considered appropriate to manage a specific risk from both a technical and a cost-efficiency point of view.

Table 3: Proposed monitoring plan template with example information. Additional information may be included in the monitoring plan as described throughout Section 5, such as an explanation of how monitoring ties to risk treatment, a justification for the choice of each technology or methodology to address specific risks, and the requirements set by the competent authority or local jurisdictions.

Parameter to be monitored*	Technique adopted	Category of monitoring			Project phase and frequency				Location	Normal situation		Alert value		Contingency value (significant irregularity)	
		Mandatory	Required	Contingency	Pre-inj.	Inj.	Post-inj.	Long-term stewardship		Expectation value	Accuracy	> Threshold 1	Action**	> Threshold 2	Contingency measure***
Injection rate	Flow meter	x				Cont.			Wellhead						
Pressure	Pressure device	x			Baseline data	Cont.	Cont.	Every year	Wellhead + downhole			Larger than hydrostatic pressure	Micro seismic monitoring of seal	Larger than fracturing pressure	Stop injection
Temperature	Thermometer	x			Baseline data	Cont.	Cont.	Every year	Wellhead + downhole						
Injected gas composition	Gas samples	x				Cont.			Wellhead	Defined %		Allowed fluctuations	Adapt gas composition, reduce injection rate		Adapt gas composition, stop injection temporarily
Fault integrity	Repeated 3D seismic; fibre-optic sensors		x		Baseline survey	Order of years, based on modelling	Possible survey after several years	Possible survey after several years	Fault area	No signal changes		Signal change in the seal		Signal change above the seal	
	Aqueous chemistry (CO_2, pH)		x			Roughly yearly									
Well integrity	Annular pressure		x			Order of few months			Wellbore	t.b.d.		t.b.d.		t.b.d.	
	Wireline logging		x			Order of few months			Wellbore	t.b.d.		t.b.d.		t.b.d.	
	Optical well logging		x			Order of few months			Wellbore	t.b.d.		t.b.d.		t.b.d.	
	Cement bond logging		x			Order of few months			Wellbore	t.b.d.		t.b.d.		t.b.d.	Cement
Microseismic monitoring	Geophones behind the casing of a well			x	Baseline data	Cont.	Cont.		Injection well	No events in caprock		Events in the caprock		Large events in the caprock	Stop injection

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*Follows on from the risk assessment

** To be decided by the operator, examples are updating model, additional monitoring

*** By operator, examples are stop injection, back-production, well workover, contingency monitoring
Note: This table is not intended to represent a full monitoring plan, but to show example information to illustrate how the table should function. The numbers and data do not represent real site-specific values. Information in actual monitoring plans must be detailed and adapted to national requirements in place.

5.2.3. Plan implementation, reporting and performance management

5.2.3.1. Reporting and documentation

According to the CCS Directive, the operator must report the results of the monitoring to the competent authority at a frequency to be determined by the authority, but at least once a year until transfer of responsibility. Monitoring is part of the wider reporting requirements that must include:

- all results of the monitoring, including information on the monitoring technology employed;
- the quantities and characteristics of the CO_2 streams delivered and injected, including composition of those streams, in the reporting period;
- any other information the competent authority considers relevant to assess compliance with permit conditions and increasing the knowledge of CO_2 behaviour in the storage site.

5.2.3.2. Data retention and ownership

There CCS Directive does not lay down any specific provisions on data retention or ownership. each Member State may choose to develop policies, laws and regulations governing who has access to and the right to use the monitoring data and who is responsible for the long-term preservation of such data. In general, Article 14(4) of the CCS Directive encourages competent authorities to collect and keep all information that they consider relevant to assess compliance with storage permit conditions and increasing the knowledge of CO_2 behaviour in the storage site.

Such pooled data could be used to better characterise regional geology, monitor regional effects of injection (e.g. basin-wide pressure build-ups) and develop better monitoring technologies and practices. It is possible that policies could call for some or all of the monitoring data to be treated as confidential business information for a set period of time after it is collected. After that period has expired, the data would be made public.

The policies regarding ownership and use must balance the project developers’ rights to retain proprietary data with the public need for transparency and openness about results and the social value of pooling of data across sites. The public value of data access in order to accelerate and disseminate learning about storage given the importance of rapid CCS deployment should also be factored in. Sharing data would help to improve the modelling, and contribute to better risk assessments, while providing valuable information for research and innovation activities.

The policies on data retention may also consider the obligations of the site operator to retain both raw monitoring data and processed data for specific periods of time. Presumably much of the processed monitoring data will have to be retained to create the operating history needed when responsibility is transferred (see GD 3). The policies might also cover who within the government would retain copies of the monitoring data submitted by the operator during the injection and the post-closure pre-transfer period. Policies are also needed regarding the long-term retention of monitoring data after the transfer of responsibility phase.

All such policies might consider exactly what data are to be retained, the format (including use of a consistent coordinate reference system) and the type of media to be used for data storage and back-up.

5.2.3.3. Interpreting monitoring results and site performance

Annex II to the CCS Directive sets out the following requirements for interpretation and updating.

- ‘The data collected from the monitoring shall be collated and interpreted. The observed results shall be compared with the behaviour predicted in dynamic simulation process of the 3D pressure-volume and saturation behaviour (of CO_2) undertaken in the context of the security characterisation pursuant to Article 4 and Annex I Step 3’.
- ‘Where there is a significant deviation between the observed and the predicted behaviour, the 3D model shall be recalibrated to reflect the observed behaviour. The recalibration shall be based on the data observations from the monitoring plan, and where necessary to provide confidence in the recalibration assumptions, additional data shall be obtained’.
- The risk assessment for the site/complex (steps 2 and 3 of Annex I) ‘shall be repeated using the recalibrated model(s) so as to generate new hazard scenarios and flux rates and to revise and update the risk assessment’.
- ‘Where new CO_2 sources, pathways and flux rates or observed significant deviations from previous assessments are identified as a result of history matching and model recalibration, the monitoring plan shall be updated accordingly’.

The parameters and thresholds used to flag any significant irregularities should be described and planned through discussions with the competent authority and the operator. They should be clearly included in the monitoring plan.

If a leakage is detected or significant irregularities occur that might lead to leakage, the operator must immediately inform the competent authority under the CCS Directive as well as the authority responsible under the ETS Directive.

Under the CCS Directive, corrective measures must be implemented immediately and monitoring carried out to check their effectiveness. The operator is also required to implement the monitoring approach to quantify the leakage under the EU ETS.

Quantification of the leaked CO_2 will then be carried out according to the monitoring plan and reported annually. The monitoring and reporting guidelines for CCS set out various options for establishing when a leak started. The operator must provide evidence of the last point in time that the leakage was not detected. If this is not possible, reporting of the leakage might cover the whole timeframe since injection started.

The quantification approach will have been included in the monitoring plan, which must be approved by the competent authority under the EU ETS. This may warrant updating in light of any new information concerning the leak.

After corrective measures are taken and the leakage can no longer be detected, the leakage can be deleted as an emission source from the storage site's EU ETS permit.

This process requires clear and timely communication between all authorities involved. It requires not only knowing the respective contacts, but also giving guidance on the minimum information that must be provided and giving staff members an appropriate level of training to be able to correctly interpret the information received.

5.2.3.4. Inspections

Inspections are required under Article 15 of the CCS Directive. Member States are required to establish a system of inspections, both routine and non-routine inspections of the storage complex. The purpose of these inspections is to check and promote compliance with the CCS Directive and to monitor the effects on the environment and on human health.

Inspections should be planned and implemented by people with the relevant knowledge and should cover all monitoring domains surrounding the storage complex (see Section 3.3.8), and site-specific risks.

Inspection activities may include site visits, auditing of record-keeping, and may also include evaluations of initial and updated risk assessments, static and dynamic models, and monitoring plans to ascertain that there are no negative effects to the environment or human health.

The scope and frequency of inspections is clearly stated in the CCS Directive (Article 15).

- 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.
- Routine inspections must be carried out at least once a year until three years after closure and every five years until transfer of responsibility to the competent authority has occurred. They must 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 must be carried out:
    - if the competent authority 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; or

    - in other situations where the competent authority considers this appropriate (e.g. after increased seismic activity).

- Following each inspection, the competent authority must prepare a report on the results of the inspection. The report must evaluate compliance with the CCS Directive and indicate whether further action is necessary. The operator may be given the opportunity to review the report for inaccuracies regarding information provided to the competent authority during the inspection, although the opportunity may also be made available to the operator during the inspection process. The report must be communicated to the operator concerned and be made publicly available in accordance with relevant EU legislation within two months of the inspection.

5.2.3.5. Evaluation of performance

The comparison and evaluation of the predicted performance and measured performance of a CO_2 storage site can consider performance in terms of:

- safety and environment (CCS Directive);
- effectiveness in emission reduction (ETS MRG); or
- evaluating the performance (by the operator, competent authority and/or an independent third party).

Under the CCS Directive, the competent authority is responsible for evaluating overall performance. Evaluation under the CCS Directive covers regular evaluations of monitoring data from different reports and the baseline measurement, comparisons with predictive models and identifying any additional risk management measures needed during the injection and post-injection stages.

5.3. Updating the plan

Monitoring plans must be ‘updated, at least every five years’, to account for changes to assessed risk of leakage, changes to the assessed risks to the environment and human health, new scientific knowledge and improvements in the best available technology. The initially installed monitoring system and related procedures may also need to be updated as a result. Competent authorities may set a more stringent frequency.

The plans should also be updated as a matter of urgency in the event of a leakage or significant irregularities as changes in monitoring are likely to be required as part of the corrective measures and for the purposes of quantifying the leakage.

5.4. Post-closure monitoring

Monitoring in the post-closure period will supplement the monitoring data acquired before and during injection in order to demonstrate permanent containment, as described in Article 18(1)(a) and Article 18(2) of the CCS Directive. This includes data on:

a) whether the actual behaviour of the injected CO_2 complies with the modelled behaviour;

b) the absence of any detectable leakage; and

c) that the storage site is evolving towards a situation of long-term stability.

Plans for post-closure monitoring will be based on the risk assessment, characterisation, and monitoring data collected up until closure. They may require additional or new (techniques, frequency, technologies) data collection for further characterisation. The post-closure monitoring plan must also provide the information needed for transferring responsibilities to the competent authority. Additional guidance on the requirements for site closure and post-closure monitoring are provided in GD 3.

Depending on the specific operational history of the site, the intensity of the monitoring can be expected to fall over time, provided that the risk assessment indicates that risk is decreasing. Additional guidance on site evaluation criteria is provided in GD 1.

6. Corrective measures

6.1. Legislative context

Corrective measures are actions, measures or activities taken to correct significant irregularities, or to close leakages in order to prevent or stop the release of CO_2 from the storage complex (Definition 19, CCS Directive). They are designed to ensure the safety and effectiveness of geological storage. Corrective measures are part of the overall risk management process designed to ensure the safety of geological storage and to manage the risks from leakage during the project life cycle. Under Article 7(7), operators must submit a corrective measures plan with the storage permit application for approval by the competent authority as part of the storage permit.

Corrective measures are not required for the migration of CO_2 within the storage complex unless a significant irregularity is identified. The operator must support analysis of scenarios that would indicate a leakage, including prudent modelling and monitoring.

Under Article 9(6) of the CCS Directive, the permit must also include the requirement to notify the competent authority in the event of a leakage or significant irregularities, with the approved corrective measures plan and the obligation to implement the corrective measures plan in the event of a leakage or significant irregularities under Article 16.

Article 16 of the CCS Directive requires that Member States ensure:

- that the operator of the storage site immediately notifies the competent authority in the event of leakage or significant irregularities and takes the necessary corrective measures including measures to protect human health;
- the corrective measures must be taken as a minimum on the basis of a corrective measures plan submitted to and approved by the competent authority; and
- if the operator fails to take the necessary corrective measures, the competent authorities must take these measures and recover the costs from the operator, including by drawing on the financial security under Article 19 of the CCS Directive.

The general principles for the overall approach to corrective measures are quite similar to, and closely linked to the risk assessment and monitoring of the complex. Corrective measures are recommended to be:

- risk-based; linked to identified risks from site and complex characterisation (and risk assessment) and subject to the limitations of available technologies (as discussed in GD 1);
- specific to the storage site and complex;
- suitable for use to tackle leakage or significant irregularities from identified leakage pathways and specific leakage mechanisms out of the storage complex and any leakage to the surface;

- closely linked to monitoring plans and monitoring (covered in Section 5 of this document), including identifying triggers for the use of corrective measures by identifying any leakages or irregularities;
- used when there is any leakage or significant irregularities; and
- ready to use when injection operations commence.

The plans should be updated, as appropriate, as part of the storage permit review required under Article 11 of the CCS Directive.

6.2. Relationship to monitoring and monitoring plan updates

Monitoring and corrective measures are closely linked. Operators should develop the plans and activities in a holistic manner along with the risk assessment. The competent authority is recommended to seek to ensure close integration between these measures.

Corrective measures must be deployed in the event of leakages or significant irregularities, which are usually detected through monitoring results, interpreting monitoring data or during inspections.

It is recommended that operators design monitoring plans to allow for early warning of significant irregularities. This enables early intervention to be taken through corrective measures to prevent the situation escalating and to reduce the risks associated with leakage from the storage complex.

In addition, monitoring will be used to assess the effectiveness of corrective measures, and additional monitoring activities may be required in the event of any leakage or significant irregularities.

Ultimately, the corrective measures will need to be specific to the actual leakage or significant irregularity, taking account of the precise location, nature and the specific situation and circumstances in which the leak occurred. The risks associated with performing the corrective measures should also be factored in as there may be additional related threats or consequences. A flexible approach is needed to update and change the plan according to each specific situation.

Rapid and effective interaction between the competent authority and the operator is recommended during the response and when implementing corrective measures. It may require strong technical expertise in drilling, well engineering and geosciences. Specialist consultants may also be involved. The authorities are recommended to assess available expertise within their organisations and, where required, to draw on external expertise.

6.3. Responsibilities during project phases

The operator must prepare an initial assessment of the corrective measures and submit this as part of the storage permit application for approval by the competent authority.

Corrective measures may be used at any stage in the life cycle after the storage permit is awarded. These may be additional to or different from those laid out in the corrective measures plan.

It is expected that corrective measures will be used mostly during the operations (injection) phase and post-closure pre-transfer phase. After transfer of responsibility, corrective measures may still be required, although the likelihood is reduced from then on as the site evolves towards a condition of long-term stability.

After the transfer of responsibility or the withdrawal of the storage permit, all activities are the direct responsibility of the Member State. After the transfer of responsibility, the purpose and aims of corrective measures are similar to earlier stages. However, because of the requirements around stability of the injected CO_2 and containment for transfer of responsibility, it is expected that there will be little requirement for any corrective measures unless there is unexpected leakage or irregularities.

6.4. Scope and format of corrective measures plan

Corrective measures plans are recommended to be based on the risk assessment, which is in turn site-specific and closely related to the site and complex characterisation. Potential and contingent corrective measures are recommended to be described for each of the main risks identified during each phase of the project lifecycle.

Site characterisation (see Section 3 of this document) is recommended to guide the risk assessment, which informs the monitoring plan and in turn the corrective measures plan. As a result, the corrective measures plan will link to the specific risks of a storage site, storage complex and the surrounding area, including considerations such as the CO_2 storage setting, trapping mechanism(s), location and other uses of the site.

Monitoring plans should link directly to the corrective measures plan, indicating specific monitoring triggers, alert thresholds and the timing for deploying corrective measures. For each identified key risk (see GD 1) in each project lifecycle phase, the following components are recommended to form part of the corrective actions plan:

- a description of the significant irregularity that would prompt a corrective measure and rationale for the identified thresholds;
- monitoring method(s) to identify the significant irregularity and rationale for their use;
- a description of the corrective measure(s) to be taken and the rationale for their use;
- a timeframe for response and completion of the corrective measure(s);

- a description of contingent corrective actions.

The operator must develop an initial proposed corrective measures plan before injection operations begin. As the site-specific risks may change over time, (some risks may be mitigated or new risks may arise) the corrective measure plan will also require updating as the project progresses (see Article 11 of the CCS Directive). Threshold values that trigger the need for corrective measures may be set after baseline data is acquired. In addition, the viability and cost of corrective measures depends on the nature of the risks and pathways, and there may be few options for corrective measures for certain kinds of risks. In some cases, only very generic measures such as reducing reservoir pressure or stopping injection may be proposed.

It is recommended to maintain close dialogue and contacts between the competent authority and the operator during the development of corrective measures plans, in order to further specify the definition and the triggers for deploying the plan.

The competent authority is recommended to set minimum requirements tailored to the CO_2 storage setting and associated risks. These may include, for example, lowering injection rates or changes to injection schedules, reservoir pressure management, environmental remediation and sealing the identified leakage.

6.5. Documentation and reporting

The CCS Directive specifies the need for the operator to submit a corrective measures plan as part of the application for a storage permit which is subject to approval by the competent authority. The plans should be updated, as appropriate, as part of the storage permit review required under Article 11 of the CCS Directive.

Reporting on corrective measures is also covered by the requirements to report monitoring under the CCS Directive. Under Article 14, the operator is required to report the results of the monitoring to the competent authority at a frequency to be specified by the competent authority (at least once a year) until transfer of responsibility.

The occurrence of significant irregularities, leakages, and implementation of corrective measures will determine the extent to which corrective measures are reported. Where these have occurred, the competent authority is recommended to ensure that reporting includes documentation of the corrective measures taken, and that the operator has met its obligations to assess the effectiveness of corrective measures taken, in accordance with the monitoring requirements in Article 13. The operator should also report updates to the corrective measures plans and assumptions (i.e. risk, measures and methods).

This information might also be used to review and update the corrective measures plan, as appropriate, alongside the review of the storage permit (see below). For example, if new information provides sufficient evidence about specific leakage risks, such as where injected CO_2 has encountered specific wells or faults without evidence of irregularities, then the plan for corrective measures could be refined.

The competent authority is recommended to ensure that the effectiveness of any corrective measures taken during the project life cycle is reviewed at the time of transfer of responsibility in order to identify any outstanding corrective action.

6.6. Interpreting the results and performance of corrective measures

It is important to assess the effectiveness of any corrective measures taken to determine whether leakage or significant irregularities have been sufficiently mitigated. In addition, Article 13(f) of the CCS Directive specifies that monitoring must be carried out to assess the effectiveness of any corrective measures taken.

The operator is recommended to integrate an assessment of corrective measures with the assessment of monitoring results (see Section 5 of this document). In particular, the results and performance of corrective measures are recommended to be reviewed in order to meet the requirements specified in Annex II (step 1.2) to the CCS Directive.

Based on the revised risk assessments and the updated monitoring plans, the corrective measures plans should also be revised accordingly.

6.7. Inspections

As described in recital 26, in the event of leakages or significant irregularities and thus when corrective measures are implemented, the competent authority must carry out non-routine inspections and the costs incurred in carrying out these non-routine inspections must be recovered from the operator. These non-routine inspections should also assess the effectiveness of the corrective measures implemented. As such, monitoring and modelling reviews may be included.

6.8. Updates to the corrective measures plan

Although there are no formal requirements for routine and regular updates to the corrective measures plans in the CCS Directive, they should be updated, as appropriate, as part of the storage permit review required under Article 11 of the CCS Directive.

These updates would take account of new information from the project including the results of monitoring and updates to the site characterisation, the assessed risk of leakage, changes to the assessed risks to the environment and human health, new scientific knowledge and improvements in best available technology.

With increased knowledge about the storage site, previously identified risks might be considered irrelevant or new risks might emerge for which corrective measures are needed. Over the lifetime of a storage site, new techniques and technology for corrective measures might emerge or the approach might change.

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