



Experience in developing CO₂ storage under the Directive on the geological storage of carbon dioxide

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Executive summary

The Intergovernmental Panel on Climate Change (IPCC) report 'Climate Change 2022 – Impacts, Adaptation and Vulnerability' describes the current impact of climate change including hot extremes, wildfires, heavy precipitations, flooding, tree mortality, biodiversity loss, reduced food and water security, increase in diseases, rising displacements, and damages to key economic sectors and infrastructure. To stay in line with the 1.5°C scenario, the EU needs reach net-zero greenhouse gases emissions by 2050. The European Climate Law puts this objective at the heart of the European Green Deal and the EU climate action.

Carbon capture and storage (CCS) are proven and cost-efficient technologies, available now and necessary for Europe to reach net-zero CO₂ emissions by 2050. CCS technologies can make a significant contribution to climate change mitigation. Their potential for carbon emissions abatement and removal is scientifically proven and acknowledged by the European Taxonomy for Sustainable Activities and the European Commission's 'Clean Planet for All' scenario.

The EU benefits from the North Sea basin, which has tens of billions of tonnes of CO₂ storage capacity and has safely stored CO₂ since 1996. The recently launched CCS project Longship in Norway and the positive developments in the Netherlands, with Connecting Europe Facility (CEF) funding being

awarded to PORTHOS, are prime examples of permanent CO₂ storage capacities in Europe. Such projects provide the storage infrastructure required to reach and exceed the Commission's goal.

The success of these permanent CO₂ storage projects relies on a clear legal framework that provides operators with regulatory certainty. The Directive on the geological storage of carbon dioxide, adopted by the European Parliament and the Council in 2009, aims to provide such clarity. The purpose of the guidance documents published in 2011 is to help in the implementation of the Directive.

The main objective of this report is to highlight how the Guidance Documents could be made simpler, clearer and easier to use, and to propose improvements to these Guidance Documents to support the work by regulators and project developers. The Directive itself should not be opened up for review, since storage permit applications have been developed under the Directive and increasing experience with regulators and project developers is already showing evidence of evolving interpretation. Another objective of this report is to share knowledge with companies, projects, governments, and competent authorities based on previous experience.

The key message in the report is that competent authorities should engage early

and frequently with operators and project managers. Another key message is to avoid increasing or further detailing the requirements in the Guidance Documents.

Reflections and recommendations

Section 2 of this report highlights the importance to clearly communicate the functional requirements for CO₂ storage operation. ZEP would like to recommend the following updates to the Guidance Documents:

- Competent authorities should engage with the project early in the process to provide clarity and to avoid misunderstandings and delays.
- Operators should have the right to object to surface and subsurface activities impacting the viability of an ongoing project.
- The operator should have the possibility to update the interim documents/plans more efficiently, and directly after the commissioning phase of the storage system.
- The competent authority should provide clear oversight of the project and support the process after the start of injection.
- The competent authority should not apply more stringent requirements to depleted hydrocarbon reservoirs than to new deep saline formations.

Section 4 analyses the transition from the production of hydrocarbon to future CO₂ storage activities. ZEP would like to recommend the following updates to the Guidance Documents regarding the case when the current operator aims to stop activities in the current production license area:

- The current operator must report its intention to the competent authority upfront, so that other plans can be

made and operations can remain efficient.

- The competent authority needs to decide on liabilities of asset owners and production license holders.
- The competent authority needs to develop a clear pathway that allows future storage operators to access the information required and to undertake site appraisal activities.

ZEP would like to recommend the following updates to the Guidance Documents regarding the case when the current operator aims to stay and start a CCS project:

- The competent authority should ask the existing joint-venture partners to give the production license back or become partners on the new project.
- The competent authority should either take over the partners' shares to ensure further progress in CCS or find new partners, if the joint-venture partners do not want to work on the new project.
- In case of competition between the current operator and interested third parties, the competent authority should develop a strategy to evaluate all available project plans and ensure that permits are granted on objective, transparent and non-discriminatory criteria.
- Competition must be limited to the contract area or returned production license areas.
- The Guidance Document should provide more clarity regarding the consequences and responsibilities if a storage site is used in a different stratigraphic interval.

ZEP would like to recommend the following updates to the Guidance Documents regarding the case when an existing operator is blocking a license:

- The competent authority should require from an operator holding a production license to annually publish their plans for CO₂ storage.
- The competent authority should publish a guideline to provide advice on how to manage a field and its abandonment.

Section 5 discusses the closure and transfer of responsibility to the competent authority. ZEP would like to recommend the following update to the Guidance Documents:

- The competent authority should discuss and agree with the operator the criteria for the demonstration of permanent storage on a case-by-case basis.
- The competent authority should make sure that provisional post-closure plans and the financial mechanism do not increase in scope unless a significant irregularity occurs during site operations.

Section 6 addresses the fact that the operator must set up a fund to cover the costs after the transfer of responsibility of the storage site. ZEP would like to recommend the following:

- The operator should set up insurance schemes that include public and private funding. If that is not possible, the operator should calculate the size of the fund based on a percentile of costs and not on expected values.
- National governments should have a robust and independent review of the risks and impose risk criteria for low-probability incidents.

Finally, in section 9, ZEP is recommending specific amendments to Guidance Documents 2, 3 and 4.

1. Introduction

1.1 Background

Climate change is one of the biggest challenges of our times – temperatures are rising, drought and wildfires are starting to occur more frequently, rainfall patterns are shifting, glaciers and snow are melting, and the global mean sea level is rising. As one of the signatories of the Paris Agreement, the European Union has adopted the European Climate Law in 2021 that states *“solutions that are based on carbon capture and storage (CCS) and carbon capture and use (CCU) technologies can play a role in decarbonisation, especially for the mitigation of process emissions in industry”*. Twenty EU Member States (MS) have included CCS in their National Energy and Climate Plans (NECP) for the period 2021 – 2030¹.

To enable emitters across Europe to connect to safe geological CO₂ storage, European non-discriminatory, open-access CO₂ transport and storage infrastructure will be crucial. For the CO₂ transport infrastructure there is a need for a new EU regulatory framework. The Zero Emissions Platform (ZEP) is currently preparing a proposal for how such a framework should be designed. ZEP has proposed an EU CCS and CCU strategy² where the focus is the successful development and large-scale deployment of storage infrastructure.

1.2 The Directive

The geological storage of CO₂ is regulated by the Directive on the geological storage of CO₂ (‘the Directive’), which sets out the requirements for safe and secure storage³. Member States (MS) retain the right to determine the areas within their territory from which storage sites may be selected. MS also have the right not to allow storage on their territory at all (or to give priority to any other use of the subsurface). The Directive has been transposed into national legislation in all MS. The Directive is accompanied by four non-binding Guidance Documents (GD) which were released in 2011:

- GD1 – CO₂ Storage Life Cycle Risk Management Framework
- GD2 – Characterisation of the Storage Complex, CO₂ Stream Composition, Monitoring and Corrective Measures
- GD3 – Criteria for Transfer of Responsibility to the Competent Authority
- GD4 – Financial Security and Financial Mechanism

Even if these Guidance Documents are non-binding, experience has shown that, at times, these GDs are treated as binding. Geological storage of CO₂ is allowed in nineteen countries in Europe – although, in some cases, certain regions are excluded, or limits are imposed –

¹ CO2Geonet. ["State-of-play on CO2 geological storage in 32 European countries — an update"](#) (2021).

² Zero Emissions Platform. [EU Strategy for CCS and CCU](#) (2021).

³ Eur-Lex. [Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide](#).

while it is prohibited to store CO₂ geologically in nine countries⁴. This means that CO₂ storage activities in Europe will have to comply with the Directive. Permit applications and draft permits for CO₂ storage are required to be submitted by MS to the European Commission ('the Commission') for opinion.

The Directive "establishes a legal framework for the geological storage of CO₂ and specifies that environmentally safe CO₂ geological storage means the permanent containment of CO₂ in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health"⁵. Key elements of the Directive are:

- the requirement to set up a Measurement, Monitoring and Verification programme that is fit for purpose;
- the transfer of liability after the end of injection and after a post-injection period (until CO₂ has become stable in the reservoir); and
- the provision of a financial security for both is expected – e.g., post-injection monitoring, facilities removal – and unforeseen cost – e.g., post-closure leakage and remediation.

An assessment of the Directive was carried out in 2015, following the timeline set out in Article 38 of the Directive. At that time, the Commission concluded that there was insufficient experience with application of the Directive to perform an in-depth assessment of its effectiveness and efficiency⁶. A review of the Directive was delayed until more experience with CCS in the EU becomes available.

The Directive is a legal framework, as such it

does not provide all desired details. Member States are responsible for the interpretation of the framework, transposition, and application of the Directive. Both project developers and competent authorities will be developing experience in translating the requirements set out in the Directive into effective and efficient practical requirements and this process will challenge the first wave of projects. Indeed, based on their experience in CO₂ storage development and their interactions with regulatory bodies in several Member States, ZEP has found that there might be ambiguity in the way the Directive is interpreted.

1.3 Objective of the report

The aim of this report is to facilitate the work of operators and public authorities working on the deployment of CO₂ storage projects. The recommendations provided here aim to improve the guidance documents supporting the Directive on the geological storage of CO₂ and provide stakeholders involved in CO₂ storage projects with the best possible advice. This report brings together results and findings of several first-of-a-kind CO₂ storage projects that have been or are being developed under the Directive, for the benefit of new regulators and project developers. Where possible or relevant, suggestions are given to competent authorities or project developers to speed up and facilitate the development of future storage projects.

This report aims to be a reliable, independent reference document for authorities and applicants, by addressing uncertainties, suggesting potential solutions and providing recommendations in the dialogue between operators and competent authorities. The

⁴ CO2Geonet. "[State-of-play on CO2 geological storage in 32 European countries — an update](#)" (2021).

⁵ European Commission website. Implementation of the CCS Directive. [Guidance Document 1](#).

⁶ European Commission. Report on review of Directive 2009/31/EC on the geological storage of carbon dioxide (2015). [Annex 2](#).

authors of this report have experience in applying for permits for CO₂ storage in the EU and the UK.

The report does not request changes to the Directive. Nor has a need been identified for further or more detailed requirements in the Guidance Documents. Several storage permit applications have been developed under the Directive and increasing experience with regulators and project developers is already showing evidence of evolving interpretation of the Directive. The report offers suggestions to improve the Guidance Documents, which also aim to support regulators and project developers.

This report discusses the following topics:

- Learnings from the storage permit application process (Section 2)
- How the Directive applies to different storage types and how risks impact closure (Section 3)
- How their typical risks can be managed through injection system design, monitoring, and operation (also Section 3),
- And how these risks impact closure, handover (Section 5) and financial security (Section 6).

Section 4 discusses some of the key issues around the transition from hydrocarbon production to CO₂ storage. These are related to the interplay between legislation on exploration and production activities and licenses on the one hand, and exploration and storage activities and licenses on the other. Section 7 discusses combining hydrocarbon production and CO₂ storage. The findings in this report may be used in an update of the Guidance Documents to the Directive. Proposed improvements to the existing Guidance Documents are listed in the Annex.

2. Storage permit application

The Directive establishes a legal framework for the environmentally safe geological storage of CO₂ with the purpose of permanent containment to prevent negative effects and risks to environment and human health. Member States need to ensure that storage permits are awarded on the basis of objective, published and non-discriminatory criteria. Nevertheless, CO₂ storage developers should face similar requirements for the permitting and operation of a storage project across Member States.

Once the Directive is implemented in legislation, Member States still have the right to adopt national provisions, e.g., to provide more clarity on the requirements. Practical experience from the storage license applications in the Netherlands (P18-4 in 2011, P18-2 in 2021⁷) has shown that some parts of the Directive (and Guidance Documents) could benefit from increased clarity regarding the intent and expectations around content and deliverables, and better describe potential criteria that must be taken into consideration before starting the storage license application process. These elements of the Directive are discussed below.

The required clarifications could find a place in an update of the Guidance documents. The focus should be set on specifying functional requirements instead of unnecessarily

imposing restrictions or requirements for future projects. Before detailed technical requirements can be properly defined, more experience with CO₂ storage projects still needs to be accumulated to sufficiently cover the diversity of storage cases.

2.1 Data about the potential operator

This subsection addresses the need for a fully transparent communication of a) the requirements potential operator(s) need to be proven technically competent for CO₂ storage operation, and b) the related evaluation criteria. Flexibility needs to be granted with regard to modifications of the operator's organisation, which can potentially be required at a later stage.

The competent authorities (CA) should be fully transparent on the requirements potential operator(s) need to submit to successfully demonstrate technical competence. This could be supported by providing a detailed list of essential requirements and evaluation criteria that form the basis for their review. During the permitting process, some flexibility is needed in case of a reorganisation on the applicant's side.

Information about the applicant is of course part of the storage permit and therefore to be

⁷ Website of the Rijksdienst voor Ondernemend Nederland (*Netherlands Enterprise Agency*). Onderwerpen (*Topics*). Bureau Energie projecten (*Office of Energy Projects*). Lopende projecten (*Ongoing projects*). [Porthos Transport en opslag van CO₂](#) (*Porthos Transport and storage of CO₂*).

communicated to the CA. Any changes related to these details, but also regarding modifications to the operator's organisation structure, need to be provided and might initiate another full review. In case of the latter, the CA needs to make sure that the same evaluation criteria are applied with the same level of detail. In general, however, a storage permit application is submitted several years prior to the start of injection (ca. 4-5 years). This means that the details of the organisation, roles, legal entities etc. will not be established at this early stage. The CA needs to make sure that these aspects shall not interfere with the more technical application. The final proof of competence can therefore realistically be done months before the actual injection once the establishment of the legal entities has been completed.

To summarise, these are the recommendations to MS:

- CAs are advised to provide clarity around the requirements for CO₂ storage permit applicants
- Given the relatively long duration of a storage project, there should be some flexibility in the permitting process, related to changes in the organisation (e.g., legal entities) of the storage project.

2.2 Characterisation of the storage site and complex

Characterisation is an essential part in the storage license application. A review of other activities planned in the area is crucial to ensure safe storage operation. Containment of the storage site is key and requirements for the assessment need to be communicated by the CA at an early stage of the license application process.

The definition and characterisation of the storage complex is an essential part in the storage license application, in particular in relation to containment requirements. This involves, among others, a careful definition of the caprock, especially where several sealing layers are included in the storage complex. In such a case, one needs to define the main ("primary") caprock and the additional ("secondary"), shallower layer with sealing potential. Annex I of the Directive and GD 2 provide a high-level overview of the main steps to be followed by the operator for the characterisation and assessment of the storage complex and surrounding area, but do not indicate the level of detail of the underlying studies. This provides the flexibility to perform site-specific analyses.

While site and complex are defined in the Directive, the translation of these concepts into licensing in MS is, in essence, left to the project developer and CA. The bounds of the storage complex, highly relevant to project developers, will be strongly site specific. In addition to the limits of the storage complex, storage capacity is also one of the key properties that define the viability of a storage site. CA guidance in this area would be needed at an early stage of storage feasibility assessment. Therefore, consultation and discussion between the project developer and the CA should start before project development reaches an advanced level and should be held on a regular basis.

Apart from activities related to the CO₂ storage project, which will happen within the storage complex, activities above or below the storage complex also need to be addressed, (e.g., installation of wind farms). These activities may hinder monitoring plans and could therefore potentially hold up CCS project development. New projects should therefore consult with ongoing projects and take into

account their impact. In case of interference, existing projects should have the right to object. The Dutch “Noordzee akkoord⁸” may already be a good structure to manage different uses of the Dutch North Sea sector.

Many operators are now employing structured risk assessment techniques to demonstrate that containment is expected to be secure. There is still a lot of uncertainty, however, in areas where expert opinion judges that the geological and engineering evidence will indicate storage security, but where there is not direct “proof”. Operators spend a lot of time debating if the CA will agree with the operator assessment or not. Some CAs are willing to engage early on, while others take the position of “submit the permit application and we will make an assessment”. It would be recommended that the GDs encourage CAs to engage early and often in establishing their acceptance or otherwise of the operator’s containment assessment. Furthermore, the Directive and GDs focus on aspects of CO₂ storage in (deep saline) aquifers without reference to storage in depleted hydrocarbon reservoirs.

The following recommendations are made:

- it is recommended that CAs engage early and often in the development of storage projects, specifically in relation with the definition of the boundaries of the project (i.e., storage site and storage complex), and potential interference with other activities in the area.
- New projects need to consult with ongoing projects. There should be the right to object to activities impacting the viability of an ongoing project. This includes surface (pipelines, power cables, wind farms etc.) and

subsurface activities (causing changes in pressure).

- It is advised that storage in depleted fields should be equally addressed in the GDs than storage in saline aquifers, as their properties may lead to different criteria, risks and timelines that are more stringent compared to storage in deep saline aquifers.

2.3 CO₂ purity & Injection

This subsection highlights the importance to clearly communicate the functional requirements for storage operation and addresses the discussion about CO₂ specifications.

The CA could support the applicants by sharing functional requirements regarding storage operation, whereby safe storage is the main goal. For example, it is essential to know the type of maximum allowed pressure (initial, hydrostatic etc.) and its reference (depth). In addition, the expected pressure safety margin needs to be communicated upfront. It is recommended that site-specific geo-mechanical assessments and modelling are taken into account for this purpose.

Furthermore, the information from GD 2 that a CO₂ stream needs to consist “*overwhelmingly of carbon dioxide*” is not specific but should prevent a disposal of other waste products via the CO₂ flow. Potential impact on pipeline and storage integrity, but also public health and environment, that might be related to CO₂ stream composition, needs to and will be critically evaluated by the CA in the course of an environmental impact assessment. However, the GD could provide support by describing the considerations that might apply for different aspects of the CCS chain and are

⁸ Website of Noordzeeloket. Nieuws (News). [Noordzeeakkoord](#) (North Sea Agreement) (2020).

related to CO₂ specifications. Corrosion of transport facilities, well material and other equipment due to impurities, wet conditions, solids etc. needs to be addressed, along with safety issues for local population, e.g., regarding H₂S content. Based on current CCS experience, a definitive standard for CO₂ specifications cannot be established, i.e., they should therefore be agreed on a case by case basis. The GDs (notably GD 2) should, therefore, advocate for possible limits to certain impurities for HSE reasons but leave the operability of the CO₂ stream to the projects. The purity of the CO₂ stream should have a technical operational basis, not a legal or permitting basis.

An EU-wide approach could promote the development of a common understanding of CO₂ specifications, their impact on all parts of the CCS chain and the process of reaching interoperability. A future EU standard for CO₂ specifications would be highly recommended in light of a unique capturing process on the emitter's side, but, more importantly, for future cross border CO₂ transport provided that this does not prevent perfectly good projects by imposing unnecessarily restrictive limits on contaminants.

Both topics discussed here, pressure limits in the storage site and composition of the CO₂, will have a strong impact on the underlying business case of a CO₂ storage project. To summarise, these are the recommendations suggested improvements to the GD:

- The CA should clearly communicate the functional requirements to storage operations from the beginning.
- The GD should describe the considerations and possible limits that might apply for different aspects of the

CCS chain, including corrosion and safety issues.

- The EU should support the development of a common understanding on CO₂ specifications, e.g., by funding further research and inviting relevant experts to establish a benchmark satisfying all parts of the CCS chain (from emitter via pipeline/shipping transport to storage). Such research projects should investigate the interaction of impurities within the CO₂ stream with pipelines, wells, storage formations etc.

2.4 Seismicity & Monitoring

EU-wide approved CCS-specific technical standards are generally very limited or not existent (e.g., well abandonment, seismic risk analysis and monitoring). It would be useful if the GDs were to provide some guidance about the minimum technical requirements that need to be met when standards of related activities are used as reference while CCS-specific standards are still unavailable.

A risk-based approach is beneficial, especially when assessing risk of containment and induced seismicity. One suggestion can be to make use of the bow-tie method⁹, which appears to be well suited to CO₂ storage projects. The bow-tie risk assessment also reflects the nature of the barriers to prevent threats and mitigate consequences related to a potential hazard. In addition, expert judgement melded with quantitative failure frequency data is used to analyse risk / hazard. Furthermore, the GDs could also discuss the level of acceptable risk (e.g., the level of seismicity onshore vs offshore). Another example is HSE risk assessments, which need

⁹ Website of BVT Engineering Professional Services. [Using the bow tie method to develop critical risk controls.](#)

to be done for environmental and personal safety. Would extra flexibility in case of unmanned offshore injection sites be acceptable in that case? Such considerations would have a considerable impact on the closure plans for the storage complex and subsequent post-abandonment monitoring and allow some room for maneuver – within the accepted limits – during the CO₂ injection period.

The focus on safety is essential but needs to be reasonable with regard to what is technically feasible (site-specific) and what can be delivered when (ALARP¹⁰). The latter requires mutual understanding between authorities and CCS operators, especially when it comes to the level of detail of provisional versus final versions of risk management, monitoring, closure, and corrective measures plans (see also the next subsection). The combination of proven technical capability, focus on safety via a risk-based approach, along with a transparent and open communication can also help to increase public acceptance.

Since the drafting of the Directive and the Guidance Documents, monitoring techniques have made progress, including in what is known as ‘attribution monitoring’. These are a suite of techniques for surface and near-surface monitoring that enable an anomaly of higher CO₂ to be determined whether it is from the stored CO₂ or from another origin such as biogenic sources. This is important because, as it is written, when monitoring under the Directive suspects a leak, it triggers monitoring under the EU ETS Directive to quantify emissions, whether or not they are from the CO₂ storage site. These attribution techniques have been tested and proven at several projects including at controlled release

projects, onshore and offshore. Suggestions are made in the Annex to improve the GD2 by the addition of an attribution step in the process before triggering quantification monitoring¹¹.

The following recommendations to EU are made with regard to suggested improvements to the GD:

- While CCS-specific standards remain non-existent, the GDs could provide support by discussing the applicability of standards from other related activities; relevant topics include well abandonment, seismic risk analysis and monitoring.
- The sections on monitoring in the GDs could be extended with a discussion around ‘acceptable risk’, applied to different storage options, such as onshore vs offshore.
- GDs could be updated regarding monitoring, taking on board recent advances.

2.5 Permit documents & updates

This subsection addresses the need for a certain level of flexibility regarding potential updates of permit documents at a later stage, once new data becomes available. Mutual trust based on frequent communication between the CA and the operator will be a prerequisite for a successful permit application.

According to the Directive, several plans and assessments need to be submitted in the course of the storage permit application:

¹⁰ ScienceDirect. “[As Low as Reasonably Practicable \(Process Safety\)](#)”, Bai and Jin (2016).

¹¹ International Journal of Greenhouse Gas Control. “[Improving monitoring protocols for CO₂ geological storage with technical advances in CO₂ attribution monitoring](#)”, Dixon and Romanak (2015).

- Assessment of CO₂ storage safety including risk management;
- Monitoring plan;
- Abandonment / Closure plan;
- Corrective measures plan.

In addition to the above, local regulations may require additional plans and assessments as part of the permit application.

At the time of the submission of the application, not all details of the injection and storage system are available. This explains why these plans are “interim” versions. These initial documents already need to have sufficient quality and level of detail, which again underlines the importance of clear requirements communicated upfront. After review of the storage application documents, the CA can award a storage permit if the documents are regarded as sufficient but will insist that the four documents be updated before first injection (and again after a defined period). When the Front End Engineering and Design (FEED) is completed and the parameters of the final transport and injection system are known, the documents can be updated. However, an update of the documents is likely to be made once the first monitoring and injection data are available during the system’s commissioning phase. This may include changes to the monitoring plan, following improved insight in the storage system derived from early injection and monitoring data.

To enable a good understanding of the requirements for a storage permit application, frequent communication, e.g., through open discussions between operators and CA, including their technical advisors, would be beneficial already at an early stage. Such a low-threshold approach would provide more clarity and early guidance to the applicants and could avoid delays caused by misunderstandings or

ambiguities related to the application process and the detail of its requirements. Transparent discussions providing consistent information could be ensured by assigning spokespeople, preferably unchanging over the whole period of preparation and the storage application process itself (3-10 years expected). After the start of injection, CAs may want to have experience exchange sessions to discuss data and potential anomalies. This could be done by introducing a Technical Committee per storage site where the CA and their advisors together with the CO₂ storage operator have a seat.

To summarise, these are the recommendations to Member States:

- Early engagement of CAs is needed to provide clarity (e.g., on the required level of detail in the interim documents/plans) and guidance where needed and to avoid misunderstandings and delays.
- It is suggested to CAs that the delivery of the updates of the documents/plans may be done more efficiently, shortly after the commissioning phase of the storage system.
- A well-organised project oversight and support process after the start of injection would be beneficial.

3. Storage types / principles

3.1 Introduction

There are a range of deep geological storage options for CO₂, including saline aquifers and depleted/depleting hydrocarbon fields (Figure 1).

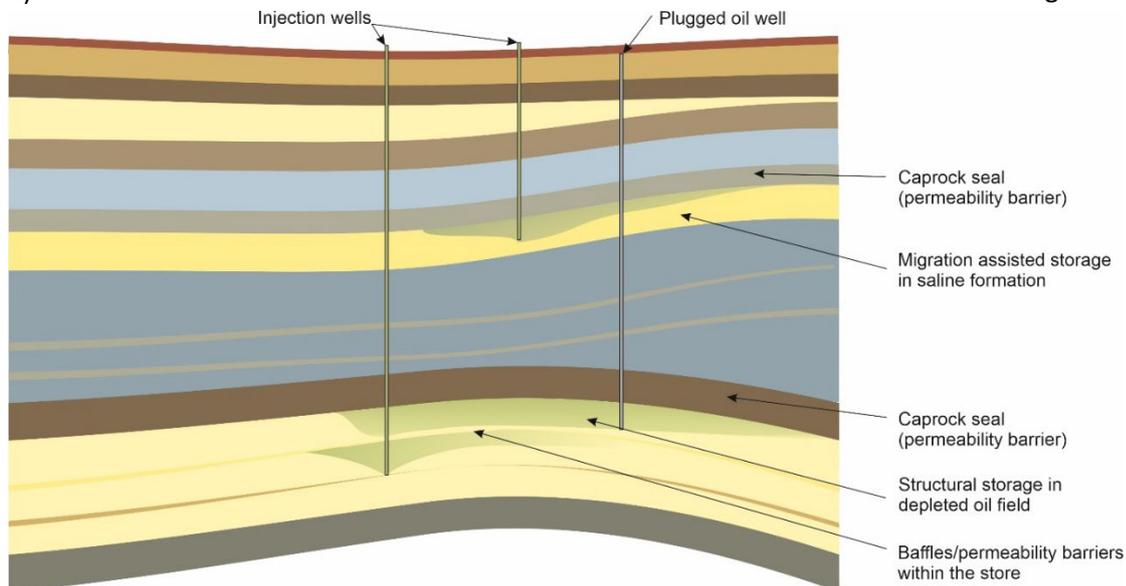


Figure 1: Injection of CO₂ into multiple geological formations at a storage site; a saline aquifer (upper reservoir) and a depleted oil field (lower reservoir). Image courtesy Shell (Tucker 2018).

The identification of storage sites requires exploration to characterise and assess potential storage sites. The CO₂ Storage Resources Management System¹² provides a consistent approach to describing projects and associated storable quantities, progressing from Prospective Storage Resources to Commercial Capacity. An assessment of Total

Storage Resource for Europe has been attempted through several research projects. Where data is available, CO₂ storage resources have been identified through European

research projects such as FP7 CO₂StoP and H2020 ESTMAP. These are displayed on the EGDI platform¹³. Data availability and maturity of assessment varies.

Potential storage sites or stores need to fulfil the essential criteria of having sufficient commercially accessible capacity for the desired quantities of CO₂. This capacity typically comprises well-connected natural spaces (pores/fractures) within the rock. The other prerequisite for a potential geological store is that there must be high confidence the

¹² Society of Petroleum Engineers. "CO₂ Storage Resources Management System" (2017).

¹³ Website of the European Geological Data Infrastructure. [Map viewer](#).

injected CO₂ will remain securely trapped within the storage site, which is usually provided by an overlying impermeable seal that can trap the buoyant CO₂. Additionally, storage sites are usually selected such that lateral movement of the CO₂ is restricted by the structural or storage formation rock properties of the geological trap, as lower permeability barriers reduce the area potential for lateral migration beyond storage complex boundaries and therefore, the area that needs to be characterised and monitored to provide assurance that the CO₂ is securely stored. To enable efficient use of the potential capacity, geological CO₂ storage sites are usually selected so that CO₂ is stored at sufficient pressure to be in a dense liquid-like phase (typically below approximately 800 m).

For stores with sufficient capacity, the next consideration is how much of the pore volume can be utilised in a technically and economically viable way. This is largely controlled by the permeability (connection between spaces within the rock) and connectivity of the store to surrounding rock bodies. CO₂ injection will increase pressure within the storage reservoir. The impact of this pressure increase will depend on the connected space within the storage reservoir, which may extend far beyond the limits that will be reached by the injected CO₂. Pressure increase will be more rapid in stores that have nearby impermeable barriers. Connectivity of the storage reservoir that allows outflow or inflow of fluids is also important: if a potential store is well connected, then injected CO₂ can more easily displace native pore fluids (mostly salty water) increasing storage potential. The pressure increase may raise pressure above the initial pressure of the store. Assessing usable storage capacity therefore requires

consideration of pressure support and permeability barriers.

ETI (2016) and Tucker (2018) categorise stores in terms of connectivity and discuss associated implications¹⁴¹⁵. A summary is presented here:

- Fully confined (or closed) stores; storage reservoir is hydraulically isolated and the CO₂ is trapped by structural/stratigraphic permeability barriers (Figure 2b). Where hydrocarbons have been extracted from such stores, low reservoir pressures can result. Where these structures are filled with brine, pressure management will be required to avoid increasing pressure to the point where trap integrity is negatively impacted.
- Partially-confined (or open) stores; where buoyant CO₂ is trapped by structural and/or lithostratigraphic boundaries but hydraulic connection enables pressure equilibration over time. Geological permeability barriers retain the buoyant CO₂ within a confined area (Figure 2a). These traps may contain (or may have contained) hydrocarbons and may be connected to a large saline aquifer system. As oil and gas are extracted, depending on the connected aquifer, pressure may be (partially) maintained as saline water flows into the trap to replace the hydrocarbons. Pressure support via hydraulic connection to the trap will affect CO₂ storage capacity and injection strategies.
- Unconfined stores; CO₂ is injected at depth into a large hydraulically connected storage formation. CO₂ is retained through dissolution and

¹⁴ Energy Technologies Institute. [“Progressing Development of the UK’s Strategic Carbon Dioxide Storage Resource”](#) (2016).

¹⁵ IOPscience. [“Carbon Capture and Storage”](#), Tucker (2018).

residual trapping (i.e. CO₂ left behind as the plume migrates – Figure 2c). Where these potential stores have a high degree of hydraulic connectivity, careful resolution of issues, with regard to lateral confinement and the main mode of trapping the CO₂ underneath the seal, is required.

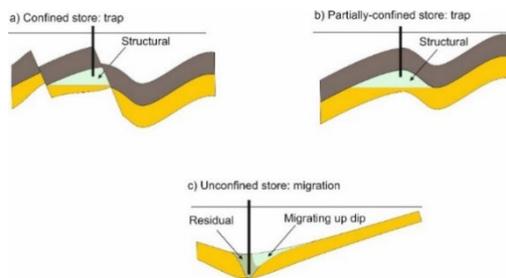


Figure 2: Storage categories (Tucker, 2018), courtesy Shell

For open and partially open stores, the pressure footprint will be larger than the CO₂ footprint and the implications of this in terms of storage integrity and impacts on adjacent users of the subsurface require consideration.

3.2 Depleted hydrocarbon fields, without pressure support (confined stores)

Where the pressure has been reduced, this offers the opportunity to achieve high storage efficiency since the pore space is readily available. One challenge where hydrocarbon fields lack pressure support is if very low pressures have been achieved as a result of hydrocarbon extraction. In this highly depleted case CO₂ injection strategies are required to avoid solid hydrates forming at the injection point. In confined stores the monitoring requirements are very simple since the CO₂ is contained in the original “closed box”. The injection operator can also elect to leave the store at a reduced pressure (below that of the water pressure in the surrounding rock

formations – termed sub-hydrostatic) if they so choose. In theory a simple pressure gauge and application of a variation of the ideal gas law can completely monitor such a store.

A key advantage of depleted fields without pressure support is that high injection rates are possible without risk for too high local pressure (as no water has to be pushed away) nor a risk of unstable displacement and potential escape of CO₂ under any spill point. Confined stores, where the final pressure is maintained below hydrostatic, reduce the chance of CO₂ escaping during injection as any well-related open pathway will see fluids flow into the store. After closure the well pathways are plugged and geological pathways will have been excluded by characterization helped by the fact that the gas field existed and was demonstrated to be highly depleted. It is possible to inject above initial pressure till near the formation strength of the caprock seal, but there is not much scope for expansion due to rapid pressure rise per injected mass. Examples of confined hydrocarbon stores without pressure support are the P18-2 and P18-4 proposed storage sites of the PORTHOS project in Rotterdam.

3.3 Depleted hydrocarbon fields, with pressure support (partially-confined stores)

Hydrocarbon fields may contain oil, gas, condensate or a mixture of fluids. These stores are generally at least partially confined since in an open hydraulically connected volume, hydrocarbons will migrate until trapped by structural/stratigraphic features. The ability for the store to trap buoyant fluids over geological time scales is often considered proven by the presence of hydrocarbons.

Where hydrocarbons have been extracted, pressure is usually reduced compared with the initial pressure which presents the opportunity to inject CO₂ until the initial site pressure is reached. This is generally viewed as a positive aspect since the trap has proven integrity at the initial site pressure (provided the seal has not been damaged by the reduction in pressure during hydrocarbon operations which is extremely rare and unlikely). Medium to strong pressure support can reduce available capacity if the aim is to reach initial pressure of the storage reservoir. However, as long as some overpressure is permitted, strong pressure support is excellent for storage because it demonstrates the ability to dissipate pressure (what flows in quickly can flow out quickly). In order to optimise use of the potential store, where data and models indicate trap integrity will be maintained, there is the potential to inject substantial mass above the initial pressure (little pressure increase per injected mass).

Sites with pressure support (depleted hydrocarbon fields, partially confined aquifers) can achieve good storage efficiencies owing structural storage (buoyancy compared to water helps) but typically require lower injection rates and/or more wells as the water that invaded the field has to be carefully pushed back out.

A major consideration when evaluating re-use of hydrocarbon fields for CO₂ storage is legacy wells. These may need to be re-entered and decommissioned to ensure storage integrity – at times this can require drilling of intersection wells as the practice of leaving a clean seabed (safety and environmental reasons) means that once a well has been decommissioned offshore it is not possible to reattach. Onshore it can be done but excavation and a process termed “reheading” a well. This is not a simple or low-cost operation. For increased storage

resource (residual and dissolution trapping as well as structural trapping) CO₂ injection wells might aim for the deeper flank of the structure or stratigraphically deeper, but hydraulically connected parts of the storage reservoir or re-use of existing wells and top-down filling of the trap is also an option and can result in lower exposure to geological risk and salt precipitation challenges.

Well completions also need to consider the implications of the mixing of CO₂ and reservoir fluids. An additional consideration is to assess if there is the possibility for hydrocarbons to migrate out of the trap as CO₂ is injected. A special case worth mentioning for storage in hydrocarbon fields is the potential pressure implications if CO₂ is injected into depleted regions of hydrocarbon fields where other regions are still producing if these areas are in pressure communication.

Data and models from the hydrocarbon production history will inform and provide confidence in models of the site response to CO₂ injection. Hydrocarbons and CO₂ can result in a similar response from some geophysical techniques therefore monitoring CO₂ injected into depleted hydrocarbon fields requires a different monitoring programme to saline aquifers. The risks are, however, different as mentioned before: a depleted field is a trap that has held hydrocarbons often for millions of years.

3.4 Producing hydrocarbon fields

Injection of CO₂ into hydrocarbon fields can be used to accelerate recovery rates through pressure support or by reducing viscosity of the fluid moving through the reservoir. The Directive does not regulate this activity, but states that, in case CO₂ storage is an objective

in an enhanced production project, the Directive provisions for environmentally safe storage of CO₂ should apply. Some discussion on 'blended storage' is included later in this report. At the moment, no Enhanced Oil Recovery (EOR) projects are operating under the Directive, i.e., projects injecting CO₂ with the additional objective of storing CO₂.

Experience from the USA, where CO₂ is injected into the Denver Unit of the Wason field and is qualified for storage under the Environmental Protection Agency Part RR regulation, is that the monitoring programme for operating the EOR field was sufficient for storage monitoring. This is, naturally case specific, but an operating EOR field collects a lot of monitoring information to ensure that the economic objectives are achieved so it is likely that only small modifications to this will be sufficient for CCS Monitoring, measuring and verification (MMV).

3.5 Saline formations (partially-confined stores)

Saline aquifer stores can be open formations or structural/stratigraphic traps. Saline aquifers are generally believed to offer the largest storage capacity. There are generally fewer data than for hydrocarbon fields due to fewer commercial opportunities and therefore aquifer stores generally have greater uncertainty that needs to be resolved through site investigation, and unfortunately (for operators and funders wanting pre-startup confidence of sustained injection rates), often during the early years of injection.

CO₂ injection would be expected to raise pressure above initial levels owing to the presence of native brine. Where confined, brine production may be necessary to manage pressure in the storage reservoir (this is the

case for the Gorgon CO₂ store in Australia). At the depths considered for CO₂ storage, the reservoir fluids are usually much 'saltier' than seawater, with associated disposal considerations. Pressure support and permeability barriers would control achievable injection rates and storage capacity.

The contrast in properties between brine and dense phase CO₂ is an advantage for monitoring. In addition, in aquifers that are not near to exploited oil or gas resources, there are generally few or no legacy wells, avoiding the requirement for extensive well re-completions. However, it must be noted that although there are normally many fewer wells, unfortunately these wells can often lack deep isolation plugs – there was no risk of hydrocarbon leakage so only shallow environmental plugs may have been installed. This means leakage paths via legacy wells must also be carefully assessed for saline formations. Sleipner is an example of a partially confined aquifer store, here the size of the store and reservoir properties are such that water production has not been necessary.

3.6 Saline formations (unconfined stores)

Where a large saline aquifer without permeability barriers is being considered for storage, CO₂ is retained through residual trapping and dissolution trapping as the plume migrates. CO₂ dissolves rapidly into contacted native brine pore fluids till the brine is CO₂ saturated then the process slows almost to a halt (it can be forecasted to continue on a millennial scale!).

As a result of the large hydraulically connected volume, pressure impacts would be expected to be minimal, unless there are undetected permeability barriers. The location of the CO₂

plume would need to be tracked to verify modelling predictions and confirm location of the plume with respect to geological and manmade (wells) potential leak paths. Saline formations, like depleted fields, may also be penetrated by legacy wells and these wells may need re-completion to ensure security of storage.

3.7 Risk-led management through monitoring, modelling and verification

Risk-led site management seeks to ensure secure storage of CO₂ by managing and mitigating the identified risks at a specific site. Many risks will be common to all storage sites, but the mitigation techniques and the available data to inform risk management will vary (Table 1). Risk also varies over time as data is collected during CO₂ injection and the response of the site is proven. There is a common perception that geological risk is highest at the cessation of injection (when pressure is at its highest), however, this will be mitigated by data collected during CO₂ injection. Uncertainty in the ability of traps in saline aquifers to contain the CO₂ is higher compared with traps in hydrocarbon fields that have been proven to trap buoyant fluids of geological timescales.

Monitoring storage sites enables operators to provide assurance that the CO₂ is securely trapped and that the site is responding as expected (Table 2). The monitoring footprint of the site will depend on the extent of the expected impacts of CO₂ storage and the identified risks for CO₂ migration out of the storage trap, here the benefit of fully/partially confined stores is clear.

An iterative loop between data collection (monitoring) and modelling will show improving confidence that the storage site is well understood and ultimately that it can be safely decommissioned after cessation of injection. A catalogue of monitoring techniques is provided by IEAGHG¹⁶. The maturity of these techniques in terms of application to CO₂ storage site varies from proven to experimental. There is no shortage of techniques either adapted from decades of hydrocarbon exploration and production or developed specifically for CO₂ storage sites. The applicability of these techniques to storage sites will vary depending on the geological characteristics and fluids within the reservoir. It is common for the range of monitoring tools to reduce over time as understanding of the storage site increases and the value of techniques is proven at a specific site.

¹⁶ Website of IEA Greenhouse Gas. [Monitoring Selection Tool](#).

Table 1: Summary of risks most applicable to various storage types

Depleted field storage, no pressure support	Depleted field storage with pressure support	Partially-confined saline aquifer formation storage	Unconfined saline aquifer storage
If fully isolated with no hydraulic support: pressure will be lower than surrounding rock including after injection ceases (operator choice), near-zero containment risk.	If substantial or full hydraulic support then pressure may remain close to hydrostatic and to the pressure in surrounding rocks.	Pressure at or greater than surrounding rock during injection, pressure equilibration after injection ceases: risk of loss of containment highest at end of injection (highest pressure); then slowly decreases.	Pressure impacts expected to be small unless permeability barriers are present .
CO ₂ fully contained by structure. Selection of storage site always on integrity basis.	CO ₂ may migrate outside the original gas/oil location and the storage site needs to include the region to which the CO ₂ (and hydrocarbons) might migrate.	CO ₂ may migrate outside the original gas/oil location and the storage site needs to include the region to which the CO ₂ might migrate.	CO ₂ not contained by structure; plume tracking required.
Boundaries ensure CO ₂ location is fully constrained, differential pressure keeps CO ₂ in place. CO ₂ tracking serves limited to no purpose – this is a closed box with gas in it.	CO ₂ tracking to confirm location over time and demonstration of trend toward gravity stable equilibrium.	CO ₂ tracking to confirm location over time. CO ₂ tracking to confirm location over time and demonstration of trend toward gravity stable equilibrium.	Lack of boundaries requires CO ₂ tracking to establish location over time and allow prediction of rate of migration and ultimately forecasting of plume stability and progress toward leak risk areas.
Injection and legacy wells are the only feasible potential leak pathways and these can be monitored by simple point monitoring techniques (onshore and offshore). Only if pressure is increased above initial (or there is significant flow into the system leading to recharge) is leakage possible – and again this should be of a point source nature and detectable.	Injection and legacy wells are once more the largest leak risk. Monitoring during injection can demonstrate the absence of leakage.	Injection and legacy wells are once more the largest leak risk. Monitoring during injection can demonstrate the absence of leakage.	Injection and legacy wells are once more the largest leak risk. Monitoring during injection can demonstrate the absence of leakage.

Table 2: Summary of monitoring requirements for various storage types

Depleted field storage, no pressure support	Depleted field storage with pressure support	Partially-confined saline aquifer formation storage	Unconfined saline aquifer storage
No plume. CO ₂ mixes with residual gas or oil inside sealed structure.	Plume (CO ₂ + hydrocarbons) to be monitored if it will extend beyond original hydrocarbon location (e.g. seismic).	CO ₂ plume to be monitored to prove stability (e.g. seismic).	CO ₂ plume to be monitored to confirm it has not migrated outside the area predicted by modelling (e.g. seismic or observation wells, possibly with geochemical sampling).
CO ₂ does not displace water. CO ₂ blends with gas or oil. There is no plume. 3D seismic cannot differentiate between CO ₂ and gas but there is the possibility to inject into the water leg to improve residual trapping and increase storage resource by enhanced dissolution, then CO ₂ plume would be visible.	Blended CO ₂ + hydrocarbon plume displaces and dissolves into water. There is a plume which can be tracked with 3D seismic and maybe observation wells.	CO ₂ displaces and dissolves into water. There is a plume which can be tracked with 3D seismic and maybe observation wells. There is a plume which can be tracked with 3D seismic, also post-injection.	CO ₂ displaces and dissolves into water. There is a plume which can be tracked with 3D seismic and maybe observation wells. There is a plume which can be tracked with 3D seismic, also post-injection.
Boundaries ensure CO ₂ location is fully constrained. Differential pressure keeps CO ₂ in place. Monitoring requirement significantly reduced, pressure monitoring required.	CO ₂ tracking to confirm location over time.	CO ₂ tracking to confirm location over time (e.g. seismic).	Lack of boundaries requires CO ₂ tracking to establish location, hence monitoring requirement.
Monitoring of injection (annuli and well pressures) and legacy wells (surface locations) to demonstrate that there are no active flow pathways to atmosphere or water			

4. Transition from production to storage

Since depleted hydrocarbon reservoirs are becoming highly attractive for CO₂ storage projects, the transition from previous production to future CO₂ storage activities needs to be planned in an appropriate manner.

A hydrocarbon operator is obliged to place human and environmental safety at the forefront of their plans. In addition, operators aim to reduce cost once an asset reaches the end of its life. This means that operators seek to safely decommission wells and infrastructure as soon as possible after the end of production operations. Even after hydrocarbon production has ceased it can still cost millions of euros per year to maintain a platform, and even more to upgrade facilities to make them ready for further decades of service for CO₂ injection. Note too that every visit to an offshore facility or every marine survey place staff at risk – this risk is managed to as low as reasonably practicable (ALARP) but still exists. The first step in the safety pyramid is to avoid the activity that creates the risk. At the end of hydrocarbon production rapid removal is always beneficial, as the older the platform the more corrosion takes place on legs and topsides. Finally, the safest well is a plugged and abandoned well. As a result, there has to be a compelling reason for a production operator not to remove infrastructure as rapidly as possible.

This preference for rapid removal is at odds with the desire to adapt multiple platforms and wells for CO₂ storage service in an orderly and planned way. Some facilities might need to wait many years before conversion to CO₂ storage duty.

Regarding this topic, three potential cases have been identified, which range from the situation where the current operator aims to stop its current activities (Case 1), intends to continue, and start a CCS-project (Case 2) or is blocking the current license (Case 3).

Case 1

It is assumed that the current operator aims to stop activities in the current production license area.

The intent shall be reported to the authority upfront, such that other plans can be made, and slack can be avoided. Smart handling with regard to decommissioning is crucial as infrastructure from hydrocarbon production might be needed for later CCS projects. Cost efficiency needs to be checked first, as certain activities can only be done (from a cost efficiency point of view) for a certain amount of time, e.g., mothballing. In any case, decommissioning obligations must certainly be taken over, although the precise actor responsible for the takeover needs to be discussed. Since hydrocarbon operators often cooperate with partners for their activities, they also need to decide if they wish to stay in the field or leave, since CO₂ storage might not be part of their core business. In case they decide to leave, there needs to be a discussion on how they will be reimbursed for the value of their assets (i.e., platform, wells, remaining production left in the ground) and whether/to whom they must pay the latest estimates of decommissioning (some of this is already covered in hydrocarbon law). At this stage it needs to be noted that CO₂ high pressure decommissioning is always much more expensive than depleted pressure gas decommissioning driven mainly by the need for full bore formation plugs.

Tax leakage is a topic that must be addressed. In some jurisdictions petroleum tax is much higher than standard corporation tax. Operators are allowed to reclaim the cost of decommissioning against profits taxed in earlier years. If the facility is transferred to a CCS operator which might be exposed to lower taxation, tax relief for decommissioning might be lost. How will operators who leave the partnership be assessed for decommissioning costs when tax leakage is involved? According to Article 6.1 of the Directive, Member States shall ensure that no storage site may be operated without a storage permit [...], and that no conflicting uses are permitted on the site. A carve out of the storage site from the production license is therefore best done at production cessation. The storage site is officially part of a storage license when in force, which it is likely to be on the day of first injection many years later. So, there is a period with the storage site outside any permit, but decommissioning and other liabilities for the closed reservoir, wells and maybe platform (if dedicated to single reservoir) must sit somewhere. It therefore needs to be decided what liabilities sit with owner of assets and which with production or storage license holder. If everyone agrees to do a simultaneous carve out/carve in, it is highly recommended to go for the required preparations well in advance to avoid having the carve out / carve in procedure delay the first injection.

The following recommendations are made for Case 1:

- The intent of the current operator (and potential joint venture (JV) partners) shall be reported to the CA upfront, such that other plans (e.g., re-use of existing infrastructure instead of decommissioning) can be made and slack can be avoided.
- The CA needs to decide on liabilities of asset owners and production license holders.
- A clear pathway needs to be developed such that any future storage operator is able to access the information required to undertake site appraisal activities (e.g., re-use of wells, well maintenance records, annulus pressure data, reservoir performance etc.).

Case 2

It is assumed that the current operator aims to stay and start a CCS project within the current production license area.

In any case, existing joint-venture partners need to be taken into account and will have to agree to give the production license back or become partners on the new project. Reactions from joint venture partners can vary between being extremely eager (they may even wish to take over operatorship of the storage permit), to wishing an immediate (and profitable) exit. A discussion about the costs and reimbursements will follow. Reimbursement could be made either for share of the remaining production value left in the ground, or for assets "value" by being relieved of decommissioning liability (*see paragraph on tax leakage above*) by the receiving party. Another open question might, however, arise if none of the existing partners are interested in a participation. In this case it needs to be defined who will be taking over their shares. In case there are no other interested parties, this role might potentially have to be taken by the State to ensure further progress in CCS. Eventually, other industrial partners may get on board, e.g. via an application or bid round.

In addition, potential competition might come from third parties that also want to start a CCS project within the same license area. In such a case, the CA needs to have smart strategy to evaluate all available project plans and therefore ensure that the permits are granted on the basis of objective, transparent and non-discriminatory criteria. Proof of the technical competence of the potential operator(s) certainly is an essential part of the storage application process (Article 7.2). The current operators are very likely to have an advantageous position here, based on their long-term activities and experience in the field, however, there is no priority to them according to the law. Based on the subsurface know-how they have gathered over the years, there's most likely also no need for them to first apply for exploration storage license to generate the information necessary for selection of storage sites.

Somewhat more clarity is needed on the priority given to exploration license holders, as indicated in Article 6.3 in the Directive. Except for Norway, where the storage license system is legally independent from the petroleum license system, it must be clear that a storage exploration permit cannot be awarded or held for a potential storage site that is already producing and part of an existing production permit. The latter seems obvious, especially when referring to those parts of the Directive where it is given that Member States shall ensure that no conflicting uses of the storage complex are permitted during the period of validity of the permit. However, it is not specifically mentioned.

There is the interesting case where a storage license is sought for a stratigraphic unit that is different from the hydrocarbon producing unit. In the Norwegian Northern Lights project the Johansen formation is deeper than the Sognefjord formation from which the Troll field produces. Exploration license 001 – the first exploitation license issued under the Norwegian CO₂ storage regulations – does not really overlap with the Troll production license, but the CO₂ plume is expected to ultimately (after Troll ceases production) migrate to under the Troll field. In the UK the Strategic CO₂ storage appraisal project (UK Strategic Storage Appraisal Project UK SSAP, funded by DECC) identified a potential Bunter store overlying the deeper producing Schooner field.

Apart from the exception given by the Norwegian system, competition can generally be for open acreage, or returned production license areas, but never for potential storage sites inside existing production licenses (in the same stratigraphic interval), to ensure no conflicting uses of areas with granted licenses. Where a store is in a different stratigraphic interval, questions start to arise around decommissioning of wells that potentially penetrate the store. It is recommended that MS consider the consequences of overlaps and make it clear where responsibility lies for zonal isolation so that storage potential is not damaged. Similarly, injecting CO₂ near or above a producing field can alter the pressure

conditions in the annuli of existing wells, potentially causing sustained casing pressure, CO₂, or brine flow to surface, and even integrity issues. These co-location issues should be discussed, and ideally addressed in Guidance Documents and ideally also in local legislation.

The following recommendations are made for Case 2:

- The existing joint-venture partners need to be asked upfront to agree to give the production license back or become partners on the new project.
- In case existing partners do not want to continue, the State might decide to step in (or alternatively find new partners) by taking over their shares to ensure further progress in CCS.
- In case of competition between the current operator and interested third parties, the CA needs to have smart strategy to evaluate all available project plans and therefore ensure that the permits are granted based on objective, transparent and non-discriminatory criteria.
- It is recommended that competition shall be limited to open acreage, or returned production license areas, but never for potential storage sites inside existing production licenses (in the same stratigraphic interval), to ensure no conflicting uses of areas with granted licenses.
- The GD, and ideally also MS, should provide more clarity regarding consequences and responsibilities in case of a storage site being used in a different stratigraphic interval (with regard to decommissioning of wells, zonal isolation to avoid damaging storage potential etc.).

Case 3

It refers to the situation of an existing operator blocking a license, which in any case should be avoided to guarantee continuous progress in the energy transition.

This case might explain why there is no clear priority given to current operators in the storage application process. To overcome this potential standoff, it is recommended that operators holding production licenses are asked to annually publish their plans (or lack of plans) for CO₂ storage for every field, especially those listed and ranked high in a national CO₂ potential storage database kept up to date by a national authority. Guidance on how to manage a field, and its abandonment, to enable future CO₂ storage should be published. These should include subsurface isolation strategies as well as data acquisition recommendation.

Such a guideline would support further progress in the future of CCS. In case operators are reluctant to store CO₂ it is recommended that they shall annually publish their estimate of production cease date and agree with the CA to market/advertise/offer high ranking fields long in advance of production cease. This means that data in huge quantities are being made available to interested parties, e.g., through CO₂ storage exploration licenses, and operator/JV parties (who may be interested), being obliged to negotiate/plan/submit storage permit applications.

The following recommendations are made for Case 3:

- It is recommended that operators holding production licenses are asked to annually publish their plans (or lack of plans) for CO₂ storage for every field, especially those listed and ranked high in a national CO₂ potential storage database kept up to date by a national authority, ensuring data is appropriately archived where a field does not immediately transition to a storage site.
- A guideline should be published to provide advice on how to manage a field, and its abandonment, including subsurface isolation

strategies as well as data acquisition recommendation.

5. Closure and transfer of responsibility

Closure and subsequent transfer of responsibility to the CA is allowed by the Directive when all available evidence indicates that the stored CO₂ will be completely contained, when financial obligations have been met (Article 20 – financial contribution to post-transfer costs), when the site has been sealed and the injection facilities have been removed, and after a minimum period after closure, no shorter than 20 years (unless otherwise agreed with the CA).

Different storage sites have differing risk profiles. The difference in the risk profiles of the various storage types show that the criteria for transfer of responsibility should primarily be based on technical merits (elements of evidence showing that CO₂ will remain safely stored) rather than on a minimum period. For instance, depending on confinement, the time to reach plume stability may vary immensely: it should be rapid in the case of a depleted reservoir without pressure support, while it can take years in stores with pressure support. For a structural/stratigraphic store it would be better to use the term “approaching a gravity stable equilibrium” rather than “plume stability”.

The 20-year minimum monitoring post closure and before transfer of responsibility to the CA and 30-year monitoring contribution post transfer to the State are regarded as very unhelpful when trying to justify investment in CO₂ storage. It would be much more helpful if the GD could lay out the framework in the context of the relevant risks, so that the CA agrees first the criteria for demonstration of permanent storage and then agrees the format of the post transfer to the state monitoring, if any.

Any reference to minimum periods should be removed or ignored – there is no universal technical justification for such periods. Each store should be evaluated in a site-specific manner, examining the evolution of containment risk over time, and the effect of conformance and containment monitoring during project life on constraining the forecast bounds of the risk evolution.

The recommendation is therefore that criteria for demonstration of permanent storage are discussed and agreed with the CA on a case-by-case basis. For structurally constrained storage the aim will be to demonstrate that the injected CO₂ is approaching a gravity stable equilibrium in the store, and that the well penetrations and caprock seal system are effective. If the store is in a depleted field with no appreciable hydraulic connection to the wider formations, then the pressures will not increase, barring some thermal effects, for millennia. If the store is in hydraulic connection to a wider saline formation, then the pressure might decline if the CO₂ has been injected at rates that cause a local pressure build-up or if the store was not depleted or might increase if the store has not reached hydrostatic equilibrium and is still recharging from a depleted field state.

For migration assisted storage the key is to demonstrate that the plume will not approach or interact with areas of enhanced leakage risk – this might be an obviously leaking fault zone, the end of the caprock, an outcrop, or more likely legacy well penetrations (Table 3).

Table 3: post-closure monitoring

Depleted field storage, no pressure support	Depleted field storage with pressure support	Partially-confined saline aquifer formation storage	Unconfined saline aquifer storage
<p>No useful monitoring is possible after closure.</p> <p>Delays in closure increase risk – wells are only possible leakage path. The risk of blowout is greatest when intervening in a well. An open well is always a risk.</p> <p>Min 0 years monitoring</p>	<p>Post-injection and post-closure monitoring possible – generally focused on wells.</p> <p>Min 20 years + min 30 years, or shorter if progress toward gravity stable equilibrium can be demonstrated.</p>	<p>Post-injection and post-closure monitoring possible – generally focused on wells.</p> <p>Min 20 years + min 30 years, or shorter if progress toward gravity stable equilibrium can be demonstrated.</p>	<p>Post-injection and post-closure monitoring possible.</p> <p>Min 20 years + min 30 years, or shorter if stability of plume can be proven or if it can be shown that conformance is calibrated and that forward modelling shows no increase in risk.</p>
<p>Above-zone monitoring (overburden, seabed, water column) serves no purpose, but shallow seismic and seabed surveys may be sufficient.</p>	<p>Above-zone monitoring (overburden, seabed, water column): shallow seismic or seabed surveys may highlight catastrophic breaches, otherwise for migration out of storage complex to higher layers will not bear useful info before centuries or more have elapsed.</p>	<p>Above-zone monitoring (overburden, seabed, water column): shallow seismic or seabed surveys may highlight catastrophic breaches, otherwise for migration out of storage complex to high layers will not bear useful info before centuries or more have elapsed.</p>	<p>Above-zone monitoring (overburden, seabed, water column): shallow seismic or seabed surveys may highlight catastrophic breaches, otherwise for migration out of storage complex to high layers will not bear useful info before centuries or more have elapsed.</p>

The key in all cases is to demonstrate that the risk of a *significant irregularity* is decreasing over time. It is important to stress too that the monitoring does not start at the end of the store, it generally starts at the point of baseline characterisation and, in the case of a depleted field, starts at the beginning of production. As a result, many stores will have between 30 years and 70 years of monitoring already booked.

In all cases the characterisation process, combined with monitoring during operation, is designed to reduce the chances of catastrophic leakage to near zero. It is highly likely, therefore, that closure and handover can proceed much faster than the indicated 20 years. CCS projects require certainty – in general

the storage operator is often requested to project the cost of storage at the beginning of the project. The duration of the closure period and the nature of monitoring can impact these costs. It would be advantageous for projects if the expectation were that the provisional post closure plans and the *Financial Mechanism* (FM) were not foreseen to change (increase) in scope unless a *significant irregularity* were to occur during site operations.

6. Financial security

6.1 What is it?

Article 19 of the Directive requires that operators set up a Financial Security (FS) to be able to “*meet the obligations of the permit*”. The FS should be valid before the start of injection, after closure and until the transfer of responsibility. After the transfer of responsibility, the Directive asks for a Financial Mechanism to cover the costs, mostly of long-term monitoring. This chapter focuses on the FS.

The main principle behind the FS is that Member States should not have to pay if the operator fails in any way. Any permit awarded comes with associated requirements and so the FS should cover the costs of these requirements, in the situation where the operator is not able or willing to pay. It is useful to distinguish expected and unexpected requirements. Expected requirements are composed of:

- Eventual continuation of operations
- Monitoring and reporting during operations
- Closure of the site (including well abandonment)
- Post-closure monitoring

Unexpected requirements are those that arise in case of leakage or significant irregularity:

- Implementation of corrective measures
- Additional monitoring
- Acquisition of emission credits in case of leakage to the atmosphere or the water column.

In practice, this FS can take many forms and GD4 lists many possibilities ranging from upfront cash deposits to private insurances.

6.2 What is the issue?

The main issue with the FS is that its amount can vary a lot depending on interpretations. If MS requires a large FS, to be provided almost exclusively by the operator, this can:

- Prevent “smaller” operators from acquiring a storage permit, if they are not able to collect the funds upfront or provide enough financial guarantees.
- Increase the cost of CO₂ storage for society as a whole: providing cash upfront is not “free” and so it can be a substantial line in the operator’s budget. This means that the operator must increase its fee for storage to stay within its profitability target. In the end, if storage of CO₂ is a service to society (mitigation of climate change), then this service becomes more expensive.

There is indeed an optimal range as a too small amount of FS means that the MS will need to use public money to cover expenses if the operator just stops.

The biggest issue in determining the correct range of amount in the FS is in dealing with the unexpected requirements. By design, the likelihood of leakage or significant irregularities should be low to very low. For instance, ZEP indicated in a report a conservative value of 1.79% risk of a significant irregularity over 500 years¹⁷. We can illustrate the point with different scenarios:

- Scenario 0: operations happen as planned. No significant irregularity detected. The operator

¹⁷ Website of the Zero Emissions Platform. ["CO₂ Storage Safety in the North Sea: Implications of the CO₂ Storage Directive"](#) (2019).

fulfils all requirements of the Directive. Amount of FS needed is €0.

- Scenario 1a: operator ceases activity during injection, MS has to take over, continues operations for N years, then closes and abandons the site. No significant irregularity occurs. The amount of FS needed is equal to the cost of operations and monitoring for N years, plus the cost of closure and post-closure obligations.
- Scenario 1b: operator ceases activity during injection; MS takes over for 5 years before transferring activities to another operator. The amount of FS needed is equal to the cost of operations and monitoring for 5 years.
- Scenario 2: a significant irregularity is detected, and the operator takes the appropriate corrective measures. Amount of FS needed is € 0.
- Scenario 3: a significant irregularity is detected, and the operator fails to take the appropriate corrective measures. MS has to take the corrective measures, and then operate and close the site. Amount of FS needed is the cost of corrective measures (including ETS credits) plus the cost of operations and monitoring for N years and cost of closure and post-closure obligations.

Scenario 3 is significantly less likely than all other scenarios (assuming it is not unlikely that an operator will default), and yet is probably an order of magnitude above the others in terms of costs. For illustrative purposes, let us assume that costs for expected requirements (i.e., cost of routine monitoring, operations, and closure) is about €10 million. We make the hypotheses of two kinds of irregularities: “moderate” irregularities, which have a 1% chance of happening and may cost up to €50 million to remediate; “dramatic” irregularities, which have a 0.1% chance of happening and may cost up to €500 million to remediate. Let us also assume that the operator always defaults when there is an irregularity.

So, 90% of the time, FS needed will be zero, 8.9% of the time it will be €10 million, 1% of the time it will be €60 million and 0.1% of the time € 510 million.

If the MS requires a FS of €510 million, then it is too large for most companies, and this can impede the deployment of CO₂ storage.

On the other hand, expected costs are: $(10 \times 8.9\%) + (60 \times 1\%) + (510 \times 0.1\%) = \text{€}2 \text{ million}$; but the MS cannot accept an amount based on expected costs because € 2 million is useless 100% of the time (either not used at all, or not enough to cover any cost). This illustrates why GD4 advises against using expected costs for setting the FS.

6.3 Potential solutions

The previous part shows that it may be necessary to have separate instruments for the “expected” and the “unexpected” parts.

The main possibility to cover potentially large, but unlikely costs is to have risk-sharing mechanisms such as an insurance. Insurance schemes can be created with various shares of public and private funds. While market maturity of CO₂ storage is low, mostly public insurance schemes can provide enough leverage to help the development of CO₂ storage. Then Public-Private Partnership (PPP) can be developed when market maturity increases, and 100% private insurances can be used in a fully mature market. Public funds could be set on a European, regional (e.g., for North Sea region, or onshore western Europe) or national level. Groups of large companies such as OGCI could also help to organise such risk sharing mechanisms schemes. Such funds are mentioned in GD4.

These types of solutions are discussed for instance in the field of deep geothermal energy: see for example the H2020 GEORISK project¹⁸. Seyidov & Weimann (2020)¹⁹ show how the insurance schemes can transition depending on market maturity. The permit application for storage of the Porthos project in the

¹⁸ Website of the [GEORISK project](#).

¹⁹ Website of the GEORISK project. [Proposal for a transition in the Risk Mitigation Schemes](#), Seyidov and Weimann (2020).

Netherlands, in the depleted offshore P18-2 gas field proposes a FS fund that contains an insurance for the rare events. The preliminary response from the regulator is to accept this solution²⁰. The insurance costs appear to be M€ 25-30 (see table on page 51 of the reference). Permit annexes on the insurance costs are not publicly available.

If a shared risk mechanisms (such as insurance) is not possible, then the recommendation for individual projects, is to base the required amounts on a percentile of costs (e.g. P75 or P90), not on expected values. In the example above, it may be acceptable to cover moderate irregularities, but not large irregularities. For this to be acceptable, MS may decide to have a robust and independent review of the risks and to impose risk criteria for low probability events.

6.4 Missing definition

There is a missing definition in the Directive. It would be very helpful if a definition could be added to GD4. ‘Associated surface and injection facilities’ means the well bores, the equipment inside the wells used for injection or monitoring of CO₂ and the wellheads. These make up part of the storage site until the wells are eventually sealed and the wellheads and casing down to regulated depth removed. These do not include any equipment or installations beyond the wellheads since these play no part in sealing CO₂ underground.

Ideas:

- 1) A fund for pooled liability, which could be set up along NER or Innovation Fund lines (i.e., using emission allowances);
- 2) Create a post-closure company;
- 3) Government underwriting during early phases of CCS roll-out; and
- 4) Proper insurance system once enough CCS projects are ongoing, where ‘enough’ remains to be defined.

²⁰ Website of the Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency). [Ontwerpbesluit vergunning voor het permanent opslaan van CO₂ in het opslagvoorkomen P18-2](#) (Draft decision permit for the permanent storage of CO₂ in storage facility P18-2). Article 20.

7. Blended storage

In many European countries, mainly in the central, eastern, and south-eastern part of the continent, depleted and nearly depleted onshore hydrocarbon fields will be the primary target of first pilot and demonstration CO₂ storage projects (ECO-BASE 2017²¹, ENOS 2020²², STRATEGY CCUS 2021²³). These are usually the sites with a higher level of geological knowledge and often reduced pressure of the reservoirs, and opportunities to reduce cost by making use of existing wells and surface facilities. When compared with saline aquifers where all of this is not present, these can be much more cost effective as a climate mitigation response, though they might well be of smaller total storage resource.

Consider the case of a large gas field, still in production. In one scenario the field stops production, possibly early, and transitions to storage. The field owners need to be compensated for the lost gas production to be motivated to change the field into a CO₂ storage site. Some of the facilities need to be maintained while the field is not producing, but the old facilities can be removed, and new ones installed. In the second scenario injection starts while the field is still producing. The injectors are naturally placed as far away from the producers as possible. They might well increase pressure and CO₂ may flow to the producers. Any producer where CO₂ is detected is either shut in or diverted to a CO₂ removal unit (and the CO₂ is diverted back to injection). The downside is the need to add injection and gas separation facilities while still maintaining production facilities, but the additional produced gas sales can compensate for the

cost. In this scenario the storage project development can benefit from the knowledge and experience of the field operator and from synergies between operations. If CO₂ is recycled, additional energy is required for separation and, depending on the source of the energy, might reduce the net climate benefit compared to a pure storage operation. Similar merits can be expected for combining CO₂ storage with oil production in depleting oil fields.

Interestingly there are other benefits of the hybrid approach. Projects that look to take advantage of low-pressure depleted fields face the challenge of managing the CO₂ phase envelope and related Joule Thomson cooling. This means that they often have to have a slow start with gas phase injection or need to heat the CO₂ (requiring energy and possibly producing some GHG emissions). Early start of injection might well avoid this challenge, albeit bringing with it the potential need for gas processing and re-injection of any produced CO₂.

In an oil field combining hydrocarbon production with CO₂ injection may reduce the need for water injection to maintain pressure. In the USA some fields use CO₂ as the pressure support fluid as opposed to water, either because of water availability or reservoir or oil properties. This is CO₂ for secondary recovery not tertiary (or EOR) recovery. The downside of a switch to CO₂ support might be the need to replace all steel on surface and in wells due to risk of corrosion if the field is not already sour service (CO₂ or H₂S naturally present in the produced fluids). In some reservoirs the maintenance of reservoir pressure reduces or

²¹ ECOBASE. '[Establishing CO2 enhanced oil recovery Business advantages in South Eastern Europe](#)'.

²² ENOS. "[Towards a strategic development plan for CO2-EOR in the Vienna Basin](#)" (2020).

²³ Strategy CCUS. "[Description of CCUS business cases in Eight southern European regions](#)" (2021).

eliminates the risk of earthquakes and tremors. As the CO₂ concentration increases at wellheads the gas phase becomes less valuable or useable unless oxyburners are installed and a supply of oxygen is available, or gas treatment/sweetening is installed. The export from the installation becomes electricity and oil. The supply of CO₂ then comes from the burning of own produced gas with the oxyburner flue gas reinjected as near pure CO₂.

The second scenario is attractive, but the transition period from pure production to pure storage is, however, challenging from both technical and regulatory points of view. A supporting argument is that hydrocarbons produced with help of CO₂ injection have significantly lower carbon footprint than oil and gas produced by traditional methods (e.g., Stewart & Haszeldine (2014)²⁴), largely imported to Europe from other parts of the world. This is an important factor for the transition period before the use of fossil hydrocarbons can be fully abandoned. The Directive handles the transition period only vaguely in Article 20, as combination of Enhanced Hydrocarbon Recovery (EHR) with geological storage of CO₂. Guidance Document 2 (chapter 1.3.2) only provides general recommendations without many details that might be useful to CO₂ storage regulators. Moreover, there is no experience available in Europe concerning the transition of a producing hydrocarbon field into a CO₂ storage reservoir; this also includes the regulatory aspects of the matter. The main uncertainty relates to the conversion (or perhaps co-existence) of an existing hydrocarbon exploitation permit (production license) and a CO₂ storage permit.

There is a need for clarity about converting producing hydrocarbon fields to CO₂ storage reservoirs. While early CO₂ storage projects in Europe that use (offshore) depleted hydrocarbon fields as the storage reservoir commence injection after the end of oil or gas production, there may be advantages in merging

the tail end of hydrocarbon production with the first phase of CO₂ injection in cases where this is an option. However, future storage site operators, possible investors, as well as regulators need clear assurance that:

1. Temporary combination of CO₂ storage as described by the Directive and enhanced hydrocarbon recovery is accepted from a legal and regulatory point of view;
2. The CO₂ accumulated and trapped in the reservoir during the “blended storage” phase is considered geologically stored within the meaning of the Directive, Article 3;
3. The CO₂ back produced from the reservoir together with the hydrocarbons after CO₂ breakthrough to the production wells, captured by a gas separation unit and re-injected is still considered stored, and only the CO₂ leaked or vented from the surface facilities is reported as emitted pursuant to the Commission Implementing Regulation 2018/2066 on the monitoring and reporting of greenhouse gas emissions²⁵;
4. The back-produced CO₂ is not considered a significant irregularity or leakage from the storage complex within the meaning of the CCS Directive.

With proper oversight and with MMV programmes to ensure accounting of injected and back-produced CO₂ flows blended storage could prove a driver for subsequent pure storage. It is recommended to provide clearer guidance on the topic in the Guidance Documents.

²⁴ Scottish Carbon Capture & Storage. "[Carbon Accounting for Carbon Dioxide Enhanced Oil Recovery](#)", Stewart and Haszeldine (2014).

²⁵ Eur-Lex. [Commission Implementing Regulation \(EU\) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions](#).

8. Conclusion

The Directive sets out the requirements for safe and secure storage. It is a legal framework and, as such, it does not provide exhaustive details. Member States are responsible for interpretation of the framework, its transposition, and the application of the Directive in a country-specific manner. Both project developers and competent authorities are developing experience in translating the requirements set out in the Directive into effective and efficient practical rules. This process has been challenging for the first wave of projects.

The report presents some of the results and findings from several first-of-a-kind CO₂ storage projects that have been, or are being, developed under the Directive, for the benefit of regulators and project developers. Its authors have experience in applying for permits for CO₂ storage to the Commission. Where possible or relevant, suggestions are given to competent authorities or project developers to speed up and facilitate the development of future storage projects. In that regard the report aims to be a reliable, independent reference document for authorities and applicants, by addressing uncertainties and suggesting potential solutions.

The report does not request changing the Directive and does not identify a need for further or more detailed requirements in the Directive. Several storage permit applications have been developed under the Directive and increasing experience with regulators and project developers is already showing evidence of evolving interpretation.

The report does offer suggestions to improve the Guidance Documents, which also aim to support regulators and project developers.

8.1 Competent Authorities

One of the recurring recommendations to CA is their early engagement with project developers. CA guidance is needed in several areas.

8.2 Guidance Documents

The Guidance Documents are for guidance only, e.g., “do not represent an official position of the Commission are not legally binding”. The Directive and its requirements are legally binding. However, it allows for flexibility in relation to most concerns around post-closure responsibilities and the financial security and financial mechanisms.

Guidance Documents GD3 and GD4 have assumed storage in new deep saline formations (also known as virgin aquifers) rather than the possibility of storage in depleted hydrocarbon reservoirs. Whilst intended for guidance only, their suggestions on requirements could be misinterpreted and applied in a more stringent way to depleted hydrocarbon reservoirs than is necessary, as detailed previously in this report. For clarification in interpretation and to help avert a CA from ‘over-interpreting’ the Guidance documents for application to depleted hydrocarbon fields we suggest the addition of some text in GD3 and GD4. For GD2, it is suggested that attribution monitoring is added as a step (*see section 2*). These elements are provided in the Annex.

Annex: Guidance Documents

Relevance to storage in depleted hydrocarbon reservoirs

Guidance Documents GD3 and GD4 have assumed storage in new deep saline formations (also known as virgin aquifers) rather than the possibility of depleted hydrocarbon reservoirs. For clarification, interpretation and to help avert a competent authority from ‘over-interpreting’ the Guidance Documents for application to depleted hydrocarbon fields, the suggested amendments to GD3 and GD4 are in **bold** as follows:

“Note that the examples given in this guidance document are based upon CO₂ storage in a deep saline formation. Storage in depleted hydrocarbon reservoirs present a different risk profile and are likely to be easier to prove secure and permanent storage as required in the Directive Article 18.2(a-c), for example the Competent Authority may be able to agree a shorter minimum period for post-closure responsibilities and transfer of responsibility, as allowed for in the Directive Article 18.1(b).”

This text would be inserted at the end of the last paragraph in page 1 in GD3 and at the end of the last paragraph in section1 in GD4.

Attribution monitoring

Since the drafting of the Directive and GD2, monitoring techniques have advanced in what is known as ‘attribution monitoring’. These are a suite of techniques for surface and near-surface monitoring that enable an anomaly of higher CO₂ emissions to atmosphere or water column to be determined whether they are from the stored CO₂ or from

another origin such as biogenic sources. This is important because, as it is written, when monitoring under the Directive suspects a leak, it then triggers monitoring under the ETS Directive to quantify emissions, whether or not they are from the CO₂ storage site (Dixon and Romanak 2015).

Suggested amendments

Suggested amendments to GD2 are as follows, with new text in **bold**.

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“Environmental monitoring for leakage out of the storage complex towards, at or near the surface, on land or offshore:

- **Detection of suspected leakage anomaly;**
- **Attribution of anomaly**
- Quantification of leakage **(if attributed to the CO₂ storage project);**
- Accounting and quantification of emissions from the storage complex for surrender of emissions trading allowances for any leaked emissions under EU ETS Directive 2003/87/EC **(if attributed to the CO₂ storage project);**
- Safety and Environmental impacts **(if attributed to the CO₂ storage project).”**

Figure 5 Monitoring Plan Elements

“Environmental (Leakage)

- **Detection of suspected leak or anomaly**
- **Attribution of anomaly**
- Leak quantification
- Emissions/ETS impact

- Safety & Environmental impacts “

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Figure 6 Different methods and techniques suitable for monitoring

“Environmental Onshore

- Leak and Anomaly Detection
 - Sampling and geochemical analysis
 - Seismic
 - pressure interference
 - Soil gas
 - Vegetation stress
 - Eddy covariance tower
 - **Attribution of anomaly**
 - **Isotopic analysis**
 - **Chemical tracers (natural and artificial)**
 - **Process-based method**
- Leak Quantification
 - Soil gas
 - Surface gas measurement
 - ...
- Impact: HSE Monitoring
 - CO₂ Concentration
 - Water
 - sampling/analysis
 - Soils acidity
 - Surface deformation
 - Ecosystems surveys”

“Environmental Offshore

- **Leak and anomaly** Detection
 - CO₂ flux and concentration monitoring
 - Water sampling and geochemical analysis
 - High resolution geophysics
 - Seismic
- **Attribution of anomaly**
 - **Isotopic analysis**
 - **Chemical tracers (natural and artificial)**
 - **Stoichiometric methods**

- Leak Quantification
 - Flux gas measurement
- Impact: HSE Monitoring
 - CO₂ Concentration
 - Water sampling/analysis
 - Ecosystems surveys”

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Onshore

“For onshore sites, the strategy, issues and technology options for leakage detection and quantification will be different to offshore sites.

The detection limits of surface monitoring techniques are determined by environmental parameters as well as the sensitivity of the monitoring instruments themselves.

In near-surface systems on land, CO₂ fluxes and concentrations are determined by uptake of CO₂ by plants during photosynthesis, root respiration, microbial respiration in soil, deep natural outgassing of CO₂ and exchange of CO₂ between the soil and atmosphere (Oldenburg & Unger, 2003). Any surface leakage of CO₂ from a manmade CO₂ storage reservoir needs to be distinguished from the variable natural background (Oldenburg & Unger, 2003; Klusman, 2003a, c, **Dixon & Romanak 2015**). Analysis of stable and radiogenic carbon isotope ratios in detected CO₂ can help this process, **also chemical tracers (natural and artificial) and process-based methods**. Most techniques require calibration or comparison with baseline surveys made before injection starts, e.g. to determine background fluxes of CO₂ emissions.”

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