Securing the Underground

Managing the Risks of Carbon Storage through Effective Policy Design

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List of Abbreviations

ALDE	Alliance of Liberals and Democrats for Europe
AUV	Autonomous underwater vehicles
BECC	Bioenergy with Carbon Capture
BECCS	Bioenergy with Carbon Capture and Storage
BioCCS	Carbon capture and storage of biogenic CO_2 emissions

BUND	Bund für Umwelt und Naturschutz Deutschland (Friends of the Earth Germany)
CAN-E	Climate Action Network Europe
CC	Carbon Capture
CCS	Carbon Capture & Storage
CDR	Carbon Dioxide Removal
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CfD	Contracts for Difference
CMS	Carbon Management Strategy
CMW	Carbon Market Watch
CO	Carbon monoxide
CRA	Containment risk analysis
CS	Carbon Storage
DAC	Direct Air Capture
DACC	Direct Air Carbon Capture
DACCS	Direct Air Carbon Capture and Storage
DTL	Dangerous toxic load
EC	European Commission
ECBM	Enhanced Coal Bed Methane Recovery
ECR	European Conservatives and Reformists Group
ECSB	European CO_2 Storage Body
EDP	European Democratic Party
EEB	European Environmental Bureau
EEZ	Exclusive Economic Zone
EGP	European Greens
EGR	Enhanced Gas Recovery
EIA	Environmental Impact Assessment
EL	EuropeanLEFT
EOR	Enhanced Oil Recovery
EPA	U.S. Environment Protection Agency
EPP	European People's Party Group
ESABCC	European Scientific Advisory Council on Climate Change
ETS	Emissions Trading System
EU	European Union
GCCSI	Global Carbon, Capture and Storage Institute
H_2S	Hydrogen sulphide
HSE	Health and Safety Executive of UK Government

ICM	Industrial Carbon Management
IEA	International Energy Agency
IOPG	International Association of Oil & Gas Producers
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MAH	Major Accident Hazard
MEACP	Ministry of Economic Affairs and Climate Policy, Netherlands
MEG	Methyl Ethyl Glycol
MMV	Monitoring, Measurement and Verification
MPa	Megapascal
Mt	Million Tons
Mtpa	Million Tons per annum
N_2	Nitrogen
NABU	Naturschutzbund Deutschland e.V. (engl.: German Nature and Biodiversity Conservation Union)
NET	Negative Emissions Technologies
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NNSN	Norwegian National Seismic Network
NO_x	Nitric oxide
NZIA	Net Zero Industrial Act
O_2	Oxygen
OCNS	Offshore chemical notification scheme
PES	Party of European Socialists
PM	Particulate matter
PPP	Polluter pays principle
SCM	Storage complex monitoring
SLOT	Significant level of toxicity
SO_2	Sulphur dioxide
Ten-E	Trans-European Networks for Energy
TRL	Technology Readiness Level
UBA	Umweltbundesamt (Germany's federal environmental agency)
UNCLOS	United Nations Convention on the Law of the Sea
WWF	World Wide Fund for Nature

Summary

The urgent need to mitigate climate change has led to growing interest in Carbon Dioxide Removal (CDR) technologies, particularly those involving geological storage of CO_2. These include methods like Biomass with Carbon Capture and Storage (BioCCS) and Direct Air Carbon Capture and Storage (DACCS), which are increasingly seen as necessary to complement efforts to reduce greenhouse gas (GHG) emissions. Both the Intergovernmental Panel on Climate Change (IPCC) and German studies agree that Carbon Dioxide Removal will be critical to achieve climate neutrality, particularly in the second half of this century. However, the extent of its use is closely tied to the pace and scale of current mitigation efforts. If emission reductions are delayed, greater reliance on CDR technologies will be necessary.

Geological storage of CO_2 has gained renewed attention, though it has faced controversy. Earlier discussions about extending the life of fossil fuel power plants using CO_2 storage have faded, but the need for storage as offset for residual and negative emissions is reemerging. Current projections indicate that by 2030, the European Union aims to store 50 million tons of CO_2, with future demand likely to increase significantly by 2040 and beyond. However, the use of CDR technologies raises critical questions about their technical feasibility, economic viability, environmental sustainability, and societal acceptance.

The focus of this study is on the risks associated with the geological storage of CO_2, with a specific emphasis on offshore storage. While technologies for CO_2 capture and nature-based removals are not the focus here, the study assesses the governance structures needed to minimize risks and improve the safety and sustainability of geological carbon storage. Key risks include operational irregularities during CO_2 injection, environmental impacts on marine ecosystems, and challenges related to public perception and financial incentives. Deterring emission reductions is an important – perhaps the most important – political risk in this context. If this risk is not addressed, for example by separating targets and policies for mitigation, nature-based removals and long-term geological storage, it may be difficult to gain acceptance and public support for geological carbon storage.

1. **Regulatory and technical framework**: The EU's Carbon Capture and Storage (CCS) Directive offers a foundation for managing CO_2 storage, but there is room for improvement. Independent third-party oversight, harmonized CO_2 purity standards, and confidential reporting of irregularities are recommended to enhance transparency and public trust. A lack of regulatory standardization across EU Member States leads to inefficiencies and higher operational costs, creating unnecessary risks for project operators.

2. **Operational challenges**: Past offshore CO_2 storage projects, such as those at Sleipner and Snøhvit, have experienced operational irregularities during the injection of CO_2, leading to significant cost overruns. These experiences highlight the importance of proper site selection and injection protocols to mitigate risks. The reuse of existing infrastructure, such as pipelines from the fossil fuel industry, may seem cost-effective but often introduces additional risks due to technical incompatibility with CO_2 storage requirements.

3. **Environmental and human safety**: While offshore CO_2 storage is associated with relatively low environmental risks, they cannot be ignored. Marine ecosystems may be impacted by potential CO_2 leakage, noise pollution from increased marine traffic, and other indirect effects. For human populations, the risk of exposure to CO_2 leakage is low, but continuous and comprehensive monitoring is necessary to detect and mitigate any irregularities during storage operations.

4. **Monitoring and long-term liability**: Effective governance requires continuous monitoring of storage sites, both during the injection phase and long after closure. Independent third-party monitors should be involved in site selection, permitting, and ongoing assessments. Long-term liability

frameworks must be clear, ensuring that financial provisions are in place to cover remediation and maintenance costs post-closure. EU guidelines currently require a 20- to 40-year post-closure monitoring period, after which state authorities assume responsibility, provided that the CO_2 storage has been deemed secure.

To ensure that the deployment of geological carbon storage is both safe and environmentally sustainable, several governance enhancements are recommended:

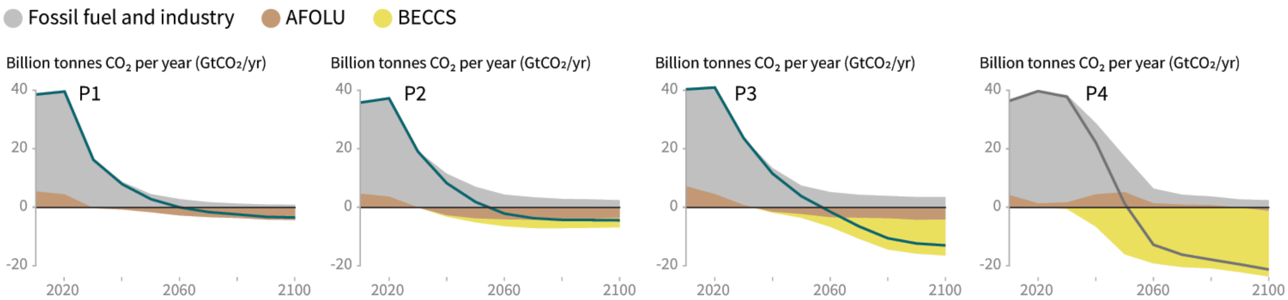
- **CO_2 purity rules**: Establishing a set of common standards for CO_2 purity across the EU would reduce regulatory uncertainties, lower operational costs, and foster cross-border collaboration. This would create a level playing field for operators and improve the overall efficiency and safety of carbon storage projects.
- **Independent monitoring**: Independent third-party verifiers, appointed by competent authorities, should oversee the monitoring of storage sites. These verifiers would increase transparency and build public confidence in the safety of carbon storage projects. Real-time monitoring systems and robust mechanisms to report and address irregularities are essential to mitigate risks.
- **Expanded environmental assessments**: Environmental impact assessments for CO_2 storage projects should be expanded to include indirect effects such as noise pollution and increased vessel traffic at offshore storage sites. Continuous monitoring of these effects should be part of the governance framework to minimize any unintended environmental consequences.
- **Integrated spatial planning**: Comprehensive spatial planning is essential to avoid conflicts with other land uses, especially in environmentally sensitive areas. For example, defining no-go zones in marine protection areas could help minimize environmental risks. Proper site selection and injection practices are crucial to ensuring the long-term success of CO_2 storage projects.
- **Post-closure financial liability**: Operators must be required to set aside sufficient financial provisions to cover post-closure costs, including potential remediation efforts. The European Commission's guidance on financial security is a step in the right direction, but it should be regularly reviewed to ensure that financial requirements keep pace with the evolving risks and costs of CO_2 storage.
- **Government involvement**: Increased government involvement in CO_2 storage projects can help address societal concerns and improve public trust. Governments can also play a key role in managing demand for CO_2 storage capacity and ensuring that storage projects align with national and regional climate goals.
- **Policy evolution:** Policymakers must remain flexible and responsive to new risks and opportunities as CO_2 storage technologies mature. Regularly reviewing and updating governance frameworks will ensure that emerging risks, such as those associated with transboundary transport and storage in environmentally sensitive areas, are appropriately managed.

While reducing GHG emissions across all sectors remains the top priority for achieving climate neutrality, geological carbon storage can play a critical role in offsetting residual emissions and achieving negative emissions, particularly in the second half of this century. By implementing the governance improvements recommended in this study, policymakers can ensure that carbon storage in geological formations is safe, sustainable, and capable of contributing to the broader goal of maintaining long-term climate neutrality. These measures will help build public trust, ensure environmental safety, and align carbon storage efforts with broader decarbonization strategies.

1 Introduction

The need to deploy industrial Carbon Dioxide Removals (CDR) which involve geological storage of CO_2, such as Biomass with Carbon Capture and Storage (BioCCS), Direct Air Carbon Capture and Storage (DACCS) and the decarbonisation of industrial processes such as cement production, is controversial. The Intergovernmental Panel on Climate Change (IPCC) assumes that CDR will most likely have to be used, especially in the second half of this century (Figure 1): "Pathways likely to limit warming to 2°C or 1.5°C require some amount of CDR to compensate for residual GHG emissions, even after substantial direct emissions reductions are achieved in all sectors and regions (high confidence)." (IPCC 2022).

Figure 1: Breakdown of CDR contributions to global net CO_2 emissions in four illustrative model pathways



Source: Masson-Delmotte et al. (2018, Figure SPM.3b)

UBA (2019) has shown in its Rescue Study that climate neutrality in Germany can be achieved solely with natural sinks (forests, carbon farming, etc.). However, this presupposes that drastic greenhouse gas (GHG) mitigation measures are implemented, which is not the case at present. Recent studies that focus on the achievement of climate neutrality in Germany by 2045 conclude that CDR will also be necessary to bring about climate neutrality (Prognos; Oeko-Institut; Wuppertal Institut 2021). Nevertheless, both the IPCC and UBA come to the same conclusion: the later and the more weakly GHG reduction measures are introduced, the greater the extent to which CDR will have to be used to achieve climate neutrality and negative emissions in the second half of this century. While GHG reduction in each sector including increased circularity and demand-side measures is the overall priority, it is becoming more and more evident that societies need to further develop the technologies and adjust the governance structures for the use of CDR.

CDR as such has therefore received increasing attention in recent years. However, the storage of CO_2 in geological formations deep underground has been somewhat under-represented in recent discussions. Geological storage of CO_2 was intensively discussed in the early part of this century in the context of extending the life of fossil fuel power plants. However, the discussion in Europe waned and only restarted when it became clear that fossil fuels would have to be phased out completely (Cames et al. 2021; Cames et al. 2022).

CDR may require significant capacities to store CO_2 geologically. In the Net Zero Industry Act (NZIA), the European Union (EU) aims to store 50 Mt CO_2 by 2030 (EC 2023). The European Scientific Advisory Board on Climate Change (ESABCC) foresees a smaller role for CO_2 storage, amounting to less than 10 Mt CO_2 in 2030, with demand increasing rapidly towards 2040 and ranging between 50 Mt and 250 Mt in 2050 and beyond (ESABCC 2023). In its modelling, the EC (2024c) assumes that approx. 280 Mt CO_2 would have to be captured by 2040 and approx. 450 Mt CO_2 by 2050 in order to achieve the targets set. According to the EC’s communication, approx. 230 Mt CO_2 should be stored in geological formations by 2040 and approx. 250 Mt CO_2 2050 (EC 2024f).

As most CDR activities have not yet been deployed on an industrial scale, several fundamental questions have been raised about the opportunities and risks associated with their potential use. These range from technical issues (e.g. feasibility, durability, and actual emission reductions of individual technologies) to economic considerations (e.g. cost per tonne of CO_2) and environmental aspects (e.g. specific material and energy requirements, resource consumption, land requirements and biodiversity) as well as possible side effects on the biosphere, agriculture, and the population. Questions have been raised about the acceptance of different technological approaches by different societal interest groups.

Against this background, this study assesses the environmental and technological risks associated with geological storage of CO_2. It aims to identify governance structures that could minimise those risks, while balancing the risks of climate change from CO_2 emissions with the environmental risks of CO_2 storage. Deterring emission reductions is an important – perhaps the most important – political risk in this context. If this risk is not addressed, for example by separating targets and policies for mitigation, nature-based removals and long-term geological storage, it may be difficult to gain acceptance and public support for geological carbon storage. However, this issue is outside the scope of this study with its focus on carbon storage. Therefore, when carbon storage is mentioned in this study, it always refers to geological storage, unless explicitly stated otherwise.

While carbon storage may include both onshore and offshore storage in the long term, the current discussion focuses on offshore storage. In principle, the basic technical method of onshore storage is similar to that of offshore storage. Nevertheless, onshore storage also has specific challenges and advantages, such as being closer to human agglomerations but also involving shorter transport distances. As the current discussion on geological storage of CO_2 focuses on offshore sites, however, onshore storage is not specifically addressed in this study. Our analysis also includes some consideration of the risks associated with transporting CO_2 to storage sites but does not address the issues and risks associated with CO_2 capture or other types of removals, such as nature-based removals.

This study begins with a description of the process chain and the technical aspects of carbon storage projects (chapter 2) before moving on to a comprehensive analysis of the technological, geological, and environmental risks of carbon storage, and the basic outline of risk management approaches (chapter 3). We analyse the positions and proposals of key stakeholders in relation to carbon storage (chapter 4) before reviewing the current policy design with a view to improving the existing governance framework (chapter 5). While existing policies already provide a solid framework for managing the risks of carbon storage, governance poses more fundamental challenges, which are discussed from a bird's eye perspective (chapter 6). Finally, the study draws conclusions from the risk analysis and provides clear recommendations to policy makers on the ways in which existing legislation needs to be strengthened or updated and in which new legislation is needed to ensure the sustainable development and use of permanent storage (chapter 7).

2 Carbon storage projects

Pilot projects for the engineered injection and storage of CO_2 in geological rock formations deep underground have been conducted in the United States since the 1970s. The natural gas and petroleum industry primarily used technologies such as Enhanced Gas Recovery (EGR) and Enhanced Oil Recovery (EOR) to maximise gas and oil production by mobilising and extracting residual fossil hydrocarbons from almost depleted fossil gas and oil reservoirs that cannot be conventionally extracted (IPCC 2005; IEA 2022).

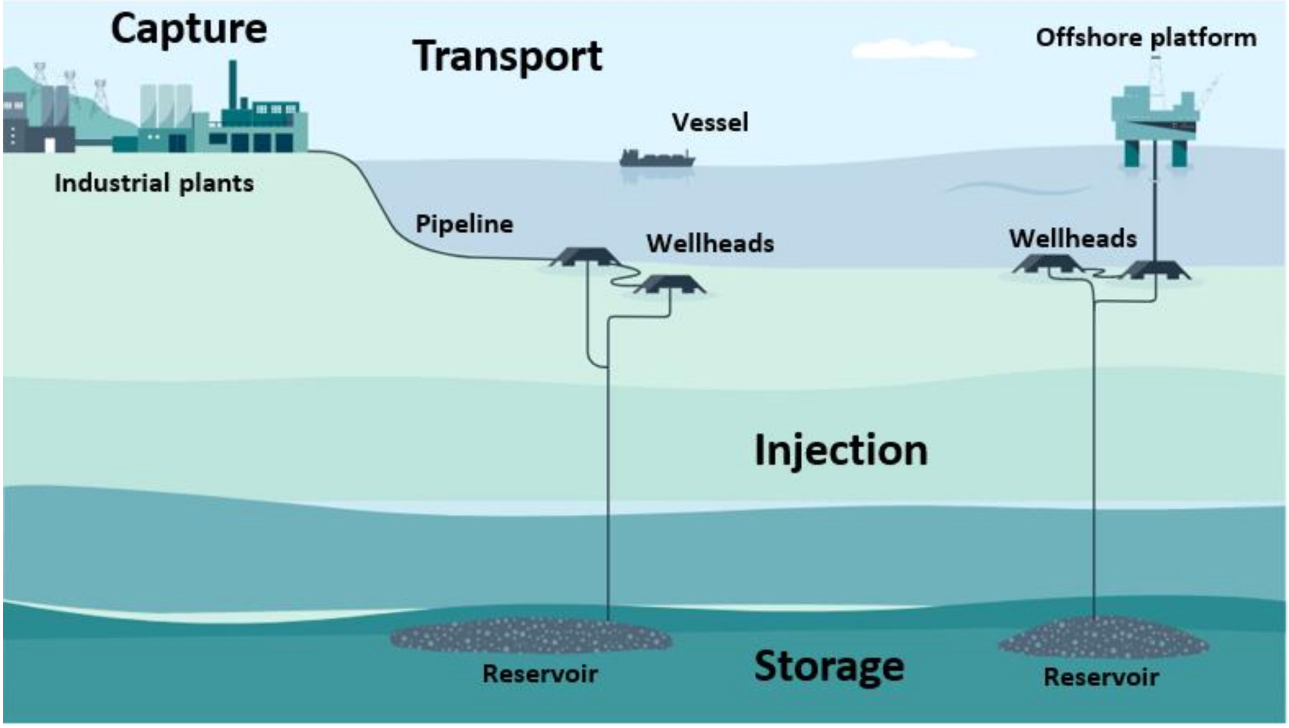
While considerable amounts of carbon are geologically stored with EGR and EOR technologies, further CO_2 emissions are inevitable due to the combustion of additionally extracted fossil fuels. Moreover, carbon storage with EGR and EOR technologies lacks storage integrity and has higher leakage rates as reservoir structures are less pristine after fossil production. Therefore, technologies like EGR and EOR tend to be net-zero emission at best, rather than providing suitable solutions for negative emission technologies (NET) (UBA 2008a; EC 2009; NABU 2022; UBA 2023b; CIEL 2023; Oeko-Institut 2023).

During the 1990s, research projects that promoted the storage of anthropogenic carbon in geological formations deep underground as part of NET emerged. In 1996, the first commercial carbon storage project dedicated solely to avoiding the release of CO_2 emissions into the atmosphere was commissioned at the Sleipner gas fields in Norway (IEA 2022). Other prominent projects followed, such as the In-Salah carbon storage project in Algeria or at the Snøhvit gas fields in the Norwegian Barents Sea (IPCC 2005; Oeko-Institut 2023; IEEFA 2023).

Carbon storage is a part of carbon capture and storage (CCS) projects. These include four process steps starting with carbon capture[1], carbon transport, carbon injection and ending with carbon storage (Figure 2). Parallel to all four steps, carbon storage projects require a comprehensive Monitoring, Measurement and Verification (MMV) Programme (IPCC 2005; May 2024).

[1] Although the process of carbon capture also involves various risks of its own, this study focuses on risks and hazards that arise during carbon transport, injection, and storage.

Figure 2: Process chain of carbon capture and storage projects



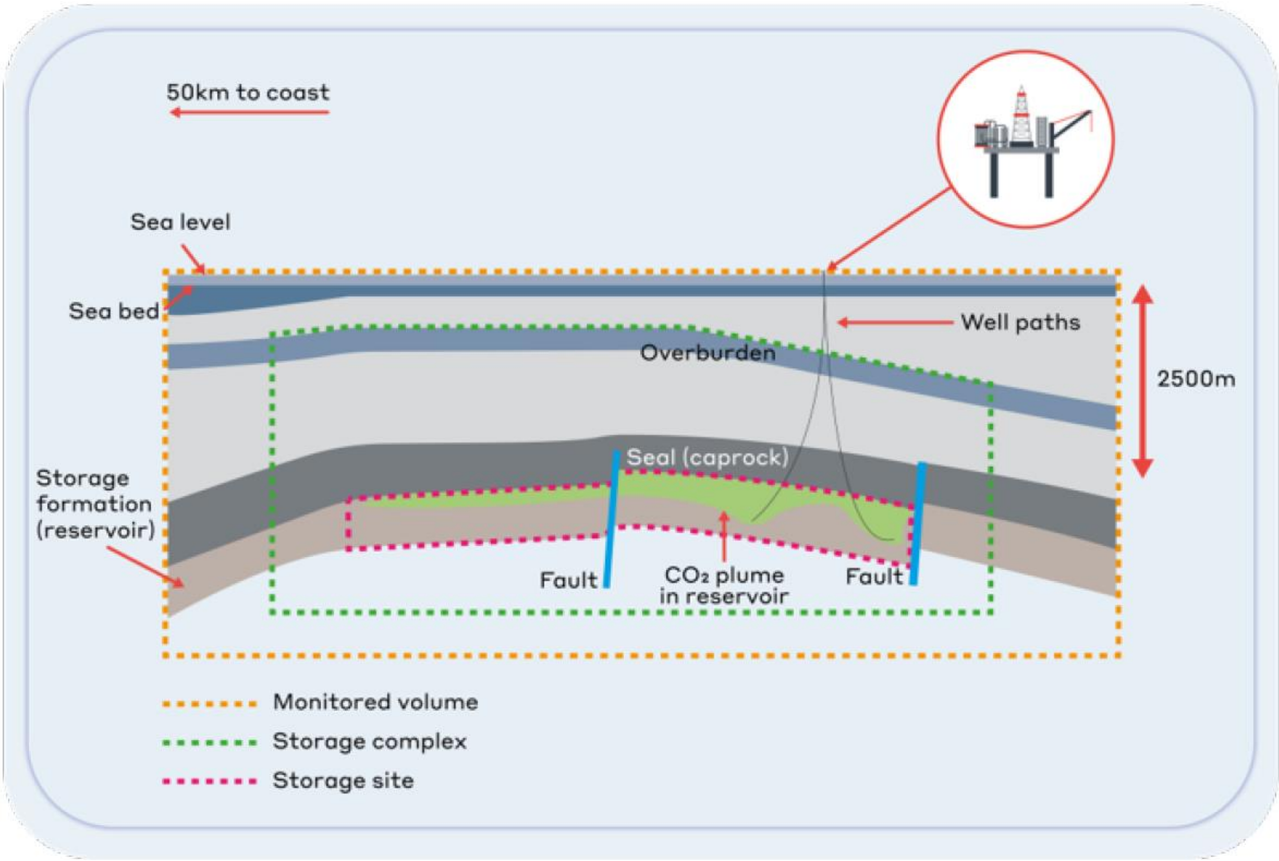
Source: Based on Equinor (2024b)

Firstly, CO_2 needs to be captured from fossil (fossil CC) or biogenic (BECC) industrial CO_2 point sources or via the direct extraction of CO_2 from the atmosphere (DACC).

Secondly, CO_2 is compressed, liquefied, and transported to the storage site (Figure 3). When industrial point sources lie far from storage sites, onshore transport is often carried out by train, truck or through pipelines (IPCC 2005). Offshore transport usually takes place via vessels or through seabed pipelines whereby CO_2 is brought to either offshore drilling platforms or to onshore receiving terminals and then transported to wellheads on the ocean floor (Figure 3). Along the process chain, CO_2 may need to be temporarily stored at industrial plants or receiving terminals (Equinor 2019). Subsequently, each state of transport or temporary storage requires that the composition of CO_2 in terms of its temperature, pressure and purity meets the ideal conditions for the process (IPCC 2005; IEA 2022).

In a next step, CO_2 is injected into geological rock formations deep underground which represent the storage reservoir (Figure 3). The storage site consists of injection facilities on the surface and the target formation in which CO_2 is stored. The storage complex comprises the geological environment surrounding the storage site, which serves as stratigraphic and structural seals (BEIS 2023).

Figure 3: Schematic structure of carbon storage sites



Source: BEIS (2023)

Conventionally,[2] CO_2 is compressed and injected via boreholes directly into the geological structures (reservoir) in the subsurface in a preferable pure[3], liquified to supercritical state (>8 MPa). Nevertheless, reservoir conditions mainly determine the purity, temperature and pressure of CO_2 during injection as rock properties like the permeability and the porosity of rocks and the prevailing pressure of formation water[4] in the reservoir can affect the amount and rate of injected CO_2 enormously (IPCC 2005; BGR 2015; Wallmann 2023; IEA 2022). For injection to be successful, the pressure of injected CO_2 must exceed the prevailing conditions in the target reservoir[5] to ensure that CO_2 remains in its dense, compressed, and liquefied phase. For successful injection, the CO_2 needs to displace the brine so that it can spread throughout the reservoir.

After injection, CO_2 migrates over time in the form of a plume through the reservoir, leaving the injection zone. Again, rock properties such as the permeability, porosity and density of CO_2 determine how quickly CO_2 moves and thus how much gas can be injected and stored. Only when CO_2

2 Recently, carbon storage technologies (e.g. Carbfix method, https://www.carbfix.com/how-it-works) have emerged which use the injection of dissolved CO_2 (as carbonic acid) into basalt and ultramafic rocks and yield for direct in-situ mineralisation, a technical approach that differs from 'conventional' carbon storage projects and is rather related to enhanced weathering technologies (Snæbjörnsdóttir et al. 2020; Clark et al. 2020). GCCSI (2021a) defines a Technology Readiness Level of between 2-6.

3 Current projects, like the Northern Lights project (https://www.equinor.com/energy/northern-lights) under the Norwegian North Sea, yield purity levels of over 95,5% for injected CO_2 and general admixtures of less than 50–100 ppm depending on the substance (Equinor 2019; IEAGHG 2011).

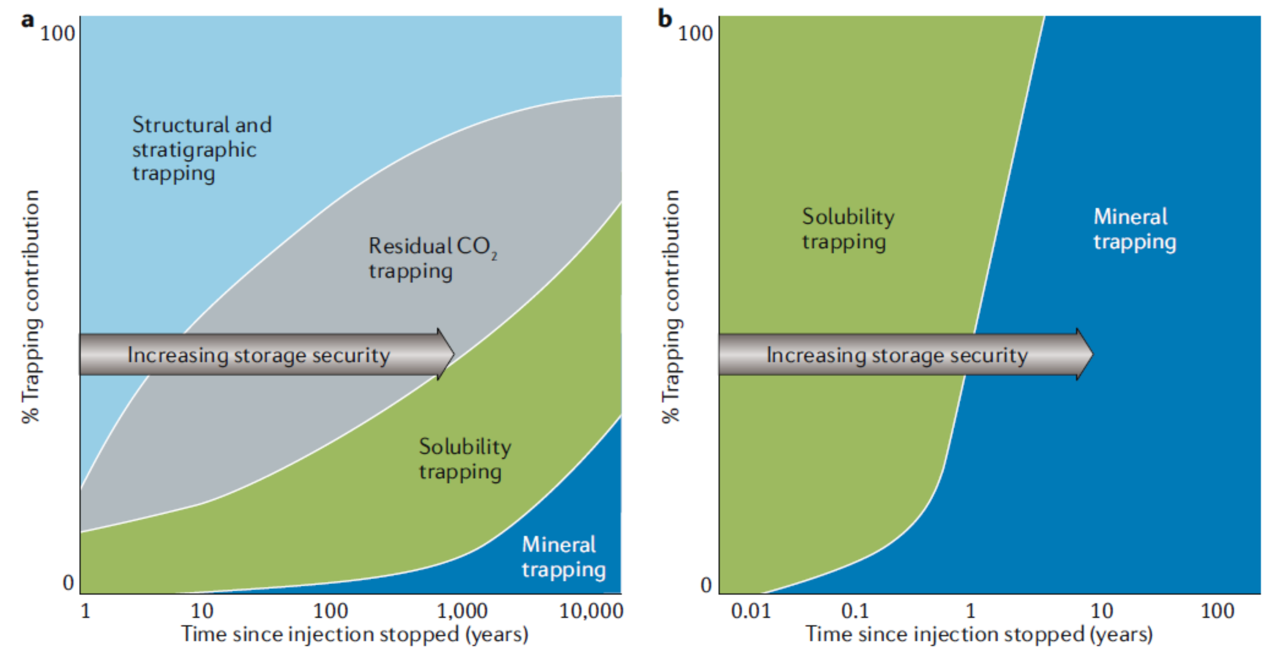
4 Formation water (or pore water) is a high salinity fluid that is displaced by CO_2 in the storage reservoir, also known as displaced brine.

5 Suitable reservoir formations usually lie at depths of over 800 metres with pressures of over 8 MPa and a temperature of around 35-40°C, conditions in which CO_2 stays in supercritical phase (IPCC 2005).

is supercritical with high density and suitable flow properties can existing pore space in the reservoir rocks be optimally used for the most efficient storage.

Consequently, a combination of physical and geochemical processes ensure CO_2 fixation and storage in the reservoir that last over thousands to millions of years (IPCC 2005; IEA 2022). These trapping mechanisms take effect at different times after injection. They contribute differently to safe containment and long-term storage security over different time scales; these contributions depend highly on the injection technique, the form of CO_2, and the geological rock properties (Figure 4).

Figure 4: Comparison of CO_2 trapping mechanisms for supercritical (a) and dissolved (b) CO_2 injections



Source: Snæbjörnsdóttir et al. (2020)

Note: Change in the contribution of the CO_2 trapping mechanism of carbon storage over time when injecting pure supercritical CO_2 conventionally into saline aquifers or depleted fossil gas and oil fields (part a) and when injecting water-dissolved CO_2 for in-situ mineralisation in basalt and ultramafic rocks (part b).

When conventionally injected in its supercritical phase, CO_2 is retained physically at first by structural, stratigraphic, and residual trapping mechanisms until the gas dissolves in formation water and solubility trapping takes effect (after several hundreds of years once the injection stopped, see Figure 4, a). When CO_2 begins to dissolve, storage security hugely increases as CO_2 no longer exists in a separate phase. After CO_2 has dissolved, it can react with minerals of the reservoir rocks leading to the mineralisation of carbonates. Once mineralised, carbon remains stable and geochemically bound in the minerals over the long term, making it the most permanent form of storage. Mineral trapping is, therefore, the storage mechanism with the greatest storage security. However, such processes are slow; it can take thousands of years for the majority of the gas to be trapped by mineralisation in the reservoir rocks (IPCC 2005; GCCSI 2019; 2021b; IEA 2022).

In contrast, unconventional methods that rely on in-situ mineralisation by injecting dissolved CO_2 in basalt and ultramafic rocks capitalise on immediate dissolution of CO_2 in formation water and mineral trapping through mineralisation with minerals of the reservoir rocks (Snæbjörnsdóttir et al. 2020; Clark et al. 2020). In this way, mineral trapping of most of the CO_2 can be achieved within the first few years (up to 95% in the first two years) after the injection has stopped (Figure 4, b).

Comprehensive MVV programs and risk management are a prerequisite for carbon storage projects to ensure storage integrity and long-term security. They should accompany all technical processes during the entire project lifetime, including the post-operational phase after the injection wells have been closed (section 3.5).

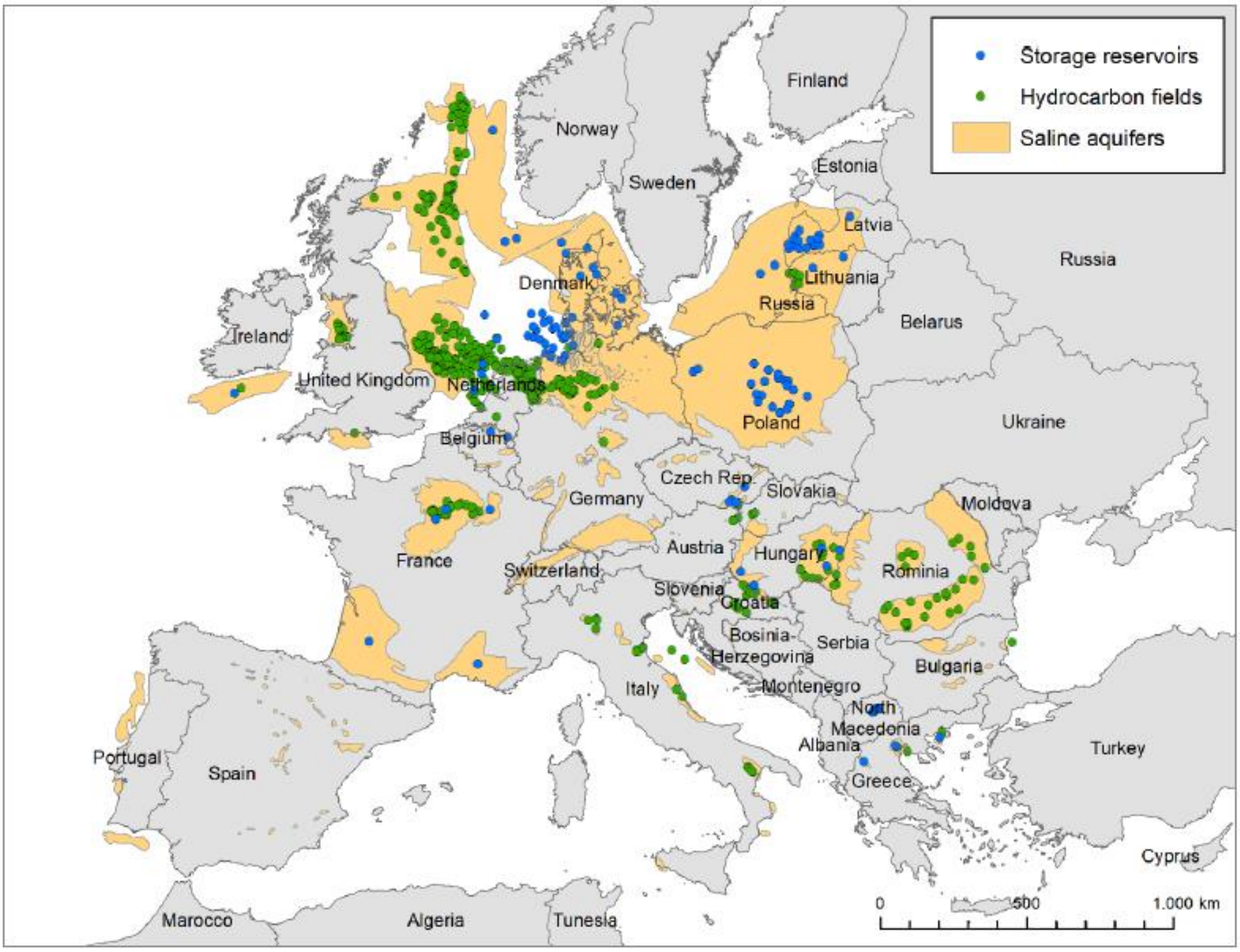
Conventional carbon storage technologies favour CO_2 storage in either saline aquifers[6] or depleted fossil gas and oil fields[7]. The geological properties of sedimentary rock formations (almost exclusively sandstones) are suitable because they have high permeabilities and porosities at a depth of around 800-3,000 metres; at best, they extend both laterally over large areas and in great thickness (IPCC 2005; Wallmann 2023). Those reservoir rocks should be overlain by geological cap rocks that function as impermeable barriers and effectively prevent the vertical migration of CO_2 from the underground storage reservoir to higher areas or to the earth's surface. Ideally, reservoir and cap rocks form structural and stratigraphic traps, which limit the vertical and horizontal migration of the gas to the reservoir structures. Other general siting criteria for potential geological storage sites include a stable geological environment away from tectonic, seismic and volcanic activity, all of which carry the risk of compromising carbon release and thus the integrity of the storage site (IPCC 2005).

Potential rock formations that provide carbon storage capacities in saline aquifers, storage reservoirs and hydrocarbon fields occur all over Europe. Centres of special interest are under the North Sea and in Germany, France, Poland, Lithuania, and Latvia as well as Hungary, Romania, and Bulgaria (Figure 5) (GEUS 2021; CATF 2023).

[6] Saline aquifers are geological formations with porous sedimentary rocks that are saturated with brine. CO_2 storage technologies in saline aquifers have Technology Readiness Levels (TRL) of 9 (GCCSI 2021a).

[7] Depleted natural gas and oil fields are deposits whose natural gas and oil reserves have already been depleted through gas and petroleum exploration. CO_2 storage in depleted natural gas and oil fields is technically mature with TRLs of between 5 and 8 as it has only been applied in demonstration projects (GCCSI 2021a).

Figure 5: Geographic distribution of potential carbon storage reservoirs in suitable geological rock formations in Europe



Source: GEUS (2021)

Note: Blue dots: Storage reservoirs are saline aquifer reservoirs with already well known structural and stratigraphic trap and barrier structures. Green dots: Hydrocarbon fields are depleted fossil gas and oil fields that have been exploited through petroleum production in the past. Yellow polygons: Sedimentary rock formations with potentials for saline aquifers.

Carbon storage projects using in-situ mineralisation of CO_2 rely on basalt and ultramafic rocks that are rich in silicate minerals. The Carbfix project in Iceland, for example, takes advantage of young, hydrothermally active, and highly reactive basalt rocks to store carbon underground (Carbfix 2024). Target reservoirs in Iceland are basalt rock formations at depths of 750 meters where the dissolved and compressed carbon is injected via boreholes and reacts at temperatures around 250°C with prevailing silicate minerals in the reservoir rocks. Iceland offers ideal conditions for the in-situ mineralisation of CO_2 in basalt and ultramafic rocks in Europe. Moreover, Clark et al. (2020) assume the potential capacities for carbon storage in basalt and ultramafic rocks along the north-western European continental margin of Norway and the UK and minor potentials possibly in, for example, Sweden, Finland, Germany, Portugal, France, and Turkey.

The realisation of CO_2 storage projects depends on the geology in the reservoirs (Knopf 2023). Permits for characterisation of the geology, deep drilling, and storage itself must be obtained and projects most likely require further approvals for storage infrastructure. Therefore, pre-operational preparation is assumed to take between three and 15 years for characterising the storage sites, constructing the infrastructure and developing the processes up to full deployment of carbon storage (IEA 2004; EC 2009; Knopf 2023).

Depending on the carbon storage demand and capacity provided, CO_2 could be injected over periods of five to 50 years. EC (2009) proposes a monitoring and control period of at least 20 years once the injection wells have been sealed.

EC (2009) assumes that the entire timespan of carbon storage projects stretches over 50-70 years. However, carbon storage projects also depend on the availability of an appropriate transport infrastructure, which is also expected to take up to 15 years to develop (BMWK 2022).

3 Risks of carbon storage

As with any technology, there are several risks associated with the permanent geological storage of CO_2. Some of those risks relate to the technology in general, others are site specific. Others are more political and value-based, such as public confidence in the long-term monitoring of storage sites and in (science-based) information, and ultimately the ability of decision-makers to decide on the local deployment of permanent carbon storage (IPCC 2005; GCCSI 2019; CIEL 2023).

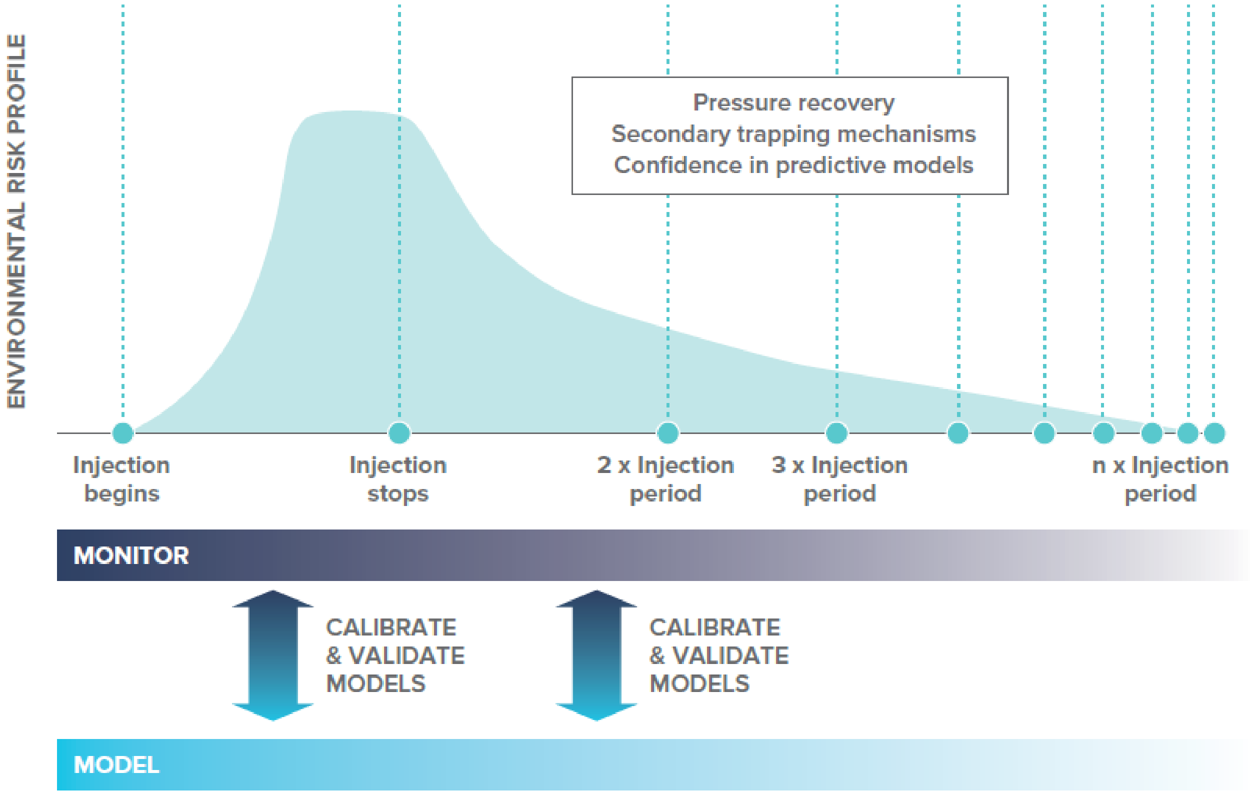
Many of the risks are well known from fossil gas and petroleum industry processes; transport, the assessment of geological reservoirs, injection, and finally surveillance and monitoring of the entire lifecycle resemble the corresponding processes of carbon storage projects. It is therefore possible to draw commercial practices from fossil gas and oil production that have been proved and utilised for many decades (IEA 2022). However, geological CO_2 storage also poses new challenges as many risks associated with permanent geological CO_2 storage are carbon-specific (GCCSI 2019; May 2024).

The greatest risk in geological carbon storage might be the unrecognised and uncontrolled release of CO_2 through leakages that occur in a variety of ways (IPCC 2005). The severity and the associated effects of leakage always depend on the volume released, the duration of release and the form of the released CO_2 (EC 2009; HSE 2011).

CIEL (2023) emphasises that the main experiences gathered with geological carbon storage at off-shore storage sites are based only on few demonstration projects (*Sleipner* and *Snøhvit*). These projects already had to deal with considerable difficulties in the run-up to injection due to unforeseeable problems with CO_2 behaviour in the reservoir. Among other things, this resulted in a huge increase of costs. CIEL concludes that the risk analysis of individual carbon storage projects would only have limited significance in terms of the general technical and geological feasibility of offshore carbon storage at other locations and environments and should always be project- and site-specific.

Just as risks and challenges associated with carbon storage occur along the entire process chain, different risks may predominate at different times during the lifecycle of carbon storage (EC 2009; GCCSI 2019; IEA 2022; May 2024). The CCS Directive (EC 2009) assumes that the entire lifespan of carbon storage projects is at least 50-70 years. Critical phases in which primary risks and hazards apply are either CO_2 transport to the storage site or temporary storage, or prominently emerge when injection of CO_2 into the reservoir begins (Figure 6).

Figure 6: Lifespan risk profile for carbon storage



Source: GCCSI (2019)

Right after injection begins, the risk profile increases and remains at this highest risk level over the operational period (5-50 years). However, the risk profile of carbon storage is not constant as the risk potential decreases significantly when the injection stops and wanes over time through the post-operational period and the post-closure of the reservoir (BEIS 2023). This peak in the risk profile is due to rising reservoir pressures during CO_2 injection and eases significantly when the CO_2 plume migrates away from the injection zone.

Furthermore, the risks and imminent hazards and impacts of CO_2 release are versatile and vary locally (ZEP 2019). While some risks may threaten the environment at the release source and its direct proximity, other risks may involve regions far away from the storage site. Local risks relate primarily to the transport routes, injection wells and the storage site. Global risks are most likely to be understood as uncertainty as to the permanence of geological CO_2 storage and thus as a threat to the global climate crisis (GCCSI 2019; IPCC 2005; CIEL 2023). The unrecognised release of CO_2, for example, will also have different effects on the environment depending on the amount and rate of released CO_2. Additionally, hazards to the environment of offshore carbon storage differ significantly to those that may occur at onshore storage sites (IPCC 2005).

This study shows general risks and challenges associated with the implementation and deployment of carbon storage in Europe along the full process chain but also sheds light on projects for which risks have materialised in the past. We focus on conventional carbon storage technologies that have proved commercial deployment or used in demonstration projects and provide TRLs of at least five or higher. Unconventional technologies[8] like carbon storage through in-situ mineralisation in basalt and ultramafic rocks in Iceland will also be briefly discussed.

To begin with, section 3.1 demonstrates the technical risks and challenges during carbon transport and injection. Then section 3.2 reveals the risks and challenges that occur during geological storage. Section 3.3 focuses on the environmental hazards and impacts that technical and geological risks trigger. Subsequently, section 3.4 takes society and politics into account and illustrates imminent socio-economic and political challenges. Finally, section 3.5 addresses risk management and shows measures that provide prevention, preparation and minimisation when dealing with risks and hazards during carbon storage. Brief conclusions are provided in section 3.7.

[8] Unconventional carbon storage technologies such as carbon storage in deep coal beds or enhanced coal bed methane recovery (ECBM) with a TRL of between 2 and 3 (GCCSI 2021a) or similar are not discussed in this study.

Table 1: Overview of carbon storage risks addressed.

Category	Issue	Page
Transport	Leakage of CO_2	28
	Impurification	28
	Use of existing infrastructure	30
Injection	Insufficient site performance characterisation	32
	Inadequate pressure management, over-pressurisation	33
	Fault propagation, reactivation of faults	33
	Reservoir rock failure	33
	Caprock failure	33
	Micro seismicity	33
	Deformation, ground movement	33
	Loss of well integrity (corrosion and blowout)	34
	Legacy wells	34
Geological	Natural pathways	36
Environmental	Release scenarios	39
	CO_2 exposure to humans	40
	Leakage of CO_2 and/or formation water to the benthic environment	42
	Leakage of CO_2 and/or formation water to the open water column	43
	CO_2 exposure to terrestrial environments	45
	Soil acidification	45
	Contamination of underground resources	46
	Contamination	46
Indirect impacts of carbon storage	Development of infrastructure	47
	MMV programs	48
	Emissions	48
Socio-economic and political	Lack in public acceptability	49
	Land use conflicts	49
	Sabotage and terror attacks	50

Source: Authors' own compilation

3.1 Technical risks

3.1.1 Carbon transport

The occurrence of technical failures during the transportation of CO_2 may result in the loss of integrity of the technical barriers in place, with the potential to cause harm to humans and the environment. Furthermore, leakage results in a reduction in the efficiency of CO_2 transportation (IPCC 2005). Technical risks associated with CO_2 transportation vary depending on the specific transport system employed. The technical features of the installations and the properties of the CO_2 stream can be used to assess risks.

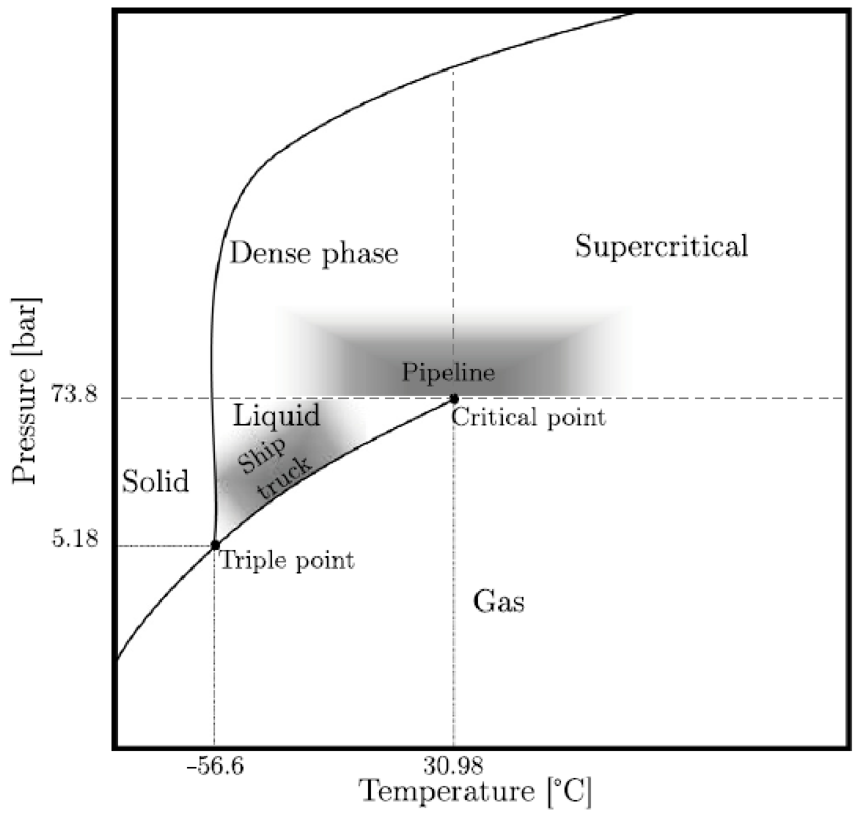
Box 1: Processes and modes of carbon transport

The quantity of transported CO_2 and distance of transport determines the best transport option (VDZ 2024). The mode of transport and the defined legislative quality of the CO2 have a significant impact on costs. Operators therefore seek to minimise costs by optimising the economic and technical reliability of their operations. Economic considerations include investment in high grade design (e.g. corrosion-resistance, purification) and running operating costs, such as are energy demand, operating restrictions, and shut-down times, as well as efforts with a view to surveillance, maintenance, and repair.

Generally, CO_2 can be transported in gaseous, liquid, dense or supercritical phase. The phase in which CO_2 is present depends on the temperature and pressure conditions. As the temperature rises, liquified CO_2 becomes gaseous. Exceeding pressure and temperature at the critical point, it moves into the supercritical phase.[9]

Figure 7 shows typical temperature-pressure-ranges of different transport modes. As each CO_2 phase consists of specific density and viscosity, discrepancies consequently determine the throughput, design, energy demand and finally efficiency of the CO_2 transportation. Operators usually strive for optimum conditions for each application (IPCC 2005; IEA 2022). These conditions should be maintained throughout the entire transportation process.

Figure 7: CO_2 phase diagram



Source: (Simonsen et al. 2023)

Notes: The phase diagram shown in the figure is for pure CO_2. Impurities will change the chemical properties and can trigger adverse effects like corrosion. Furthermore, there is an effect on the physical properties like density and viscosity and they will shift the phase boundaries and influence pressure-loss and energy demand. Phase diagram of CO_2 together with a rough estimation of

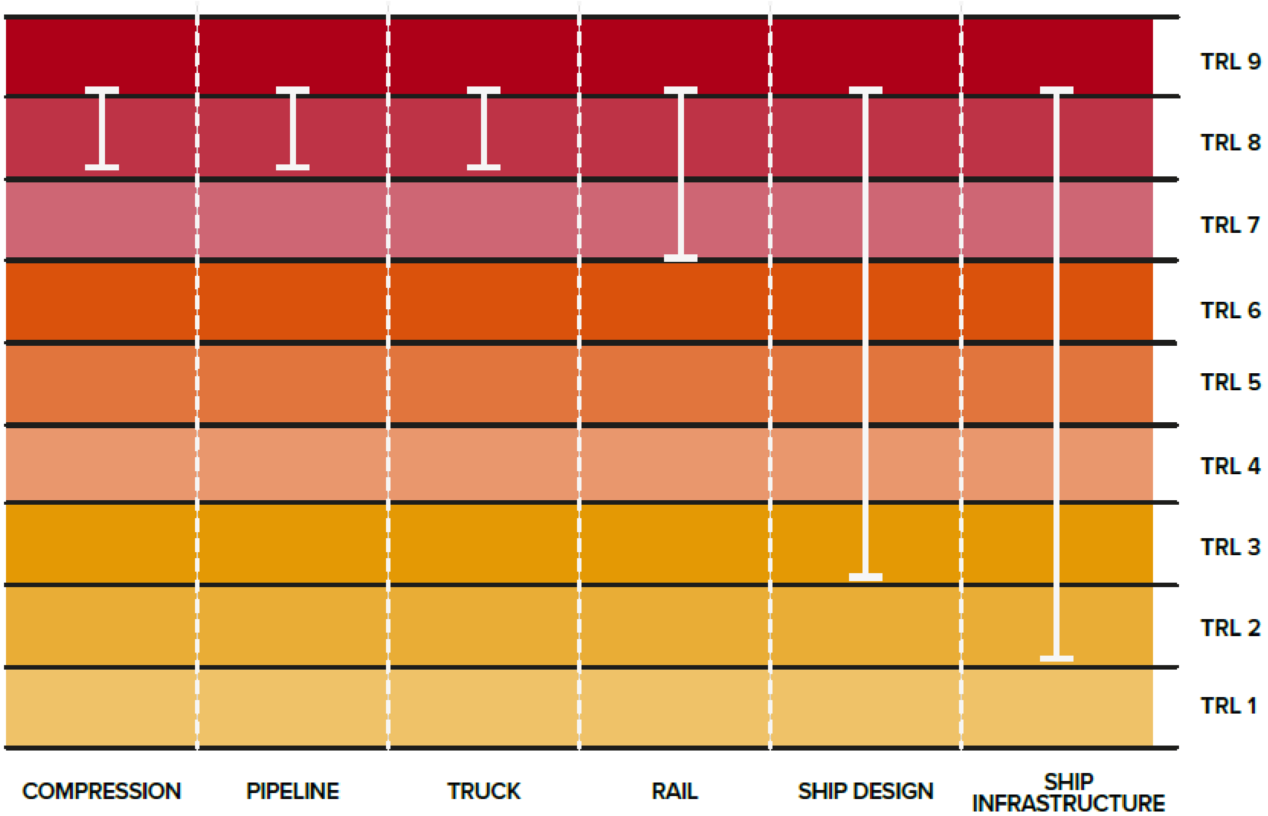
[9] When CO_2 is in its supercritical state, it has the same properties of both liquid and gas by having the same density as a liquid but having the high compressibility and low viscosity of a gas (Simonsen et al. 2023).

the operation areas for pipeline, ship, and truck transport indicated by the two grey boxes. Critical point: 304.15 K and 73.8 bar (for pure CO_2).

CO_2 transportation can be carried out by various modes. Onshore transportation can be conducted by train, truck, ship or via pipeline. Offshore transportation is carried out by ship or via pipeline on the ocean floor. Furthermore, a combination of different transportation systems, each for one section on the way to the storage site, is feasible.

Figure 7 indicates the Technology Readiness Level (TRL) of different transportation modes (GCCSI 2021a). The higher the level of a technology, the more developed the technology is. All options discussed for CO_2 transportation are based on established technologies. The adaption for a new application explains the range of the values, especially if the expansion of a large infrastructure for the required capacities is considered.

Figure 8: Technology readiness level of carbon transport



Source: GCCSI (2021a)

Notes: IEAGHG (2014) defines the following categories for TRLs: TRL of >7: demonstration; TRL of 9 is defined as normal commercial service; TRLs 4-6: development in laboratory (4) and fully integrated tests (6); TRLs 1-3: Research from basis concepts (1) to proof-of-concept tests (3).

Road and rail transportation (TRL 7-9)

On trains or trucks, the liquified CO_2 is usually transported in vessels.[10] A thermodynamic calculation determines the need for cooling and insulation. Transporting liquified CO_2 allows lower vessel volumes compared to gaseous CO_2. But there are enhanced design requirements due to high-pressure

[10] Currently, the food industry already relies on CO_2 transportation via truck or train. However, quantities that are transported for use in the food industry are significantly lower and CO_2 transport conditions easier to maintain.

conditions. Furthermore, the effort for cooling, insulation and pressurization must be considered. (IPCC 2005).

The conceptual design is analogous to the transport of Liquified Natural Gas (LNG) and Liquified Petroleum Gas (LPG). The maximum vessel pressure is usually up to 2.5 MPa. For transport by truck, a typical capacity amounts to approx. 18 tons; newer designed trucks can easily exceed a capacity of 20 tons. When transported by train, the typical capacity is around 60 tons. Differences in state and pressure mean that CO_2 has to be pressurised to a higher level to achieve the value required for temporary storage and injection when removed from transport containers at unloading terminals (VDZ 2024).

Road or rail transportation are appropriate for small quantities of CO_2. To date, these options have been used at some demonstration project sites when moving the CO_2 from the site of capture to a nearby storage site. For deployment and industrial ramp-up, transport of liquified CO_2 via trucks is not currently the main option, mainly due to limited transport capacity (VDZ 2024). Hafez and Fateen (2016) conclude that train or truck transportation is not expected to play a significant role in carbon storage deployment. Nevertheless, road and rail transportation may initially play a role during the transition towards industrial scale projects or for onshore demonstration project sites (VDZ 2024).

Ship transportation (TRL: 3-9[11])

By ship, CO_2 is carried in the liquefied phase in big tanks. The conceptual design is based on the experience of LPG and LNG. Suzuki et al. (2013) compare several types of ship that have different tank types (cylindrical, bi-lobe, spherical) and capacities. One current application is CO_2 transportation by ship for use in the food industry (Bond 2024). For this commercial use, ships with a capacity of between 20 and 50 thousand tonnes are being developed for offshore carbon transport. The indicated tank design temperature lies at -50° C, and the design pressure is ~10 MPa. Ship transportation in general needs special terminals for loading and offloading, which involve investment and construction. For CO_2 transportation, the terminal for offloading the carrier is installed close to the storage. It is applicable in both variants: onshore and offshore. Furthermore, offshore terminals can be designed as gravity-based terminals or floating terminals. Each terminal has installations for offloading and temporary storage of liquified CO_2 and, when required, for pressurisation for injection. The capacity of the temporary storage tank is determined by the quantity delivered and the requirements for a continuous injection.

Ship transportation can become favourable for large quantities and long distances especially in the beginning of carbon storage deployment (e.g. on rivers) as it takes time to develop a suitable CO_2 pipeline network (VDZ 2024). Neele et al. (2017) have evaluated several studies which determine costs for ship transport and concluded that ship transport may be cost-competitive compared to offshore pipelines at a transport distance of more than about 700 km.

Transporting solid CO_2 hydrate pellets by ship is being discussed as a future option. Accordingly, Neele et al. (2017) conclude that CO_2 transportation as hydrate pellets is a feasible option compared with liquefied CO_2 since fossil gas transportation as hydrate will be more feasible under certain conditions than LNG. The most advantageous property of hydrate pellets is their ability to exist in a relatively stable state in atmospheric pressure. More challenging are tasks such as the effective production, handling, and storage of solid hydrate pellets, the energy demand and regulatory aspects.

[11] TRL 3 relates to offshore injection into a geological storage site directly from a ship without onshore facilities. Conventional onshore CO_2 injection from facilities (e.g. offshore platforms) has a TRL of 9 (GCCSI 2021a).

Pipeline transportation (TRL: 8-9)

As with oil and fossil gas, CO_2 transport through pipelines is the most applied option (IPCC 2005; VDZ 2024). Pipelines can transport large quantities of CO_2 over long distances. A long-distance pipeline on land is divided into several sections; compressor stations are installed every 100 to 150 km for compensation of pressure losses. Shut-off devices allow individual sections to be separated for inspection and maintenance or to stop gas release in the case of damage.

CO_2 pipelines are already in operation, particularly within the scope of EOR projects to date. In the pipeline, CO_2 can be transported in a gaseous or liquid phase. Mahjour and Faroughi (2023) note that for recent carbon storage projects, CO_2 is compressed into a liquid or supercritical fluid form for transportation.

Wang et al. (2019) provide an overview on the common pipeline technology:

Gaseous CO_2 pipeline transport

When transporting in gaseous phase, the highest operational pressure in the pipeline must not exceed 4.8 MPa at normal ambient conditions. Prior to entering the pipeline, the pressure of the CO_2 stream needs to be adjusted to meet with the requirements of the pipeline. The pressure needs to be controlled and maintained at this level during pipeline transport to avoid CO_2 changing into the supercritical state. Near the storage site, the gas is pressurised again to attain the level required for injection (IPCC 2005).

The gaseous phase transport pipeline has a lower operating pressure than other transport options. The operation safety might be higher. Due to the gas compressibility, it is suitable for different throughput rates. However, compared with supercritical transportation, the pipe diameter is larger, and the investment is higher, especially for longer distances. Thus, it is most suitable for low throughput, short distances and for CO_2 from the gas phase source. It is more suitable for densely populated areas.

Liquified CO_2 pipeline transport

CO_2 is kept continuously in a liquid phase in the pipeline. Pressure is pumped up to overcome the friction and the terrain elevation difference along the pipeline. If CO_2 is transported under high pressure, it could be injected without compression at the end of the pipeline. Usually, CO_2 needs to be cooled to get into the liquid phase. Compared to gas transportation, transport in liquid phase allows a higher flow and smaller pipeline diameters for higher throughput. Compared to supercritical transportation the liquid CO_2 pipeline has lower operation pressure and usually needs an insulation layer, with the result that the investment costs are higher. It is suitable for low throughput, and short distance gathering pipelines (Wang et al. 2019).

Supercritical CO_2 pipeline transport, dense phase

Due to favourable density and viscosity conditions, CO_2 transport by pipeline in a supercritical or dense phase is the most efficient in terms of costs and throughput (Wang et al. 2019). Supercritical CO_2 is transported at temperatures and pressures above the critical point. CO_2 transport in supercritical form needs to set the minimum pressure to keep its dense phase behaviour in the pipeline. Compressor units are integrated to meet pressure requirements. With a view to design pressure limits, a thermodynamic calculation will determine whether further insulation is needed to keep the gas temperature above the critical point. VDZ (2024) assumes that CO_2 transport occurs at an ambient temperature. If so, pressurisation of 10 to 20 MPa is required.

For the future, transportation by CO_2 pipeline is assumed to be the mode of choice (Becattini et al. 2022). Therefore, the following risk assessment focuses on transportation via pipeline.

Generally, a substantial body of operational experience has been gathered with natural gas pipelines, which provides valuable insights. However, it is important to recognise that the data may not be fully transferable. The structure of the new CO_2 pipeline system will differ significantly from the existing fossil gas infrastructure. The properties of the CO_2 stream will also necessitate the development of a unique regulatory design.

Hazards of CO_2 transportation

Hazards of CO_2 leakage is contingent on the ambient concentration to which humans and the environment are exposed and the duration of exposure (section 3.3). As CO_2 is not perceptible to the human senses, it goes unnoticed when a critical concentration has been attained. A concentration of the gas that could prove harmful might persist for a longer period at specific locations in the vicinity of the leak, where air exchange is either minimal or non-existent. IPCC (2005) highlights the density of gaseous CO_2 which is 1.5 times greater than that of ambient air, facilitating its accumulation in low-lying areas and topographic depressions, including the basements of buildings. Even low-lying regions, such as valleys near pipelines, are susceptible to this risk (IPCC 2005). Leakage predominantly occurs at compressor stations, valves, or connecting devices. However, these installations are expected to be primarily located far from urban areas, thereby reducing the likelihood of direct impact to humans. Nevertheless, hazards to the environment are inevitable.

Several quantitative risk assessments for CO_2 pipelines have been performed. The risk of a pipeline failure is assessed with a very large bandwidth. There is a high degree of uncertainty as to the final distances at which harmful CO_2 concentrations can exist after an accidental release. The calculated distance ranges from <1 m to 7.2 km (Koornneef et al. 2010).

Failure rate

Onyebuchi et al. (2018) estimates the failure rates and main damage-inducing impacts of CO_2 transport pipeline as follows: “Based on the experiences of the natural gas pipelines industry, failure rates associated with leaks for CO_2 transport pipelines are estimated to range between 0.7 and 6.1×10^{-4} yr^{-1} km^{-1}. Accordingly, most recorded failures to date could have been attributed to several factors, including third-party interference, pipeline corrosion, material, and construction defects (such as welds), and operator error. Additionally, leakage may result from existing or induced defects, fractures, or along a spill position (Onyebuchi et al. 2018). Duncan and Wang (2014) estimates that 1.0×10^{-6} yr^{-1} km^{-1} can be viewed as an upper bound for individual risks associated with CO_2 transmission pipelines. To date, only minor accidents have occurred. They note that the frequency of minor accidents does not provide a basis for predicting rates of serious events.

Effects of impurities

The CO_2 contained in the gas stream destined for transport is not 100% pure; rather, it comprises a range of compounds that differ from those present in the source material and the separation technology employed. Simonsen et al. (2023) emphasise the overall importance of contributing fundamentally to the safe and economical transportation (and storage) of CO_2. This applies across all modes of transport and terrains. Consequently, operators must consider a variety of aspects, such as operational pressure, depressurisation intervals and pipeline integrity. This is also irrespective of the phase in which CO_2 is transported (Onyebuchi et al. 2018).

Simonsen et al. (2023) distinguish between non-condensable gases and corrosion-inducing impurities. Non-condensable gases significantly affect the phase behaviour and the operational pressure, thereby posing an economic risk to CO_2 transportation. Corrosion-inducing impurities become a reactive acid in the presence of water, damaging the integrity of the pipeline system. Moreover, admixtures may exhibit hazardous properties such as toxicity or flammability. Consequently, the necessity for higher-grade, corrosion-resistant materials to deal with impurities would result in a considerable rise in material costs. Therefore, operators ensure that the CO_2 stream is purified before transportation. However, there is a trade-off between investment and energy demand for the purification and the negative effects of the impurities. Simonsen et al. (2023) are sceptical that carbon transportation will be deployed by building on high-grade steel and high purity of CO_2 at the same time and assume that it will be necessary to strike the balance between them for the design of national infrastructure. In any case, the removal of free water is essential due to its corrosion-inducing effect. Table 2 provides examples for common compounds in the CO_2 which is being transported.

Table 2: Impurity tolerance and effects in post-combustion CO_2 capture processes

Component	Max. allowable concentration [Mol-%]	Effects
H_2S	3.25	Decreased solvent efficiency, promoted corrosion, catalyst poisoning
SO_2	2.5	Increased corrosion, adverse environmental effects
O_2	1.75	Solvent degradation, diminished CO_2 capture capacity
H_2	1.65	Heightened flammability, potential explosion risk
CO	0.2	Solvent regeneration processes disrupted

Source: Modified after Razak et al. (2023)

Razak et al. (2023) propose that the level of concentration at which each impurity needs to be removed depends upon several factors, such as material corrosivity, limiting chemical reactions, selected transport material constraints, process requirements, toxicity, and lastly geological storage constraints.

To date, several projects have already established substance-specific restrictions, although these have been point-to-point specific. Consequently, the quality specification has only needed to comply with the known impurities of a few emitters so far. As the deployment of carbon storage projects involves an intermingling of CO_2 streams from different point sources during future CO_2 transportation, the monitoring of impurity levels and the integrity of pipeline systems is needed for safe operation. In the long term, a transition to an overall shared infrastructure is inevitable and presents a fundamental challenge to minimise risks, both technically and economically (Simonsen et al. 2023).

Table 3 shows the quality standards of various operators in place indicating substance-specific limit values as well as the number of restricted substances to be inconsistent. In some cases, the requirements of realised projects go beyond the requirements of the ISO standard 27913:2016 (non-food grade CO_2).

Table 3: CO_2 quality specification based on ISO 27913:2016

	Northern light [92]	NETL recommended limits [38]	Dynamis [37,93]	Porthos [94]	ISO 27913:2016 [35]	EU Food-grade CO_2 [95]
CO_2	–	95%	>95.5%	≥95%	≥95%	≥99.9%
H_2O	≤30 ppm	500 ppm	500 ppm	≤70 ppm	<200 ppm	20 ppm
O_2	≤10 ppm	0.001%	<4%[a] <1000 ppm[b]	≤40 ppm	–	30 ppm
H_2S	≤9 ppm	0.01%	200 ppm	≤5 ppm	<200 ppm	0.1 ppm
N_2	–	4%	<4%	≤2.4%	–	–
SO_x	≤10 ppm	100 ppm	–	–	<50 ppm	1 ppm
NO_x	≤10 ppm	100 ppm	–	≤5 ppm	<50 ppm	2.5 ppm
CO	≤100 ppm	35 ppm	2000 ppm	≤750 ppm	<2%	10 ppm
NH_3	≤10 ppm	50 ppm	–	≤3 ppm	–	2.5 ppm
H_2	≤50 ppm	4%	<4%	≤0.75%	–	–
Ar	–	4%	<4%	≤0.4%	–	–
CH_4	–	4%	<4%[a] <2%[b]	≤1%	–	50 ppm
Acetaldehyde	≤20 ppm	–	–	–	–	–
Formaldehyde	≤20 ppm	–	–	–	–	–
Hg	≤0.03 ppm	–	–	–	–	–
Cd and Tl	≤0.03 ppm	–	–	–	–	–
Total sulphur (COS, H_2S, SO_x)	–	–	–	≤20 ppm	–	0.1 ppm
Methanol	–	–	–	≤620 ppm	–	10 ppm
Total (N_2, H_2, CH_4, O_2, Ar, CO)	–	–	–	≤4%	4%	–

[a] Aquifier.
[b] EOR.

Source: ISO (2016)

Use of existing infrastructure

Usually, the use of existing gas net infrastructure seems attractive for CO_2 transportation. The fossil gas grid consists of various pipeline systems operating on different pressure levels. For example, for the German grid, high-pressure pipelines are used for long-distance transport at over 1 to 100 bar (10 MPa) overpressure, medium pressure pipelines for regional distribution at 0,1 to 1 bar overpressure and low-pressure pipelines for house connection at less than 0,01 bar overpressure.

When considering whether or not fossil gas or oil pipelines could be used to transport CO_2, it must be taken into account that they are not designed for CO_2 transport and are therefore likely to have a low suitability for this task (VDZ 2024; CIEL 2023). The pressure needed for supercritical CO_2 transport exceeds the design base pressure for fossil gas distribution pipelines. Furthermore, the CO_2 stream including impurities differs in chemical and physical properties and may weaken corrosion resilience and the lifetime of the enclosing barriers. VDZ (2024) therefore assumes that a suitable CO_2 network has to be built predominantly from scratch.

The main components like piping elements, compressor, or pump stations as well as ancillary equipment and instruments are comparable to those in the fossil gas pipeline system; the engineering requirements, however, are different. VDZ (2024) points out that experienced technology for high pressure compression is available. When used for CO_2 transport, however, the energy efficiency is challenging. Several publications disagree with the claim that there is significant transferable experience with pipeline design. Special design considerations need to be implemented when constructing facilities for processing and pipelining CO_2 (CIEL 2023).

Box 2: Policies and regulatory framework of CO_2 transport

CO_2 is not classified as a hazardous substance, and CO_2 is not listed in the European Seveso III Directive (EC 2012). Corresponding legislative regulation and underlying standards with a view to those hazardous substances do not apply. An environmental impact assessment would be required to build a CO_2 pipeline.

In Germany, §4 (KSpG 2012) contains legal provisions for the approval process of CO_2 pipeline transportation to a geological storage. Risks arising from the CO_2 pipeline will be addressed in the approval process. To achieve the required level of technical safety during construction and operation, reference is made to the generally recognised rules of technology. Regarding the technical design, ISO 27913:2016 specifies additional requirements and recommendations that are not covered in existing pipeline standards for the transportation of CO_2 streams from the capture site to the storage facility where it is primarily stored in a geological formation or used for other purposes. In June 2024, a draft revision of the standard ISO 27913:2016 was published.

Neupert and Hilgenstock (2022) assume that national, and international standards for carbon transport in pipelines are available from a technical point of view. From a legal point of view, they criticise that the existing legal framework does not allow for the deduction of requirements for determining the current state of technology for carbon transport since the application for carbon transport has not yet occurred. Neupert and Hilgenstock (2022) recommend adaptions specific to CO_2 transport, including specialised regulations concerning pipeline transportation.

The approval for transport on rail, road, ship can be granted, based on existing transport law, national and internationally, for high pressurised and liquified gas, regardless of the application for CO_2 transport (Neupert and Hilgenstock 2022).

Comparison of transport modes

All transport modes have advantages and disadvantages which make them appropriate for different use cases or at different points in the technological development:

- **Road and rail** transportation is favourable for small quantities of CO_2 at onshore demonstration project sites and during the transition towards industrial scale projects.
- **Ship** transportation is suitable for large quantities and long distances especially in the beginning of carbon storage deployment. Depending on the distance to be covered, shipping can be cost-competitive with offshore pipelines even in the long term.
- **Pipeline**
  - Gaseous pipeline transport is favorable for different throughput rates, for low throughput and short distance, and for CO_2 from gas phase source.
  - Liquid pipeline transport is favorable for low throughput and short distance gathering pipelines.
  - Supercritical pipeline transport is favorable for large quantities and long distances. All studies agree that pipeline transportation in a supercritical or dense phase is the most efficient and feasible mode of transportation.

The risks associated with the hazardous properties of CO_2 and impurities are similar for all modes of transport. Purification would generally minimise environmental risks and reduce the likelihood of leakage due to corrosion. However, further purification entails additional costs in terms of investment and energy (Eickhoff et al. 2017); thus, purity standards need to take into account both risks and costs. Currently, operators apply different standards, which can lead to confusion and thus additional risks. Initiating a process between governments and stakeholders to establish a common purity standard that considers safety and leakage risks and the costs, with a view to establishing a standard that appropriately balances these trade-offs, would reduce uncertainty and thus risks while limiting costs.

The energy content of the volume and possible release rate increase, the higher the pressure during transport. Transport in the gaseous phase might pose lower risks than transport in the liquid or supercritical phase. Therefore, gaseous pipeline transport might be more appropriate in densely populated areas. A leak in a transport vessel results in a rapid loss of pressure followed by a decreasing release rate. The maximum leakage quantity is limited to the volume of the vessel.

It can be assumed that small leaks during pipeline operation are unavoidable. Serious accidents are unlikely but cannot be completely ruled out.

According to (Onyebuchi et al. 2018), the assessment of environmental risks for the CO_2 transport pipeline has identified ensuring the safe operation of the high-pressure pipeline as a major risk. An emergency planning zone around the pipeline, which requires detailed emergency response planning, needs to be considered during the design and planning stage. The pipeline route should not pass through densely populated areas and low-lying terrain in which CO_2 could accumulate.

3.1.2 Carbon injection

Carbon injection, besides carbon transport, may display the most critical part of carbon storage with a variety of technical risks and challenges on hand. When technical risks come to fruition, there are consequences not only directly for the integrity of the storage site but also for the storage complex and beyond (Vilarrasa 2016; Rinaldi et al. 2019; Song et al. 2023).

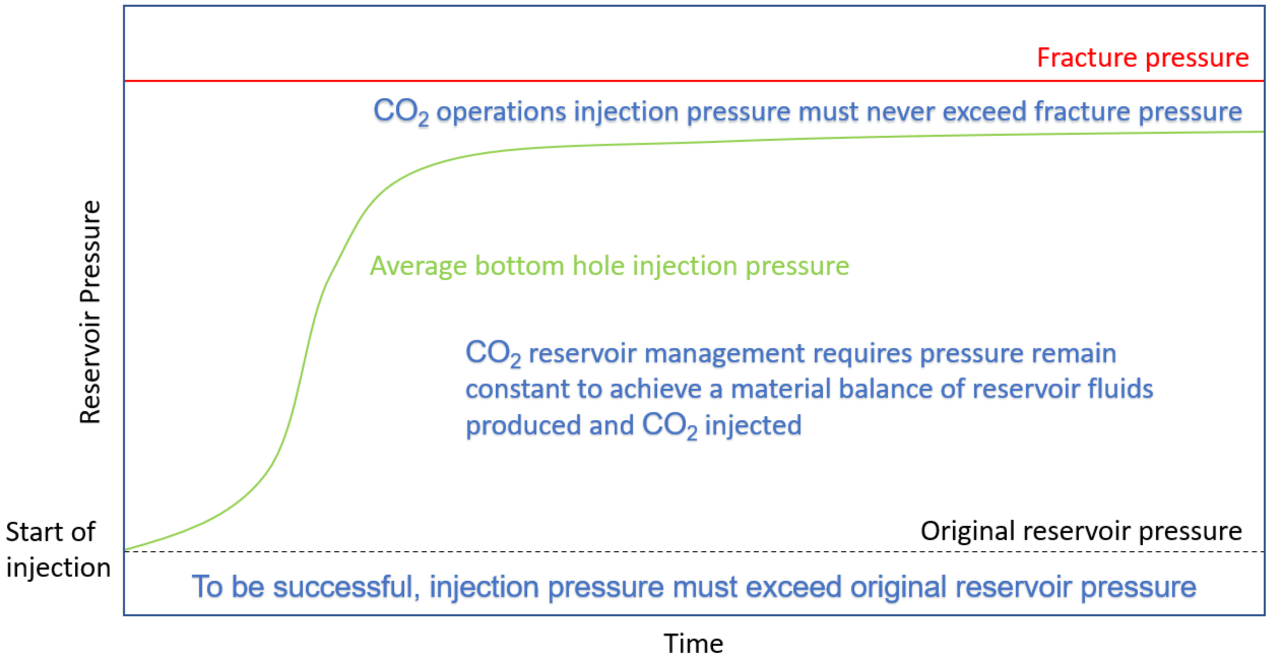
Therefore, comprehensive pre-injection site performance characterisation is key to mitigate consequences to the geological environment during carbon storage. Thereby, risks can be addressed and minimized effectively (IEA 2022). Insufficient site performance characterisation bears the risks that capacity and injectivity of a storage site is mistaken which lead to severe consequences to the geological environment harming storage security and integrity (IPCC 2005; May 2024).

For successful CO_2 injection geological conditions of the reservoir rocks in the storage site must be fully understood to match suitable pressure conditions in reservoir that guarantees storage integrity best (Figure 9). Misjudgement of capacity, injectivity, and the pressure conditions in the reservoir (pressure management) can lead to high stress conditions in the reservoir[12]. Both reservoir rocks and cap rocks in the storage complex dispose specific fracture limits which the rocks can hold. When reservoir pressure conditions exceed certain fracture limit due to high injection rates e.g., high stress will lead to fractures in the reservoir and cap rocks. CO_2 injection therefore must under any circumstances never exceed fracture pressure during operation as the integrity of the reservoir and thus storage safety can no longer be guaranteed (IPCC 2005; CO2GeoNet 2013). As a result, reservoir and site performance characterisation are prerequisites in the run-up to injection and must be site-specific as insufficient geological characterisation jeopardises safe operation (e.g., section 3.6). Furthermore as with CO_2 transport, state and purity[13] of the injected CO_2 also determines storage capacity and injectivity during injection as impurities also bear risks in terms of the impairing of reservoir rock behaviour (IEAGHG 2011).

12 Please see section 3.6 for examples of carbon storage projects where operational irregularities evolved due to insufficient pre-injection site (performance) characterisation materializing several risks.

13 Generally, operators use purities of injected CO_2 that are as high as possible. For example, for the Northern Lights project in the Norwegian North Sea, purity levels of over 95.5% are targeted for the injected CO_2 flux (Equinor 2019).

Figure 9: Simplified injection profile after CO_2 injection has begun



Source: Based on Marston (2013)

When pressure management fails, risks can materialise both in the storage site affecting reservoir rocks and putting damage to the geological environment[14] of the storage complex and beyond, bringing about far field effects (Figure 10). In the direct environment of the injection zone, technically induced stress provokes cracks and fractures within the reservoir rocks, building new permeabilities which give paths for CO_2 to migrate (IPCC 2005; Vilarrasa 2016; IEA 2022; Song et al. 2023). Thermal stresses and overpressure may induce micro seismicity in the reservoir that can be detected even at the earth's surface.

Caprock failure due to overpressure may cause the propagation of fractures, activation of low-permeability faults, and induce micro seismicity leading to pathways in the storage complex and increase the risk of CO_2 leakage[15] into areas in the overburden closer to the earth's surface (Song et al. 2023).

In the far field, pressure perturbation propagates quickly and may reactivate larger faults (Figure 10). These can lead to the extension and shrinkage of rock formations, leading to deformation, uplift or subsidence as a result of seismic activity (IPCC 2005; Song et al. 2023). Generally, the earth's surface could experience ground movement both around the injection well and in the far field. However, whereas the uplift or subsidence of rocks can affect the earth's surface easily by ground movement in the range of several tens of centimetres, seismic events tend to be in the micro seismic range and usually go unnoticed by humans. Major earthquakes are extremely unlikely (Vilarrasa and Carrera 2015; IEA 2022; CIEL 2023). Nevertheless, property damage to buildings, for example, cannot be ruled out, particularly in the case of onshore carbon storage projects in the immediate vicinity of

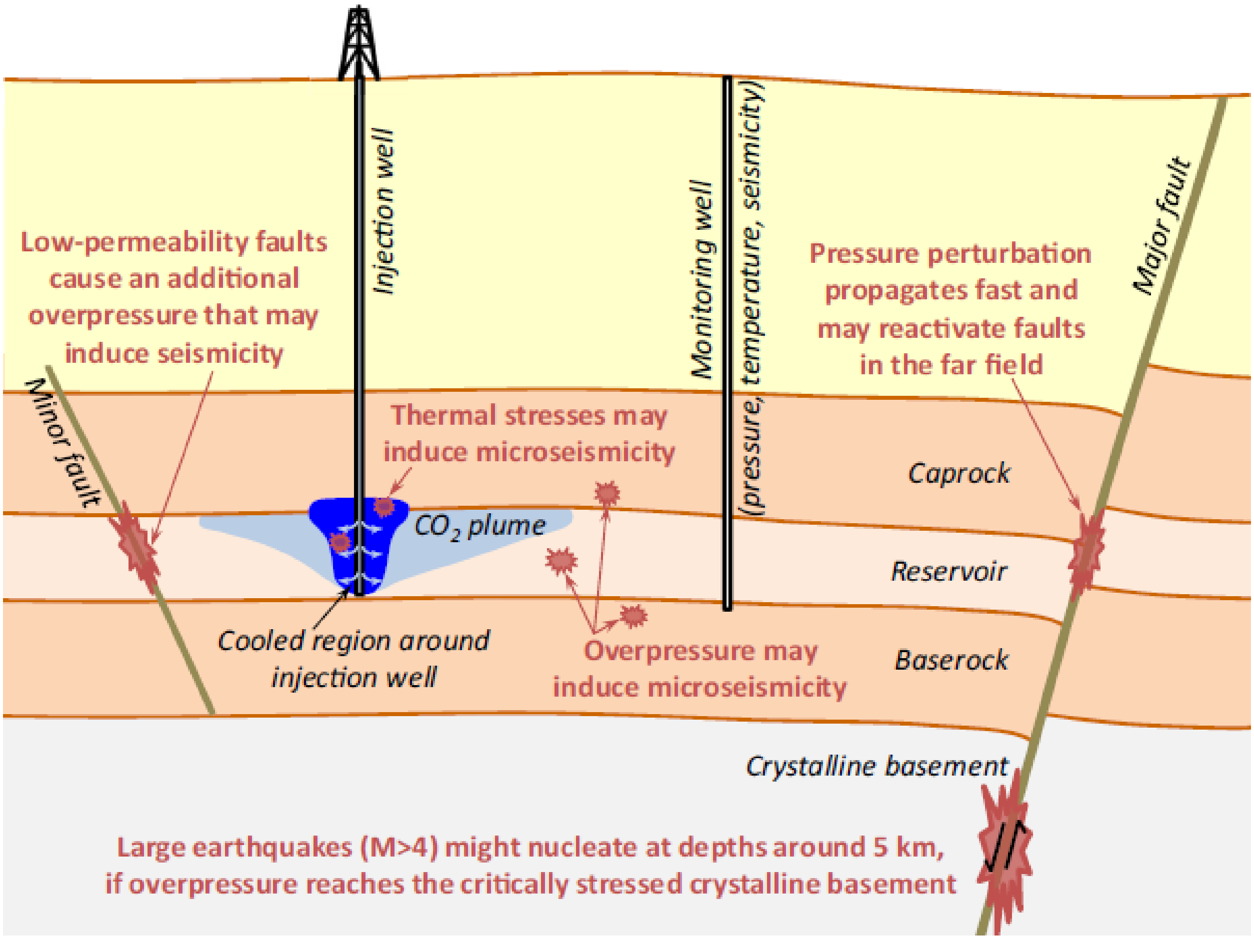
[14] Please see section 3.6.2 for the *In Salah* CS project, where inadequate pressure management led to damage of the geological environment.

[15] Leakage is formally defined as the process when CO_2 leaks out of the storage complex (Figure 3) (IPCC 2005).

urban areas (IPCC 2005). As with offshore carbon storage, this could affect above-sea surface facilities, seabed injection wells and seabed pipelines.

Measures to prevent excessive pressure in the reservoir during injection include the utilisation of laterally open system reservoirs, e.g., in saline aquifers, or the extraction of brine (formation water) from the reservoir prior to injection. However, both processes present their own fundamental challenges (IEA 2022).

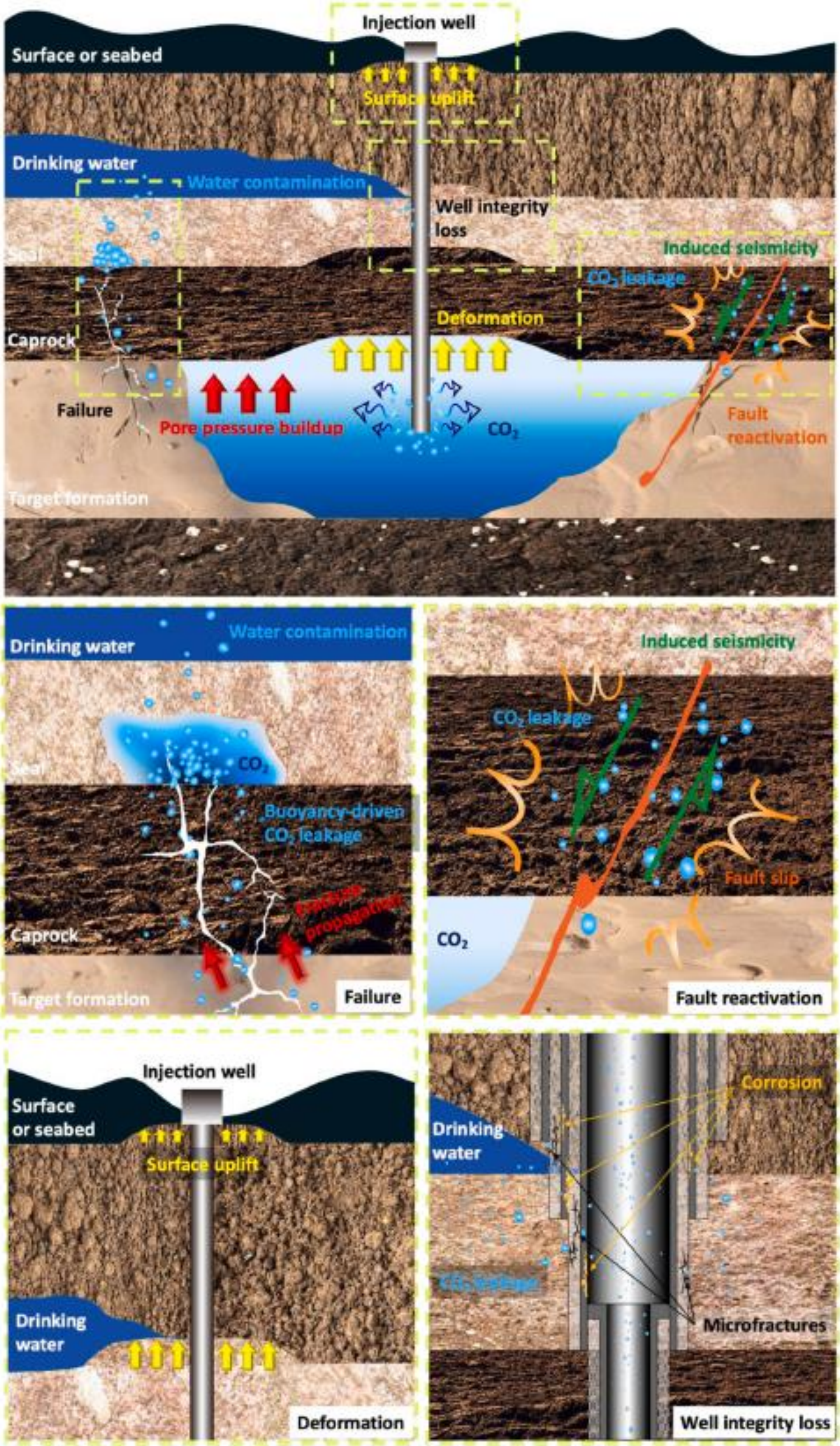
Figure 10: Potential impacts on the geological environment during carbon injection



Source: Vilarrasa (2016)

Besides insufficient reservoir characterisation and over-pressurization due to excessive injection rates, technical risks also concern well integrity (Figure 11). While loss of control of drilling pressure can lead to well blowouts and uncontrolled excess of CO_2 from the injection wells, pressure and corrosion can also favour microfractures, giving paths to CO_2 leakage in vicinity of the wells (Song et al. 2023; IEA 2022). IEA (2022) argues that the number of such accidents has been significantly minimised in the past, but the possibility of technical difficulties during injection, such as mechanical failure or damaged equipment, wrong execution and the unexpected occurrence of technical problems, must be taken into account. Even after the operational phase, the sealing and decommissioning of the boreholes presents a fundamental technical challenge. Poorly sealed or decommissioned wells (legacy wells) pose an enormous risk to the integrity of the storage site, leading to potential CO_2 leakage (IPCC 2005; Wallmann 2023).

Figure 11: Mechanisms of the potential geomechanical risks during carbon injection



Source: Song et al. (2023)

At the storage sites, surface facilities for CO_2 storage are generally like those in the fossil gas and oil industry. CIEL (2023) also points out that offshore infrastructure facilities are very complex and expensive. Above all, there are risks from extreme weather events in the wake of the climate crisis. In the event of accidents, there is also generally less potential for minimising and correcting damage due to the accessibility of the offshore facilities.

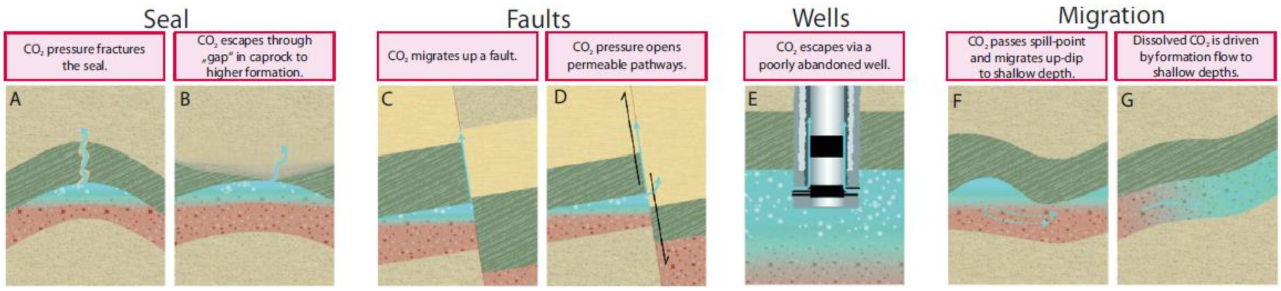
3.2 Geological risks and permanence of carbon storage

Besides impacts to the reservoir and its geological environment that are induced when technical risks materialise during CO_2 injection, there are natural and manmade predispositions in the geological environment that pose risks for the integrity and security of CO_2 (IPCC 2005). Those geological predispositions can form pathways which enable either CO_2 or displaced brine to escape from the reservoir, causing harm to the environment (3.2.1). Further, the question of the permanence of CO_2 storage is briefly addressed during this section (3.2.2) as the longevity of storage determines the impact of CO_2 storage technologies on mitigating the climate crisis (IPCC 2005; GCCSI 2019; UBA 2023b; ZEP 2019).

3.2.1 Geological pathways

Natural and manmade pathways pose the risk of unrecognised release of CO_2 from the reservoir to the geological environment or even the earth's surface (IPCC 2005). The pathways are either the containment failure of stratigraphic (seal or cap rocks) or structural (fault structures) seals, anthropomorphic activities or pathways that come about due to the natural geometry of the storage site (Figure 12).

Figure 12: Geological pathways



Source: Based on Haase (2015). A: Fracture of the overburden due to excessive pressure in the reservoir; B: Leakage of through fractures in the overburden; C: Pathways along faults; D: pressure creates new permeabilities in the rock; E: leakage via poorly sealed boreholes; E: lateral dispersion of through the overflow of drop structures; G: dissolved in formation water is transported to areas near the earth's surface.

However, CO_2 can only escape from the storage site if it is in the secondary phase – i.e. in a liquid or supercritical state. As soon as storage mechanisms take effect and the CO_2 is bound by dissolution or mineralisation (or adsorbed by coal), the risk of leakage decreases enormously (IPCC 2005). Despite the large number of potential pathways for CO_2 from the storage site, major leakage of carbon to the seabed, for example, is rather unlikely and relatively easy to detect early on throughout comprehensive MMV programmes (section 3.5.2) (IEA 2022; BEIS 2023; ZEP 2019).

Nevertheless, the leakage of carbon existing in secondary phase or brine from the storage site may occur via several different pathways (Figure 12):

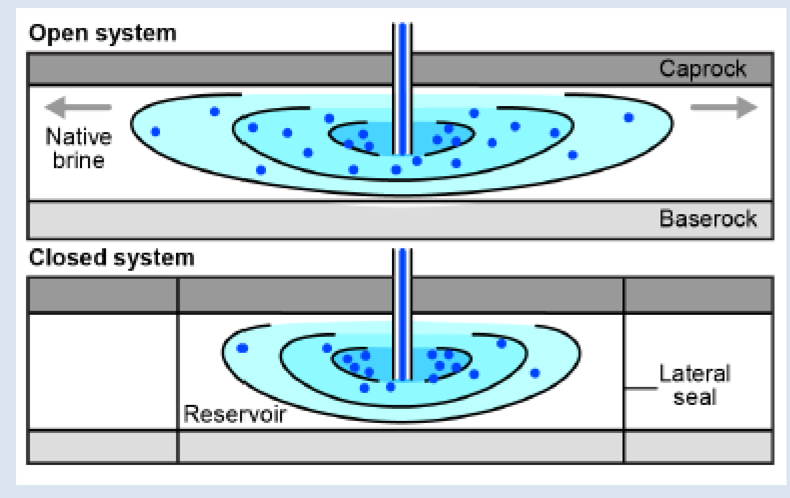
A and B: Fractures and pathways in the seal lead to permeabilities in the natural barrier structures of the storage complex. These are mainly triggered by fracture failure of the rocks (A) in the storage complex due to excessive pressure conditions in the reservoir during injection (Figure 10, Figure 11). Insufficient caps (B) such as dehydration or shrinkage of the cap rocks are usually detected during the comprehensive pre-injection storage site characterisation. Therefore, it is extremely unlikely that carbon storage sites with moderate to major leakages (50 to >1,000 t per day) due to insufficient cap rocks (B) will be viable CO_2 storage sites (BEIS 2023).

C and D: Faults can give pathways for CO_2 to migrate due to newly created permeabilities in the rock. Pathways may be triggered by high pressure of CO_2 or displaced brine. Natural permeabilities or tectonically active areas are avoided during comprehensive pre-injection storage site characterisation. Therefore, it is extremely unlikely that CO_2 storage sites with moderate to major leakages (50 to >1,000 t per day) along large faults will be viable CO_2 storage sites (BEIS 2023). Newly created permeabilities along faults (C) or their reactivation (D) is mainly triggered by excessive pressure conditions in the reservoir during injection (Figure 10, Figure 11).

E: Poorly sealed injection wells can also cause CO_2 leakage. This also includes unknown, disused, and abandoned wells from previous anthropomorphic activities, such as legacy drilling wells and earlier mining activities (onshore). At offshore storage sites, seep leakage (less than 1 t per day) through minor cracks in the casing cement of offshore wells, for example, are likely to reach the seabed. These may be considered easily dispersed or absorbed into seawater. MVV programmes can detect seep leakage relatively reliable. Nevertheless, seep leakage is expected to be unlikely to be remediated once established (BEIS 2023). Leakages with minor to moderate release rates (<1,000 t per day) are less likely to happen but more likely to be remediated (within 6 months after detection). Major leakage rates (greater than 1,000 t per day) are an unconstrained flow rate and are more likely occur due to technical failure during injection (Figure 10, Figure 11).

F and G: Storage reservoirs are usually favoured for their naturally suitable storage site geometry (Figure 13). This involves stratigraphic or structural barriers and traps that seal (close) the storage site vertically and laterally (IPCC 2005; IEA 2022). In cases in which open system storage sites are chosen, migration and escape of CO_2 from the storage complex due to overflowing CO_2 plumes or displaced brine bypassing natural stratigraphic or structural barriers and traps poses risks to storage integrity (Haase 2015; IEA 2022). (Semi-)open storage systems with non-ideal seals can also provoke displaced brine to leak through the seals into overlying/underlying formations due to natural flow in formation water (G). Both cases have an imminent impact on pressure conditions and injection rate in the reservoir and have to be addressed during MVV programmes (Zhou et al. 2008).

Figure 13: Storage system geometry



Source: IEA (2022)

3.2.2 Permanence

The question of whether carbon storage in geological formations deep underground is permanent is inevitable when assessing the viability of geological storage of CO_2. The longevity of geological storage will ultimately determine the extent to which carbon storage technologies can contribute to the mitigation of the climate crisis.(IPCC 2005; GCCSI 2019; IEA 2022; IEEFA 2023; ZEP 2019).

Already the IPCC (2005) claimed that leakage rates of less than 0.01% per year would have to be guaranteed to fulfil the climate targets, which would correspond to the storage of 99% of the injected CO_2 over a 100 years. Moreover, natural systems have shown that reservoir seals exist that confine CO_2 for millions of years and longer (IPCC 2005; ZEP 2019).

When geological storage mechanisms take place, it is relatively probable for CO_2 to be trapped permanently.[16] This is even more so the case when favoured processes such as dissolution of CO_2 in formation water and subsequent mineralisation absorb CO_2 geochemically. However, individual storage mechanisms take time to catch hold of CO_2 in the reservoir and may properly work after a few dozen to several hundred years. And yet, not all parts of the CO_2 may be trapped in the end by favoured storage mechanisms (Wuppertal Institut 2007; CO2GeoNet 2010; Kühn 2011). However, storage mechanisms that rely on structural or stratigraphic trapping, and residual trapping already most likely guarantee that CO_2 is stored for a long time. Therefore, the IPCC (2005) considers that 99% of CO_2 is still stored geologically after a 1,000 years. The German Environment Agency argued early on that leakage rates of 0.01% should not be exceeded in order to ensure that at least 90% of the injected CO_2 is retained even after a 1,000 years (UBA 2006).

Wallmann (2023) suggests using natural gas leakage rates in the North Sea, which amount to around 1-30 tonnes per year, as a reference. Accordingly, similar CO_2 leakage rates could be expected (Vielstädte et al. 2019). In addition, Wallmann (2023) points out that supercritical carbon has higher densities when compared to less dense natural gas and that carbon storage reservoirs usually lie deeper underground. These lead to the assumption that leakage rates of CO_2 could certainly be expected to be lower than the observed leakage rates of natural gas. As current CO_2 storage projects

16 Several tens of thousands of years (Figure 4).

envisage injection rates of several million tonnes of CO_2 per year, only a few tonnes of CO_2 would be released each year when taking natural gas leakage rates into account. Wallmann (2023) therefore assumes annual CO_2 leakage rates of approx. 0.0001% of CO_2 under the North Sea, which would correspond to a permanent retention of more than 99% of CO_2 in the subsurface (IPCC 2005; ECO2 2014c). GCCSI (2019) discusses a study by Alcalde et al. (2018), which still calculates a 50% probability of CO_2 that, even after more than 10,000 years, more than 98%, or 78% of CO_2 respectively (in a worst-case scenario) of the injected CO_2 would still be trapped underground.

Even if no proof of the permanent storage of CO_2 in geological formations has been provided yet, there is a broad scientific consensus that – with the technical feasibility and the necessary safety measures – CO_2 storage in geological formations deep underground not only has the goal but also the potential of making a permanent contribution to addressing the climate crisis (IPCC 2005; GCCSI 2019; CDRmare 2023; ZEP 2019).

3.3 Environmental hazards of carbon storage

Both technical and geological risks entail significant impacts on the environment that may result in fundamental hazards not only for human health but also for the earth's entire flora and fauna. Although seismic activity leading to deformation and movement of geological formation may also affect ecosystems on the earth's surface, primary leakage of CO_2 and/or formation water impose environmental hazards. However, environmental impacts and hazards are always determined by the way in which CO_2 and/or formation water escape from the storage site (IPCC 2005).

The following sections reflect on various scenarios of risk materialisation (3.3.1) and their potential impacts on and hazards for the environment (3.3.2 to 3.3.4). Finally, section 3.3.5 shows indirect impacts that the industrial ramp-up of carbon storage poses to the environment.

3.3.1 Release scenarios

Scenarios of the uncontrolled release of CO_2 and/or formation water from the storage site either comprise short-term leakage with major quantities of releases (e.g. eruptions during technical processes) or long-term leakage with low escape rates (e.g. slow release of CO_2 through natural or manmade pathways from the storage site) (EC 2009; ZEP 2019). The impact of environmental hazards also depends heavily on which substances are leaking from the storage site and in which form they reach the different environments. For example, the direct release of CO_2 to the water column at the ocean floor or to the atmosphere at the earth's surface has different impacts on the specific environment than the release of high salinity formation water to near surface areas (sections 3.3.3 and 3.3.4). An uncontrolled release of hazardous substances from the storage site can also affect different ecosystems at different times and different extents.

However, the severity of a threat to marine or terrestrial ecosystems always depends on the volume of gas leaked and the intensity of the leakage (IPCC 2005; IEA 2022). On the one hand, quick, intense releases of large quantities of CO_2 (50 to 1,000 t per day, see section 3.2.1) would result in fundamental impacts on the environment in the direct vicinity of the leakage. On the other hand, unrecognised long-term leakage (1-30 tonnes per year, see section 3.2.2) may tend to affect the direct vicinity of the release, slowly leading to long-lasting effects on the environment up to irreversible shifts in the ecosystems. Moreover, slow unremedied releases of CO_2 may even hinder the fulfilment of climate goals if they reach the earth's atmosphere (CIEL 2023; ZEP 2019).

Furthermore, impacts and hazards for the environment depend on the premises of the release (ZEP 2019). Leakage of CO_2 and/or formation water can either directly reach ecosystems (e.g. marine seabed or the earth's surface) or contaminate neighbouring geological formations, leading to interaction with other underground resources when escaping from the storage site (BGS 2014). While the former tends to involve marine environments during offshore carbon storage, the latter may rather conflict with other onshore underground utilisations during onshore carbon storage. Nevertheless, both scenarios will manifest different impacts and hazards for the environment.

3.3.2 Hazards to human health

In principle, leakage can induce direct emission of CO_2 into the atmosphere. This can lead to the exposure of humans to high CO_2 concentrations in the ambient air having significant impact on human health (IPCC 2005; HSE 2011; Roberts et al. 2011). However, hazards due to exposure of humans to high CO_2 concentrations in the ambient air primarily concerns onshore carbon storage.[17]

HSE (2011) emphasises that even a few minutes of exposure of elevated CO_2 concentrations that are above the natural level[18] are enough to cause immense damage to human health.[19] Accordingly, toxicological symptoms in humans range from headaches when exposed to CO_2 concentrations of 3% for one hour to increased respiratory and heart rate, dizziness, muscle twitching, confusion, unconsciousness, coma, and death when exposed to CO_2 concentrations of 15% for one minute. Therefore, toxicity relies heavily upon concentration and time of exposure. Asphyxiation is imminent with CO_2 concentrations of 50% and above (HSE 2011).

Nevertheless, dangerous toxic loads (DTL) that consider concentration and duration of exposure to quantify damage to human health are reached within significantly lower concentrations (Table 4). IN this context, HSE (2011) introduced a significant level of toxicity (SLOT) and the significant likelihood of death (SLOD).

[17] For offshore carbon storage, the risk is extremely low as either CO_2 is leaking at the seabed and dissolves quickly in the open water column (section 3.3.3) or distances from exit point to present humans are usually quite large. Generally, only workers at offshore carbon storage facilities could be at risk in the case of accidents associated with offshore facilities.

[18] Usually, ambient air contains CO_2 concentrations of approx.300 to 400 ppm (up to 600-900 ppm in urban areas) that are essential to human life. Levels below 1,000 ppm are expected to be hygienically harmless (HSE 2011). Levels above 2,000 ppm are hygienically inacceptable. In the EU, for example, the maximum concentration of CO_2 for a long-term and repeated exposure at work has been set at 9,100 mg/m³ (5,000 ppm), defined as a concentration with no adverse effects on health. The OSHA standards also recommend 5,000 ppm (0.5%) as the Permissible Exposure Limit (PEL) and ACGIH Threshold Limit Value (TLV) for 8-hour exposure, https://www.osha.gov/publications/hib19960605.

[19] Exposure to elevated CO_2 concentrations comprise symptoms like possible drowsiness at 10,000 ppm (1.0%), mild respiratory stimulation for some people at 15,000 ppm (1.5%), moderate respiratory stimulation, increased heart rate and blood pressure at 30,000 ppm (3.0%), immediately dangerous to life or health at 40,000 ppm (4.0%), strong respiratory stimulation, dizziness, confusion, headache, shortness of breath at 50,000 ppm (5.0%), up to dimmed sight, sweating, tremor, unconsciousness, and possible death starting from 80,000 ppm (8.0%), https://www.fsis.usda.gov/sites/default/files/media_file/2020-08/Carbon-Dioxide.pdf.

Table 4: Concentration vs time consequences for CO_2 inhalation

Inhalation exposure time	SLOT: 1-5% Fatalities		SLOD: 50% Fatalities	
	CO_2 Concentration in air*		CO_2 Concentration in air*	
	%	ppm	%	ppm
60 min	6.3%	63 000 ppm	8.4%	84 000 ppm
30 min	6.9%	69 000 ppm	9.2%	92 000 ppm
20 min	7.2%	72 000 ppm	9.6%	96 000 ppm
10 min	7.9%	79 000 ppm	10.5%	105 000 ppm
5 min	8.6%	86 000 ppm	11.5%	115 000 ppm
1 min	10.5%	105 000 ppm	14%	140 000 ppm

Note: * Concentration by volume

Source: HSE (2011)

However, realistic CO_2 concentrations associated with leakage from carbon storage are difficult to predict (HSE 2011; Roberts et al. 2011; Roberts and Stalker 2020). HSE (2011) draws from accidents in the past; for example, an accidental release of approx. 15 t of CO_2 from a fire extinguishing installation under still wind conditions in Monchengladbach, Germany in 2008 led to 107 people becoming intoxicated, of whom 19 were hospitalised.

Several studies use natural leakage rates of CO_2 in Italy (Roberts et al. 2011). In Italy, natural seepage has caused several fatalities of humans (~20) and animals (several dozens) over the last decades[20] (BGS 2014). The monitoring of the natural seep leakage shows a common flux of 10-1,000 t per day which resemble leakage rates of 0.1-1% by IPCC (2005) for a storage facility injecting approx. 3.6 Mt per year. Roberts et al. (2011) refers to modelled leakage rates from carbon storage sites to the earth's surface that are typically several orders of magnitude lower than those from Italian natural gas seeps.

Generally, the health impact of a hazardous exposure of CO_2 in humans relies heavily upon various factors that strongly affect exposed CO_2 concentrations in the ambient air (HSE 2011; BGS 2014; Roberts and Stalker 2020; Li et al. 2022):

- Intensity and duration of CO_2 leakage (e.g. phase, temperature, flow flux);
- Whether gaseous CO_2 leaks directly at the earth's surface;
- Local topography surrounding the exit point;
- Weather conditions (primarily wind speed and direction[21], and precipitation);
- Human behaviour and health predisposition of individuals (symptoms can vary drastically between individuals).

[20] Roberts et al. (2011) quantifies the risk of death from CO_2 poisoning in the population from Italian seeps at 2.8 x 10^{-8} y^{-1}, which is interpreted as extremely low and compares roughly to the risk of accidental domestic death from CO poisoning in UK households (9.2 x 10^{-7} y^{-1}).

[21] Experience gathered with atmospheric CO_2 monitoring shows that relatively low wind speeds (5 – 6 ms^{-1} at 2 m above ground) already lead to well-mixed ambient air concentrations. BGS (2014) therefore assumes that CO_2 does not reach hazardous levels unless under very still conditions.

Therefore, there is broad consensus that the general risk for humans to be exposed to hazardous CO_2 concentrations in the ambient air – even when carbon storage containment fails and stored CO_2 leaks to the surface – is comparatively very low (IPCC 2005; HSE 2011; Lary et al. 2012; BGS 2014). Roberts et al. (2011) even states that the current public concern regarding death by CO_2 leakage from onshore storage sites is overamplified, especially when compared to other socially acceptable risks.

Nevertheless, experiences gathered in the past have shown that natural degassing of CO_2 can cause death, even if frequency of incidents has been extremely rare (HSE 2011; Roberts et al. 2011). Whereas a relatively low risk of hazards to human health may apply to carbon storage, risks of major accident hazards (MAH) during CO_2 transport or injection associated with release of supercritical CO_2 must be considered and addressed differently (HSE 2011). In the case of transportation[22] of impure CO_2, admixtures also could pose a risk to human health when released (BGS 2014).

For safety reasons, HSE (2011) defines danger zones of up to 400 metres around the point of emission in the case of major short-term releases like MAH. Based on CO_2 concentration behaviour models that consider different topographies and weather conditions around wellbores, Li et al. (2022) assume lethal risk level zones with CO_2 concentration thresholds associated with health risks within a radius of 28 m around the wellbore. Downwind areas within 300 m of the wellbore have a moderate risk level. The authors indicate that those areas and areas between wellbores may not be suitable for human habitation and other land uses. BGS (2014) also emphasises that onshore carbon storage sites in the immediate vicinity of urban areas generally harbour a higher risk potential – an assumption that also holds for the transportation network. The main challenges and uncertainties in the future will be to more accurately assess and define potentially hazardous CO_2 concentrations in ambient air that pose risks to human health (IPCC 2005).

3.3.3 Hazards to marine environments

In the case of offshore storage, hazards to marine environments associated with CO_2 leakage arise either from the direct release of CO_2 into the water column at the ocean floor or from the accumulation of hazardous substances within the benthic zone[23]. In both scenarios, elevated concentrations of CO_2 and hazardous substances may change living conditions, mainly causing strong loss of biodiversity in different marine communities (UBA 2008b; ECO2 2014a; 2014b; BGS 2014). However, observations are mostly based on laboratory experiments and there is a lack of field studies on the specific effects of CO_2 on marine environments (UBA 2008b; ECO2 2014a; 2014b).

Gaseous CO_2 leaks at the sea floor in the form of bubbles assembling to a buoyant rising plume. As CO_2 is highly soluble in seawater, it will dissolve rapidly within the first metres on the ocean floor. While gaseous CO_2 escapes and disperses rather quickly, CO_2-enriched formation water dwells longer in high concentrations on the sea floor, thereby posing hazards to the benthic environment (BGS 2014).

In the benthic zone, hazards to marine communities originate due to the accumulation of hazardous substances, such as gaseous CO_2, enriched CO_2 and high salinity formation water, minerals with toxic effects, and chemical reaction products (e.g. amine, ammoniac) both below seabed in the upper soil layer of the ocean floor sediments and in the ocean floor water column (UBA 2008b).

[22] The need for purification of the stream is discussed under technical risks during carbon transport and injection (section 3.1).
[23] The benthic zone comprises all communities of organisms which live on, in, or near the seabed.

ECO2 (2014a) expects that salt-rich, CO_2-enriched and therefore oxygen-depleted fluids can impair benthic marine fauna severely in the immediate vicinity of the leakage as conditions influence fundamental marines processes such as photosynthesis and calcification (BGS 2014). Experiments show that a decrease of bottom water pH values[24] associated with acidification primarily impedes the growth of organisms with calcareous skeletons[25] as they use relatively easily soluble modifications of calcium carbonate for skeletal construction. This may also hold for corals that show slower growth in experiments at lower pH values (UBA 2008b). This also applies to cold-water corals commonly found in the North Sea and the North Atlantic.

Generally, direct influences of reduced pH values and elevated CO_2 concentrations are expected to concern the physiology of benthic organisms as conditions impede biochemical processes. Impacts on the acid base regulation, nitrogen metabolism, and ion homeostasis, for example, are known to impede the reproduction and growth of organisms and lead to higher mortality rates (UBA 2008b).

However, experiments showed that bacteria and other unicellular organisms within the seabed sediments tend to react to changed living conditions by significantly increasing, whereas foraminifera, nematodes and other microorganisms decreased. Therefore, ECO2 (2014b) assumes effects of exposures to elevated CO_2 to be highly species-specific as some benthic species may exhibit extreme tolerance to changed living conditions in the short and medium term.

While immediate effects are only observed as a result of exposures at remarkably high CO_2 concentrations, long-lasting minor impairments still can lead to the long-term damage of marine communities. Accordingly, leakage from carbon storage could provoke changes in marine community structures at the base of the food chain up to shifts in benthic ecosystems in the immediate vicinity of a source (ECO2 2014a; BGS 2014).

In the event of major long-lasting leakage with extremely large quantities of released CO_2, CO_2 plumes could also rise into the open water column. This would lead to significantly elevated CO_2 concentrations and changes in pH values, affecting inhabitants of the open water in a similar way to benthic organisms (UBA 2008b). While nektonic species like fish and cephalopods are expected to avoid areas strongly impacted by CO_2 leakage, unfavourable living conditions would tend to affect planktonic species that cannot escape exposures actively. However, if unfavourable living conditions concern fish spawning ground or nursery areas, avoidance would lead to changes in reproduction and the growth of fish populations directly affecting community structures (BGS 2014). Moreover, species of the open water are generally less resilient to changing living conditions than the benthos, resulting in significant impacts on organism health and further weakening a species that already has a low adaptability (ECO2 2014a).

Major CO_2 leakage to the open water column primarily concerns phytoplanktonic communities which will experience the strong influence of unfavourable living conditions. Changes of pH values could trigger planktonic communities changing structure and reproduction, leading to, for example, shifts of algal blooms (UBA 2008b). Calcifying species (e.g. coccolithophores) could experience similar effects as benthic species suffering from modifications of calcareous skeletons. Contrarily, elevated CO_2 concentrations trigger primary production leading to an increase of species depended on photosynthesis (e.g. planktonic, and benthic algae, and macrophytes). Shifts in the planktonic ecosystem are observed, for example, in shallow Mediterranean waters and therefore could also have influences on the marine food chain (ECO2 2014a; 2014b). Nevertheless, phytoplankton species generally live close to the sea surface in light-flooded waters and would only be at threat in relatively

24 BGS (2014) assume leaked CO_2 could theoretically reduce local pH values by as much as 2 pH units (equivalent to two orders of magnitude increase in acidity). However, this would involve extreme circumstances.

25 E.g. starfish, sea urchins; mollusks as snails and mussels.

shallow waters as the CO_2 plume most likely disperses before reaching light-flooded water layers in deeper waters. Therefore, such responses would most likely not occur in the North Sea (ECO2 2014a; 2014b).

Research conclusively expects cumulative feedback effects as dense seawater due to high concentrations of dissolved of CO_2 tends to sink to the ocean floor, leading to even more critical conditions near the ocean floor. BGS (2014) assumes that salt-rich, CO_2-enriched and oxygen-depleted fluids could spread to areas that are several tens to hundreds of metres from the source. Consequently, the benthic zone with its sessile and immobile biota will experience most of the environmental impacts during leakage of CO_2 and/or formation water as benthic communities would be exposed to a long duration moderate decrease in pH values. Moreover, results from experiments suggest that long moderate exposure to unfavourable living conditions is more damaging to biota than short but severe perturbation events (BGS 2014).

However, the extent of affected areas always depends on leakage flow rate and phase of leaked substances. Furthermore, the time of year, depth and local bathymetry determine the setting of unfavourable living conditions (UBA 2008b). As for the cool temperate North Sea, strong tidal and local currents (e.g. sea passages) will be the main drivers for leakage plume dispersion as tidal movements accelerate the mixing of water masses through elliptical movement patterns (BGS 2014; ECO2 2014a). Therefore, natural variability in driving conditions and heterogeneities makes it difficult to predict complex plume behaviour around leakages. Nevertheless, dispersion is expected to occur rapidly affecting immediate vicinities around the source (ECO2 2014a). Models suggest that such areas could still extend over areas of several meters to kilometers (BGS 2014).

ECO2 (2019) draws from experiments that suggest seafloor areas in the central North Sea where leakage of CO_2 lowers bottom water pH values by more than 0.5 units to be less than 10 m^2 in size assuming realistic flow flux (~20 t/yr). The simulation[26] of such flow flux equivalent to leaky wells limit the detectable pH anomalies in a narrow bottom water plume to less than 50 m from the source. Worst case scenarios[27] with 55,000 t/yr (emitted over a circular area of 50 m in diameter in water depths of 95 m) show less than 1 km^2 of affected area. ECO2 (2019) concludes that benthic organisms appear to be exposed permanently to low pH bottom water but tend to periodically experience impacts due to tidal currents. Furthermore, the environmental impact associated with sub-seabed carbon storage is assumed to be possible but rather small, even during the industrial ramp-up of offshore carbon storage in the European North Sea.

BGS (2014) comes to a similar conclusion based on three scenarios in a regional model of the SW English Channel, which represent the typical conditions of the NW European shelf in terms of tidal strength and hydrodynamic properties (Table 5). BGS (2014) assumes that only the temporary leakage ‘pipeline rupture’ event (9,000 t) and the continuous high diffuse leakage events (1,500 t/d) produce significant pH changes, leading to biochemical impacts over an initial 10 day period. For the low diffuse scenario (4 t/d), significant pH changes are expected for the very epicenter over the leakage dispersing within a few meters from the source.

[26] Models considered both low (10 cm/s) and high (25 cm/s) bottom current velocities.

[27] Worst case leakage rates resemble methane emission flux during natural gas blowouts.

Table 5: Physical scale of marine leakage scenarios

Release scenario	Flux Rate	Size of affected area	Impacts	Duration of impact
Continuous leakage* (Low diffuse)	4 t/d	< few meters**	No impacts visible**	No impacts visible**
Temporary leakage (e.g. rupture of pipeline)	9,000 t	~150 km^2***	Significant biochemical impacts due to pH changes	~72 hours***
Continuous leakage* (High diffuse)	1,500 t/d	~9 km^2	Significant biochemical impacts due to pH changes	Over entire observation period*

Source: Author's own compilation based on BGS (2014)

Notes: Only pH changes over 0.3 units as this falls under the natural variation.
*: initial observation period of 10 days;
**: authors expect significant pH changes at the very epicentre of the leak only penetrating a few meters of the source which is not visible due to the used model resolution;
***: after 72 hours the plume is fully dispersed and no harmful CO_2 concentrations remain.

The impact of a 'pipeline rupture' event appears to be relatively short-lived with an initially dramatic impact (~150 km^2). However, models suggest that the hazardous plume has dispersed after 72 hours into the observation period and no harmful CO_2 concentrations remain (BGS 2014). The continuous high diffuse event would lead to an affected area of approx. 9 km^2, indicating a relatively constant low pH and ecologically harmful conditions (Table 5). For both, models show areas of an additional ~120 km^2 with pH changes of less than 0.3 units which fall under natural variations[28] and given the short exposure duration would not produce any significant biochemical impacts. BGS (2014) therefore expects that unfavourable living conditions with significantly lower pH values than found naturally are confined to the immediate vicinity of the leakage only.

Box 3: Hazards to terrestrial environments

In the case of onshore carbon storage, leakage of CO_2 and/or formation water may have several impacts on the terrestrial environment when reaching the earth's surface. However, IPCC (2005) has already pointed out that the probability of CO_2 and/or formation coming into contact with plants and animal in shallower soils is generally low.

Nevertheless, elevated CO_2 soil concentrations may lead to soil acidification that would have degradation effects on plants and organisms of the pedosphere (BGS 2014). Generally, the plant response to increased CO_2 is relatively rapid. BGS (2014) observed that broad-leafed plants become stressed within 7-14 days of exposure, dying after a few weeks of continued exposure while plants with well-developed root systems appeared to be more resilient to increased CO_2 concentrations. Generally, the environmental impacts of terrestrial ecosystems depend on the predisposition of the environment like density of vegetation and population of organisms and animals, exposure to other environmental stresses, and prevailing environmental conditions like wind speed and precipitation, and local topography (BGS 2014).

However, it is well established from natural seepage in volcanic regions that elevated CO_2 concentrations at the surface lack vegetation (IPCC 2005). However, the environmental impacts are not expected to cause large decreases in yields from crops having little economic impact as leakages only affect small areas, a fact that must viewed in the context of other environmental stressors (e.g.

28 Factors like temperature, seasonal effects, riverine flows, and the Baltic input drive natural variations in pH values.

weather extremes, disease, and pests) which are likely to have greater overall impacts on crop yields (IPCC 2005).

With regard to direct emissions of CO_2 into the atmosphere, of course, animals and plants would experience harm in the same way as humans (3.3.2). Other hazards for terrestrial ecosystems involve groundwater pollution from CO_2 leakage or brine displacement (3.3.4). Moreover, BGS (2014) indicates that the effects of displaced formation water could severely harm biologically active areas and should not be neglected when discussing environmental hazards from leakage.

3.3.4 Resource interaction risks

When CO_2 and/or formation water leaks from the storage site, there is the general risk that released substances potentially interact with underground resources of the neighbouring geological environment, posing hazards to the environment (IPCC 2005; IEA 2022).

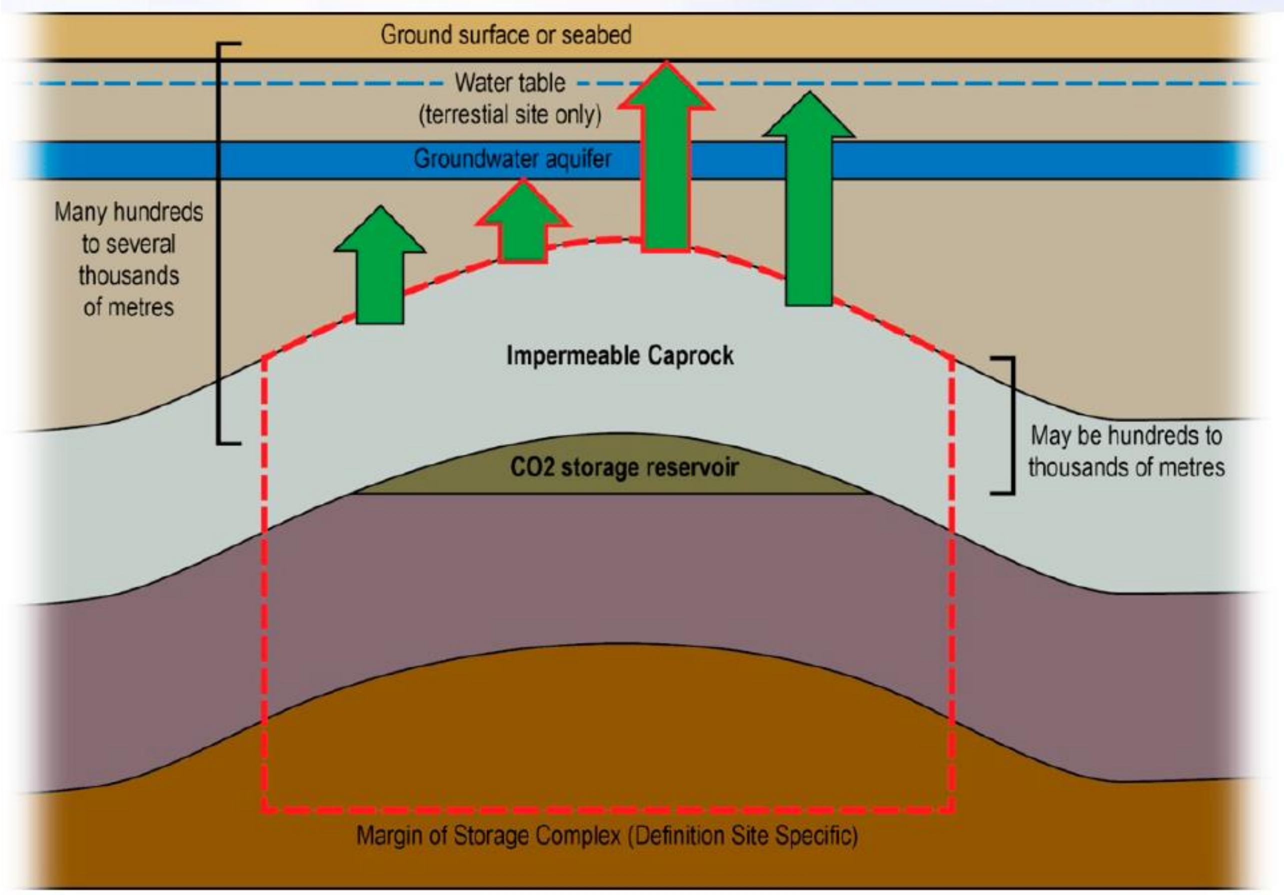
This particularly applies when CO_2 and/or formation water escapes the storage complex migrating to near-surface areas where it may potentially contaminate underground resources such as shallow groundwater and raw material deposits, leading to chemical reactions and/or mobilisation of toxic minerals (IPCC 2005; BEIS 2023). In principle, groundwater contamination can occur both because of hazardous substances escaping from the storage site and because of the migration of hazardous substances that have been mobilised and contaminated. As a result, groundwater may be exposed to pollutants like heavy metals, radionuclides, and displaced brine or hydrocarbons leading to acidification and contamination of groundwater resources. IPCC (2005) indicates that worst case scenarios would involve displaced brine infiltrating the groundwater, affecting wildlife habitats, restricting or eliminating agricultural use of land and polluting surface waters.

Resource interaction with raw material deposits (e.g. coal, hydrocarbons, minerals) bears the risk of rendering resources unusable or more expensive to mine (BEIS 2023; UBA 2023b). This also holds true for other underground utilisations (e.g. deep geothermal energy systems, H_2 storage, repositories for high-level radioactive waste, etc.) that are potentially at risk of interference from hazardous substances from the storage site.

In the case that hazardous substances reach the earth's surface, contamination of soil would result in a reduction in soil quality accompanied by a deterioration of soil air and soil acidification (IPCC 2005; IEA 2022). As a result, contamination would fundamentally affect pedosphere ecosystems, harming microorganisms, plants, and animals. Consequently, ecosystems could shift locally and become unstable.

However, effects on subsurface resources and near-surface ecosystems heavily depend on the geology, geomorphology, soil type, and climatic conditions (BGS 2014). BGS (2014) indicates that the probability of CO_2 escaping from the storage complex (leakage) will be very low at suitable sited and well-operated storage sites. Additionally, leaking substances would have to migrate over large distances (hundreds to thousands of metres) to escape from the storage complex, putting near-surface underground resources and ecosystems at risk (Figure 14). Generally, deeper resource deposits are at a higher risk of natural leakage. Nevertheless, leakage from the storage complex along man-made pathways (e.g. abandoned wells) is possible.

Figure 14: Schematic illustration of CO_2 storage showing distances that leaked substances would have to cover to reach near-surface resources



Source: BGS (2014)

Due to land use, (sub-)surface resource interaction risks are mainly associated with onshore storage as mining activities usually takes place onshore. Because of the greater distances of storage sites to used underground resources, underground resource interaction poses less of a risk to offshore storage. In principle, this also holds true for groundwater aquifers that are generally located at a greater lateral distance from offshore storage sites which would involve a considerable horizontal transport depending on the distance from the coast (UBA 2023b). It is therefore considered to be relatively unlikely that leakage from offshore storage would reach continental groundwater aquifers.

3.3.5 Indirect impacts of marine CO_2 storage

Besides direct impacts of released CO_2 and/or formation water, the ecosystems involved will experience indirect impacts during the entire process chain of carbon storage projects. Although there is a lack of studies that involve CO_2 storage in particular, insights can be drawn from the implementation of various other marine infrastructures[29], such as the oil and fossil gas industry[30], deep sea mining, and deep sea cables of the electricity grid (CIEL 2023; McLean et al. 2020; McLean et al. 2022; EEA 2011; GEOMAR 2020).

[29] https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/other-assessments/shipping-and-ports/.
[30] https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/other-assessments/impacts-offshore-oil-and-gas-industry/?promo_name=QSR#6-references.

However, indirect impacts can occur from various sources during the entire life span of carbon storage. During the development of infrastructure, carbon storage projects include both the instruction of compressor stations, shipping terminals, and harbours and the roll-out of hundreds of kilometres of onshore and offshore pipelines. Therefore, land consumption due to the development of infrastructure should not be neglected. While the construction of terminals and harbours alter large areas of marine ecosystems leading to further degradations of, for example, coastal habitats of seagrass meadows, saltmarshes, and reefs, the roll-out of seabed pipelines only has a localised but fundamental effect on benthic habitats (McLean et al. 2020; McLean et al. 2022; CIEL 2023). Those impacts concern either the destruction of habitats directly or expose marine species to high stresses reducing resilience of ecosystems indirectly.

Whereas ship traffic is expected to only rise slightly due to CO_2 transportation, maintenance and monitoring activities depend upon the frequent traffic of ships and vessels. This also involves pre-injection baseline characterisation of the storage site geology that is usually carried out by ships conducting seismic surveys and sonar observation using sea surface airguns, hydrophones on streamers and swimming sonobuoys (CO2GeoNet 2013). Subsequent monitoring, measurement, and verification (MMV) programs during operation and after site closure also rely on systematic ship traffic to conduct repeated active seismic surveys to guarantee carbon storage safety. Recently, research has indicated that noise induced by active seismic surveys not only has fundamental impacts on mammals and fish in the open water column but also hugely affects marine zooplankton (Sivle et al. 2021; Vereide and Kühn 2023; Vereide et al. 2023; Vereide et al. 2024). Therefore, trade-offs arise from MMV programs performed to guarantee storage safety that cause adverse effects to the marine environment (McCauley et al. 2017).

Basically all technical processes along the entire process chain will produce emissions, such as noise and air pollution (CIEL 2023). High noise emissions primarily affect marine mammals, sea turtles, fish, and invertebrates, both of which are critical for ecosystems and already at serious risk of extinction (Abrahamsen 2012; Chen 2021; Solé et al. 2023). The main air pollutants comprise direct and indirect emissions of NO_x, SO_2, NH_3, non-methane volatile organic compounds (NMVOCs) and pollution due to Particulate Matter (PM) that have to be dealt with during operation[31] (EEA 2011).

However, EEA (2011) indicates that actual measurements are lacking from the research, which is often based on qualitative assumptions. Although carbon storage may be generally beneficial to mitigate both air pollution and the climate crisis, it is well established that efforts to reduce the emissions of one specific group of air pollutants may come along with trade-offs and antagonistic effects concerning the emissions of other pollutants. While carbon storage contributes to the removal of CO_2 from the atmosphere on a global scale, trade-off emissions of the above-mentioned air pollutants tend to harm ecosystems on a local scale.

3.4 Socio-economic and political risks

Social aspects such as public acceptability may play a key role in the deployment and possible industrial ramp-up of carbon storage projects in the future (Dütschke et al. 2022). Therefore, there are a broad variety of possible social, economic, and political challenges that can pose risks to carbon storage projects and may constitute feedback mechanisms to each other when not addressed early on.

[31] According to (EEA 2011), emissions from construction are rather negligible.

Socio-economic risks primarily concern risk perception and the public acceptability of carbon storage as part of critical infrastructure. Over recent decades, the deployment of critical infrastructure such as expansion of electricity grids and pipeline infrastructure, site selection for repositories for the disposal of radioactive waste, or the deployment of geothermal energy have, at least in Germany, repeatedly provoked moderate to major public and local opposition (Braun 2017; Themann and Brunnengräber 2021; CIEL 2023). Consequently, stakeholders draw from these examples the expectation that part of the public will be extremely critical towards geological carbon storage (EC 2009; NABU 2022; BMWK 2022).

Therefore, communicating risks and dealing with public risk perception plays a key role during the deployment and industrial ramp-up of carbon storage. There is a broad consensus in social science research that only early involvement and participation of the public can counteract the risks of local opposition and public protest (NearCO2 2011; Upham and Roberts 2011; Szizybalski et al. 2014; Fraunhofer ISI 2015; Dütschke et al. 2022). Wuppertal Institut (2023) emphasises that both onshore transport and the temporal storage of carbon and deployment of infrastructure is commonly perceived as a risk to society and proposes the implementation of clear transport policies and a regulatory framework as soon as possible (Anders et al. 2024). A lack of knowledge or inadequate science communication or political agendas carry the risk of providing the public with false information, with the result that public perception of a risk may jeopardize the deployment of carbon storage more than the hazard posed by the risk itself[32] (Fink and Ratter 2024).

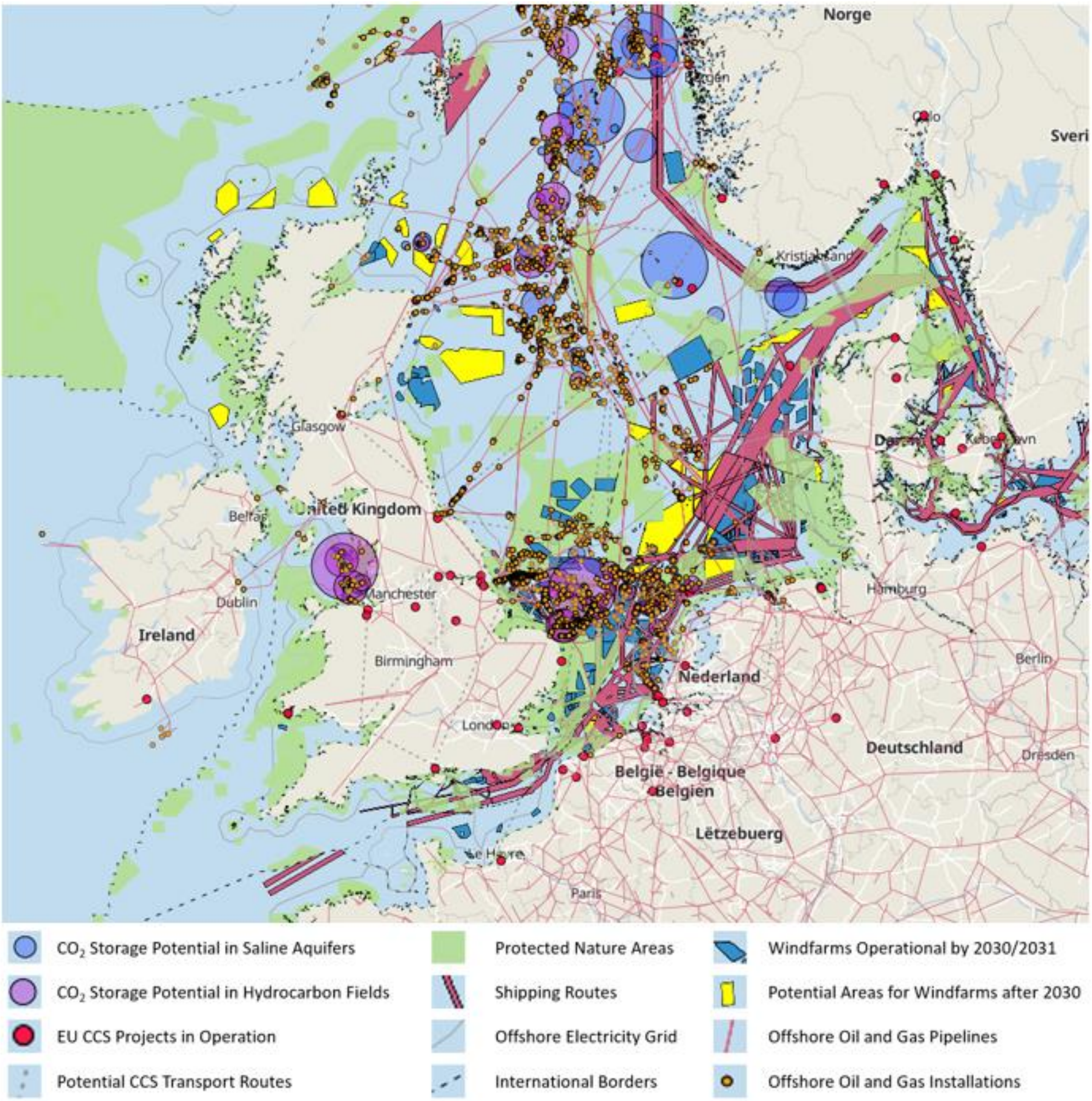
Generally, the risk perception and public acceptability of carbon storage are expected to be higher when carbon storage benefits the achievement of climate goals (Wuppertal Institut 2023). However, technologies such as EGR and EOR, which use CO_2 storage as a smokescreen to mitigate global efforts to phase out fossil fuels in order to justify fossil fuel expansion, carry the fundamental risk of jeopardizing public acceptance (UBA 2006; NABU 2022; CIEL 2023).

Socio-economic risks may also arise from land-consumption-based conflicts of interest between critical infrastructure during energy transition in the future (BGR 2024). The deployment of offshore carbon storage includes harbours and coastal hubs for transport and temporal storage, and loading, carbon container ships, the implementation of hundreds of kilometres of seabed pipelines, injection facilities on drilling platforms, and injection and monitoring facilities (SWP 2024).

Therefore, challenges may also arise from competing utilisations with other above- and underground resources and their infrastructure, such as deep-sea mining, offshore oil and fossil gas platforms, electricity grids, RES infrastructure, and nature protection reserves (SWP 2024; UBA 2023b). However, the offshore deployment of carbon storage mainly accounts for the already limited space on the water surface and will require maritime spatial planning (Figure 15). For pre-injection site performance characterisation and subsequent monitoring of carbon storage, ships systematically scan large areas on the sea surface to conduct 3D seismic surveys, which are also potentially used by shipping routes, commercial fishing, or windfarms. As a result, above sea surface land consumption might impair the characterisation of storage sites and monitoring of carbon storage (MEACP 2022; Catapult 2021; CDRmare 2023; May 2024). While land use on the sea surface could compromise the security of carbon storage, land use that prioritises carbon storage over the expansion of wind turbines could slow down the energy transition.

[32] For example, the public perception of induced seismicity is often worse than the impact posed by the risk itself (IEA 2022).

Figure 15: Land consumption of industrial, and energy utilisations and marine conservation in the North Sea



Source: North Sea Energy (2024)

EC (2009) also considers security aspects within the socio-economic and political risks. Carbon storage projects, with their infrastructure above and below the earth's surface, represent part of critical infrastructure that can always be the target of sabotage or terror attacks and must therefore be adequately secured (EC 2009; SWP 2024). Implementing the security of facilities is a prerequisite to mitigating environmental and economic feedback mechanisms which the damaged infrastructure or compensation payments for CO_2 releases would bring (SWP 2024). Generally, dependencies on other countries may always arise that should be considered.

Consequently, the feedback mechanisms of individual aspects may arise as consequences posing from socio-economic and political risks that are always related to each other and must not be neglected. There are economic risks due to unforeseen cost explosions, raw material bottlenecks, market situations, expensive long-term monitoring programmes or liability and insurance cases, and even absence of investments or their withdrawal and these will also feedback into the public perception and acceptability of carbon storage.

3.5 Risk management

Successful risk management involves the development of a strategy of measures in advance of carbon storage injection to reduce risks, guarantee safe operations, and meet authority requirements (IPCC 2005; EC 2009; Furre et al. 2020; May 2024). Moreover, regulatory requirements can determine the basic design of an overall risk management.

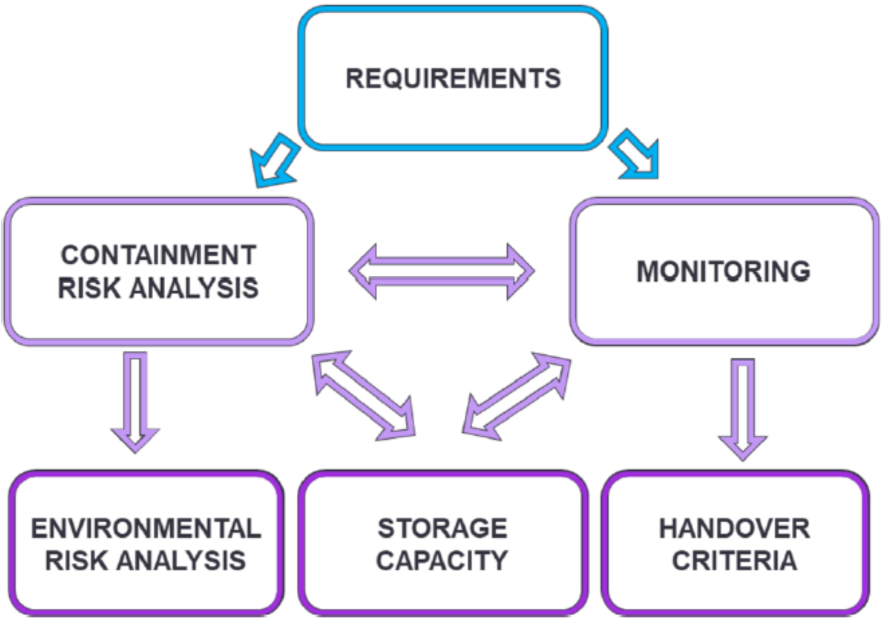
For risk management to meet the regulatory requirements, operators must carry out both a comprehensive containment and environmental risk analysis, and a solid monitoring programme over the entire process chain of carbon storage projects. This study builds on the premise that risk assessment and management for CO_2 transport can be derived from established measures and experiences gathered with common gas transport (Energinet 2023; RohrFLtgV 2002).

Therefore, this study focuses on the tools needed to establish an adequate risk management for carbon storage operations – specifically, the process steps from the pre-injection storage site characterisation until the handover of responsibility to the state authorities (May 2024). While section 3.5.1 outlines the important aspects during containment risk analysis (CRA), Section 3.5.2 addresses the monitoring, measurement, and verification (MMV) programmes. Both comprise the foundation of a required exploration program that could easily take several years to develop, depending on the geology of the storage complex (EC 2009).[33]

Nevertheless, CRA and MMV programmes are often considered to be essential barriers to not only ensuring carbon storage safety but also providing important tools to optimise injection and confirm storage volumes during operation (Furre et al. 2020). Thus, successful risk management is essential to prevent risks and to prepare for mitigation actions to minimise potential consequences in case risks and hazards materialise (EC 2009; May 2024). Figure 16 shows the interactions between prescribed regulatory requirements and the principal design of CRA and MMV programmes, and how they relate to each other.

[33] Exploration plans depend on the specific geological characteristics of a storage site and the level and availability of data with expenditures in the range of several tens of millions of Euros (depending on local drilling and seismic costs) (EC 2009).

Figure 16: Interaction between authority requirements, containment risk analysis (CRA) and monitoring



Source: Meneguolo et al. (2024)

After operations and storage site closure, EC (2009) proposes the possibility of handing over the responsibility for the storage site at least 20 years[34] after its closure to the responsible authorities of the respective EU member states. Therefore, handover criteria need to be imminently developed and should include the clear regulation of responsibilities between storage site operators and the responsible EU member states (NABU 2022; May 2024). However, evidence of containment and permanent storage is prerequisite for handover to the authorities.

The EC sets handover criteria that have to be met to enable the transfer of responsibility of geological CO_2 storage site to the authorities after closure (EC 2024b). Accordingly, operators must provide evidence of complete and permanent post-operational containment for the stored CO_2, fulfil the financial obligations, and prove successful site closure and decommission of injection facilities. Therefore, the actual behaviour of injected CO_2 must show conformance with modelled predictions. Furthermore, operators must demonstrate the absence of any detectable leakage and that the storage site is evolving towards long-term stability.

It should nevertheless be mandatory, especially from the perspective of future generations, for geological CO_2 storage to be monitored long term after the storage site has been handed over to authorities (May 2024). This serves not only to avoid risks but also to ensure that emissions are correctly accounted for. It should be urgently addressed so that the stakeholders involved, including site regulatory and licencing authorities as well as developers, investors, and the public, can be provided with assurance (see also the sections below).

[34] In Germany, according to Section 31 (1) KSpG (2012), at least 40 years are currently estimated for corresponding control and monitoring measures by the operators (BMWK 2024a).

3.5.1 Containment risk analysis (CRA)

The containment risk analysis (CRA) aims to identify CO_2 containment risks of the storage complex to assure storage and operational safety. CRA is a regulatory requirement and must be conducted before operation (IPCC 2005; EC 2009). For a successful CRA, operators must carry out baseline studies characterising the geology of the storage complex and potentially affected environments (Figure 16).

This involves a specific site characterisation to assess the reservoir units and its seals. While the assessment of the former focuses on the storage site performance, the assessment of the latter addresses potential leakage pathways within the storage complex (Zweigel et al. 2021; Meneguolo et al. 2024).

Assessment of the storage site performance provides knowledge concerning reservoir pressure conditions and allows for the modelling of CO_2 plume migration, reservoir pressure behaviour, and injectivity (Figure 17). Moreover, characterisation of reservoir units and conditions allows trapping fractions to be predicted, revealing the potential proportion of mobile and stored CO_2 over time. Thereby, modelled predictions display the storage capacity and therefore, contribute fundamentally to operational safety (Furre et al. 2020).

By assessing the storage complex and its seals, the CRA identifies potential leakage pathways[35] through which CO_2 may escape the storage complex. CRA also assesses actual leakages in terms of their potential impact and probability (Furre et al. 2020). Additionally, CRA identifies natural seismicity and potential environmental hazards using baseline studies for potentially affected environments above the storage site (environmental risk analysis, Figure 16). This involves, for example, mapping and analysing the seafloor and marine ecosystems.

Consequently, a comprehensive CRA guarantees safe monitoring and therefore sets the basis for establishing a site specific design for MMV programmes e.g. by defining key areas for focused monitoring[36] or choosing suitable[37] monitoring technologies (Furre et al. 2020; Meneguolo et al. 2024).

Box 4: Site performance characterisation of the Aurora storage complex as part of the risk management of the Northern Lights carbon storage project

In 2022, Northern Lights obtained their operation license (EL001) for the Aurora Carbon Storage complex. The EL001 license area comprises ~14 km^2 and lies approx. 80 km offshore the western coast of Norway in the North Sea at water depths of 300 m (Equinor 2022). The storage unit is the deep Dunlin saline aquifer at a depth of 2,700 m (Figure 17, c).

In 2020, Northern Lights applied for permission to build infrastructure to enable carbon storage of up to 1.5 Mt CO_2 per year. It is planned that EL001 will operate over a 10-year period followed by a second phase with a CO_2 injection of up to 5 Mt CO_2 per year (Equinor 2022). Site performance characterisation of the Aurora storage complex was part of the operating license for Northern Lights.

Figure 17 shows the predictions for the long-term storage site performance. Northern Lights aims to start operation in 2024.[38]

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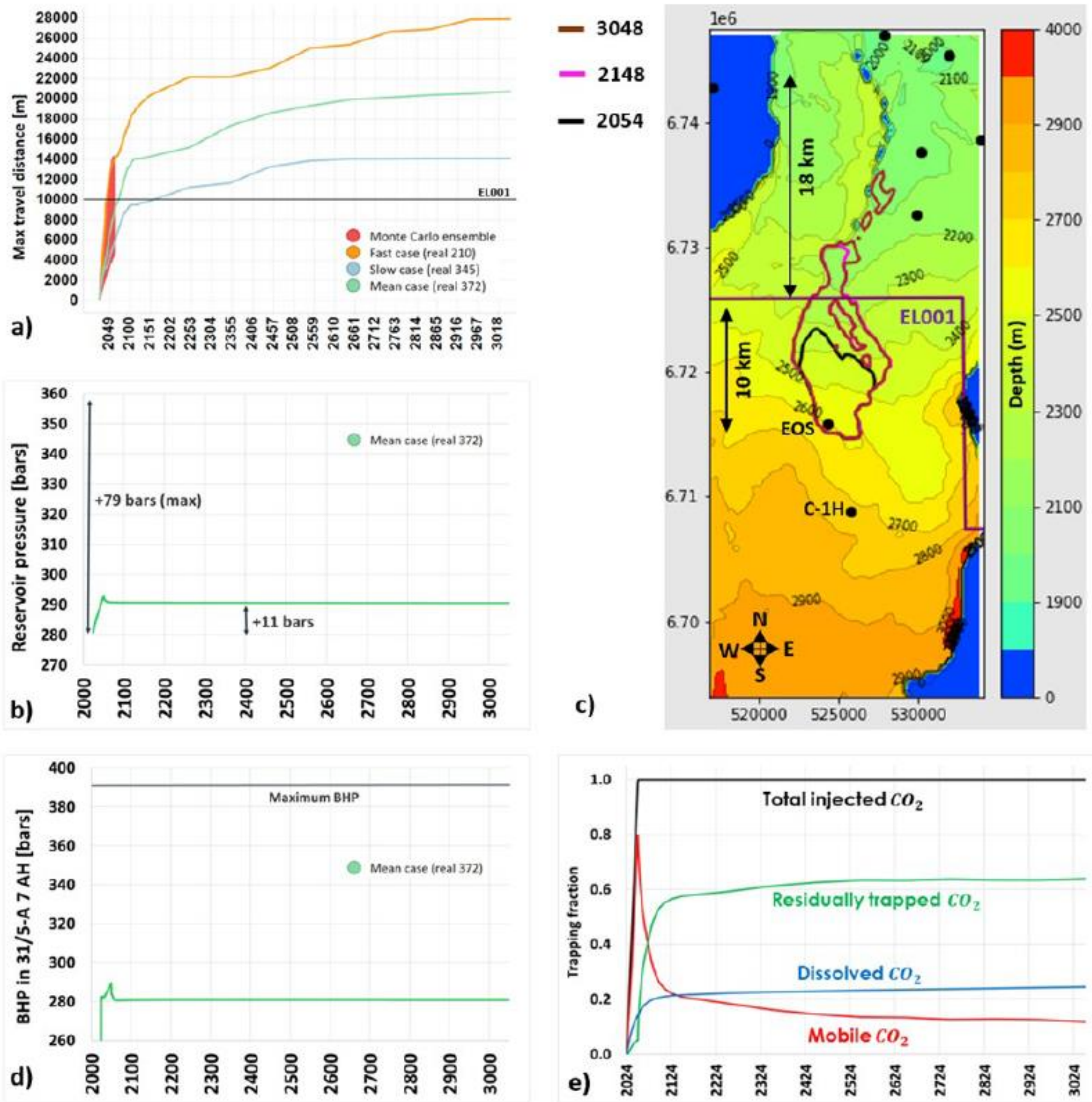
35 Both geological and man-made (well-related) pathways are identified.

36 Key areas of focused monitoring may exceed the principal monitoring of the CO_2 plume behaviour in the storage units in the event that CRA identifies remaining risks that necessitate special monitoring (e.g. legacy wells).

37 Considering, for example, reliability, feasibility, costs, land consumption, ship traffic, and the environment.

38 https://norlights.com/what-we-do/.

Figure 17: Modelling results of long-term storage site performance at the Aurora storage complex for the Northern Lights carbon storage project



Source: Equinor (2022)

Notes: a) Maximum migration distance versus time;
b) Reservoir pressure versus time; c) CO_2 distribution versus time;
d) Bottom hole pressure versus time; e) Proportion of mobile and stored CO_2 over time.

Geological and dynamic reservoir simulations for the Aurora storage complex predict the CO_2 to migrate relatively quickly from the EOS injection zone northward, up-dip within the Dunlin Group units (Figure 17, c).

Migration from the operating license is expected to occur after several decades when it is ultimately trapped under a structural high located approximately 400 m below the Troll West field, more than 20 km away. Site performance modelling results predict that the proportion of mobile CO_2 will decrease rapidly within the first few decades after injection begins (Figure 17, e).

Approx. 50 years after injection, models assume at least 65% of the injected CO_2 will be trapped residually and about 25% will have dissolved in brine, with both fractions continuously increasing over time. Mineralisation[39] is expected to play a minor role when it comes to storage mechanisms and therefore is not visible in the modelling results (Equinor 2022).

This leads to the assumption that approx. 10% of the CO_2 remains in a supercritical and mobile phase, even after 1,000 years of operation. Nevertheless, Equinor is confident that full post-operational containment can be guaranteed by relying on structural and stratigraphic traps to contain the mobile CO_2.

3.5.2 Monitoring, measurement, and verification programmes

MMV programmes draw directly from the CRA findings and are essential to guaranteeing a safe carbon storage operation (Meneguolo et al. 2024; ZEP 2019). MMV programmes comprise the entire process chain of carbon storage projects from pre-operation baseline studies until the preparation of the handover to the governmental authority[40] (Figure 16). MMV programmes focus either on the subsurface geological reservoir formations (storage complex monitoring, SCM) including the entire storage complex, and the injection and legacy wells, or monitor infrastructure outside the storage complex, such as offshore facilities, pipelines, and onshore plants. Furthermore, MMV programmes also measure the environmental impacts (e.g. on the seafloor) to detect significant adverse effects in the carbon storage project surroundings (IPCC 2005; EC 2009). In the following, our analysis focuses on the design of subsurface geological reservoir monitoring.

Storage complex monitoring (SCM) pursues two main objectives:

- conformance to confirm actual CO_2 behaviour to be in accordance with previous predictions.
- containment through detection of leakages from the storage complex to assure storage integrity.

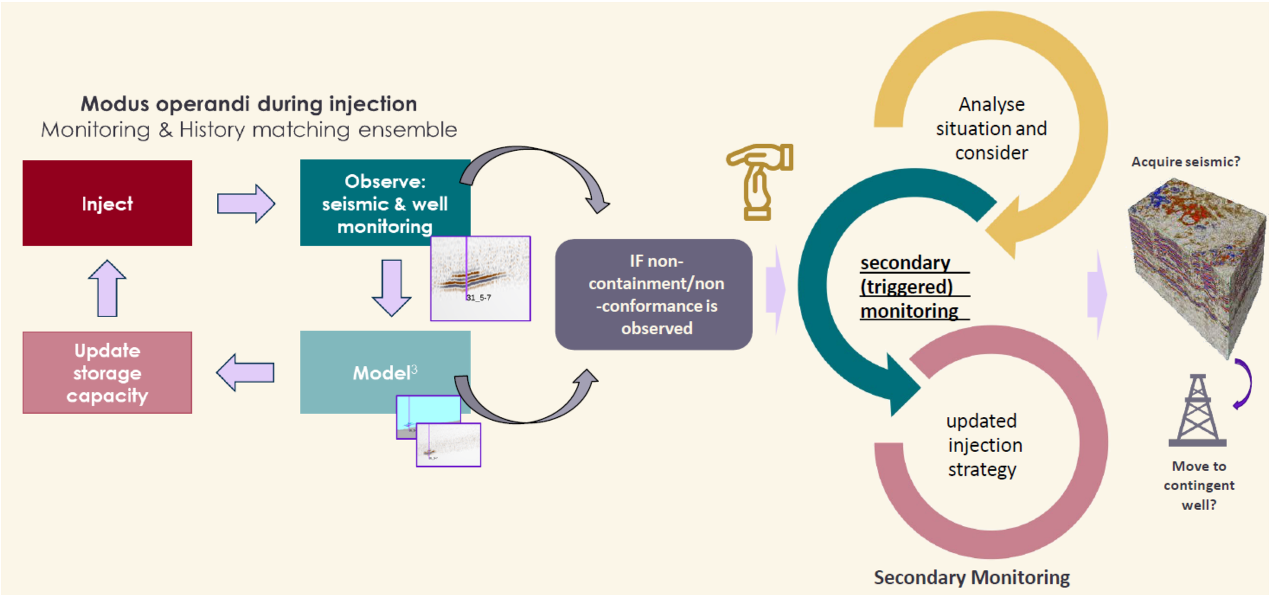
To achieve conformance and containment, SCM aims to detect anomalous behaviour concerning injectivity and reservoir pressure conditions during operation, migration of CO_2 in the reservoir, and leakage. Therefore, SCM is commonly threefold. Applications involve in-well or downhole pressure monitoring, and active and passive seismic monitoring which all run from pre- to post-injection operations, up until the handover to authorities (IPCC 2005; EC 2009; Furre et al. 2020; Acuna 2023).

Moreover, SCM commonly consists of two components. Firstly, there is a planned component that brings about conformance to model predictions of the CO_2 plume migration (Furre et al. 2020; Acuna 2023). The modus operandi of planned monitoring foresees continuous observation of injection operations and reservoir responses (Figure 18). This allows for successive adaption of forward modelling of CO_2 and reservoir behaviour and provides updated storage capacities. Planned monitoring focuses strongly on both the injection zone (down-hole monitoring in direct vicinity of the well) and a larger subsurface area of the storage complex (seismic surveys).

39 About 2-5% of total storage in a 100-1,000-year perspective.

40 After handover, operators are no longer responsible for monitoring the storage sites. Therefore, handover criteria and subsequent monitoring by authorities are essential for carbon storage safety and should be addressed further (EC 2009).

Figure 18: Modus operandi of planned and triggered monitoring components at Equinor's Northern Lights carbon storage project



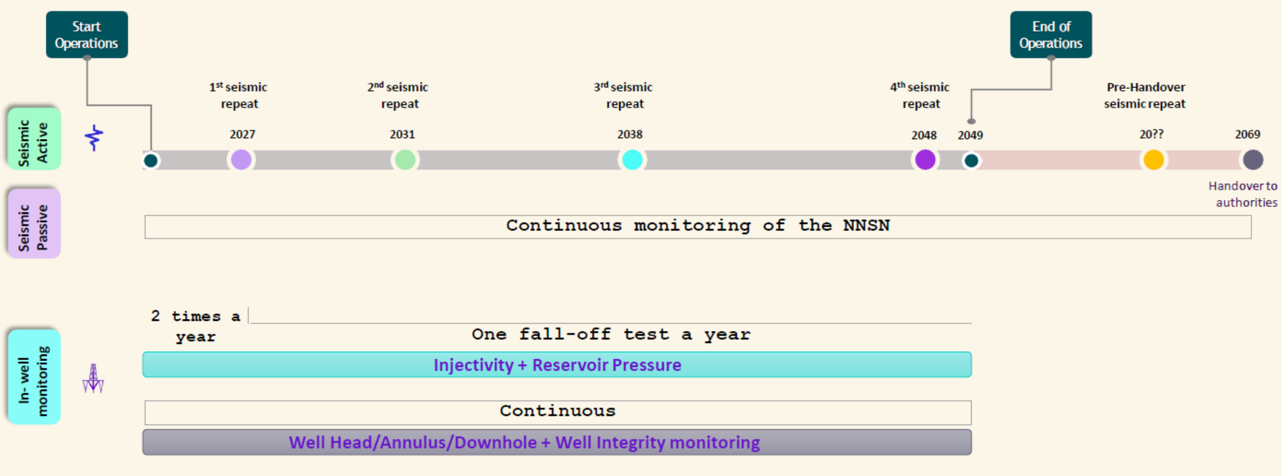
Source: Acuna (2023)

Secondly, there is a triggered component which is considered when planned monitoring indicates non-conformance or non-containment (Figure 18). Triggered monitoring involves a closer analysis of the situation considering focused subsurface monitoring of the potentially endangered areas and environmental surveys if there are indications of a potential release of CO_2 into the environment (Furre et al. 2020; Acuna 2023).

MMV programmes thereby allow for early identification of operational irregularities and non-conformance reservoir behaviour and thus enable subsequent response for preventing leakage-driven non-containment (Furre et al. 2020). MMV programmes are key to a risk mitigation strategy and facilitate immediate remediation actions. Moreover, continuous monitoring also assesses the effectiveness of any corrective measures introduced. However, the remaining risks must be dealt with comprehensive, robust, and site-specific MMV programmes to guarantee the storage integrity and long-term safety (IPCC 2005; EC 2009; IEA 2022; Acuna 2023).

Figure 19 shows a state-of-the-art procedure for the planned monitoring component at the Northern Lights carbon storage project (Furre et al. 2020; Acuna 2023).

Figure 19: Procedure of the planned monitoring component at Equinor's Northern Lights carbon storage project



Source: Acuna (2023)

Note: NNSN: Norwegian National Seismic Network.

Active 3D seismic monitoring commonly plays a major role of the planned monitoring component and is carried out by towed streamers systematically covering the water surface areas above the storage complex. Although other, much more cost-efficient tools, such as gravimetric surveys are improving constantly over time, towed streamer seismic surveys still involve detailed high-level seismic imaging best suited for active seismic monitoring (Furre et al. 2020).

Active seismic monitoring includes a 3D seismic baseline survey prior to injection beginning, followed by subsequent repeated surveys during operation[41] (Figure 19). If CO_2 plume migration is in accordance with predictions, time intervals between repeated surveys will increase gradually. Consequently, repeated 3D seismic surveys provide so-called time-lapse seismic imaging enabling high quality data with detections[42] of relatively small movements of CO_2[43] (Acuna 2023).

Simultaneously, MMV programmes foresee additional passive seismic monitoring (Figure 19). Passive seismic surveys are carried out by a network of seismic sensors (~50) that cover the seabed in clusters (BGR 2024; Wallmann 13.03.24). These sensors allow detection of seafloor motions above the storage complex and micro seismic events provoked by operational irregularities, such as overpressurisation. Micro seismic events[44], which stand out from background seismicity, indicate released energy from propagation of pressure fronts and fractures in the rock formations (reservoir and seal).

Passive seismic monitoring accompanies injection operations and lasts until the handover to authorities. Thereby, passive seismic monitoring provides a viable tool for continuous monitoring of injection operations which cause significantly fewer environmental impacts when compared to time- and cost-consuming active 3D seismic surveys (Wallmann 2023; Wallmann 13.03.24). Nevertheless,

41 Northern Lights considers four repeated 3D seismic surveys during operation and another post-closure survey before the handover to the authorities (Acuna (2023).

42 Detectability generally increases if CO_2 migrates into shallower areas due to better preservation of high seismic frequencies and CO_2 property change (Furre et al. 2020).

43 Recently, active 3D seismic monitoring at Sleipner was able to detect a minimum volume of 10 kt CO_2 rising confidence that no CO_2 migrated to the overburden yet (Furre et al. 2024).

44 Seismic events caused by injection-driven introduction of new or reactivation of existing fractures are not expected to exceed magnitude 3, nevertheless potentially standing out from background seismicity significantly. Generally, risk of losing containment due to injection operation is expected to be very low (IPCC 2005; Vilarrasa 2016; White and Foxall 2016; Wallmann 2023).

baseline studies recording prevailing natural background seismicity is essential to assessing operation-driven micro seismic deviations from natural or artificial background seismicity.

The third element of the planned monitoring component consists of so-called in-well or downhole pressure monitoring (Figure 19). In-well monitoring measures the downhole injection pressure and temperature, reservoir pressure, and overall injection performance parameters to detect potential anomalies (Furre et al. 2020; Acuna 2023).

In-well monitoring is usually carried out by two sets of downhole gauges that can monitor pressure responses during injection operations in the near-well area and the injection zone (in a radius of a few kilometers around the well). On the one hand, there is a continuous measurement of injectivity and downhole injection pressure. On the other hand, there are regular fall-off/step-rate testing every six months minimum within the first three years to monitor reservoir pressure, and injection performance parameters respectively (Acuna 2023). Afterwards regular testing is reduced to one test a year. Besides, continuous measurements of well head pressure and temperature using venturi flow meter guarantees well head and well integrity monitoring.

Triggered monitoring generally draws on a wide spectrum of measurement and verification methods and is highly case-specific according to the actual non-conformance/non-containment. The triggered monitoring component aims to characterise the situation and assess possible impacts and hazards that can lead to immediate mitigation actions, such as modifications in the injection and monitoring programme. This may involve either well interventions and repair, relocation of injection wells, or repeated and focussed monitoring (Furre et al. 2020). Therefore, undesirable behaviour or operational irregularities determine the trigger-based surveys heavily in design, extent, and timing (Furre et al. 2020; Acuna 2023).

For example, if CO_2 migrates through the overburden posing the risks to be released at the seabed, hydroacoustic surveys can detect CO_2 seeps at the seabed and along abandoned wells (CO2GeoNet 2013). Hydroacoustic surveys can be carried out using echo sounders from streamers at the surface (active monitoring) or rather using autonomous underwater vehicles (AUV) at the seafloor (passive). These instruments can detect CO_2 bubbles in the water column (releases of < 1 t per year). When leakage is discovered, chemical sensors measure CO_2 and pH in the bottom water to assess the environmental impacts supported by biochemical surveys both in seabed sediment and bottom water.

3.6 Experiences gathered with carbon storage projects

The following sections provide selected examples of carbon storage projects in the past where risks and hazards materialised during operation and shows how they were addressed.

3.6.1 Sleipner (Norway)

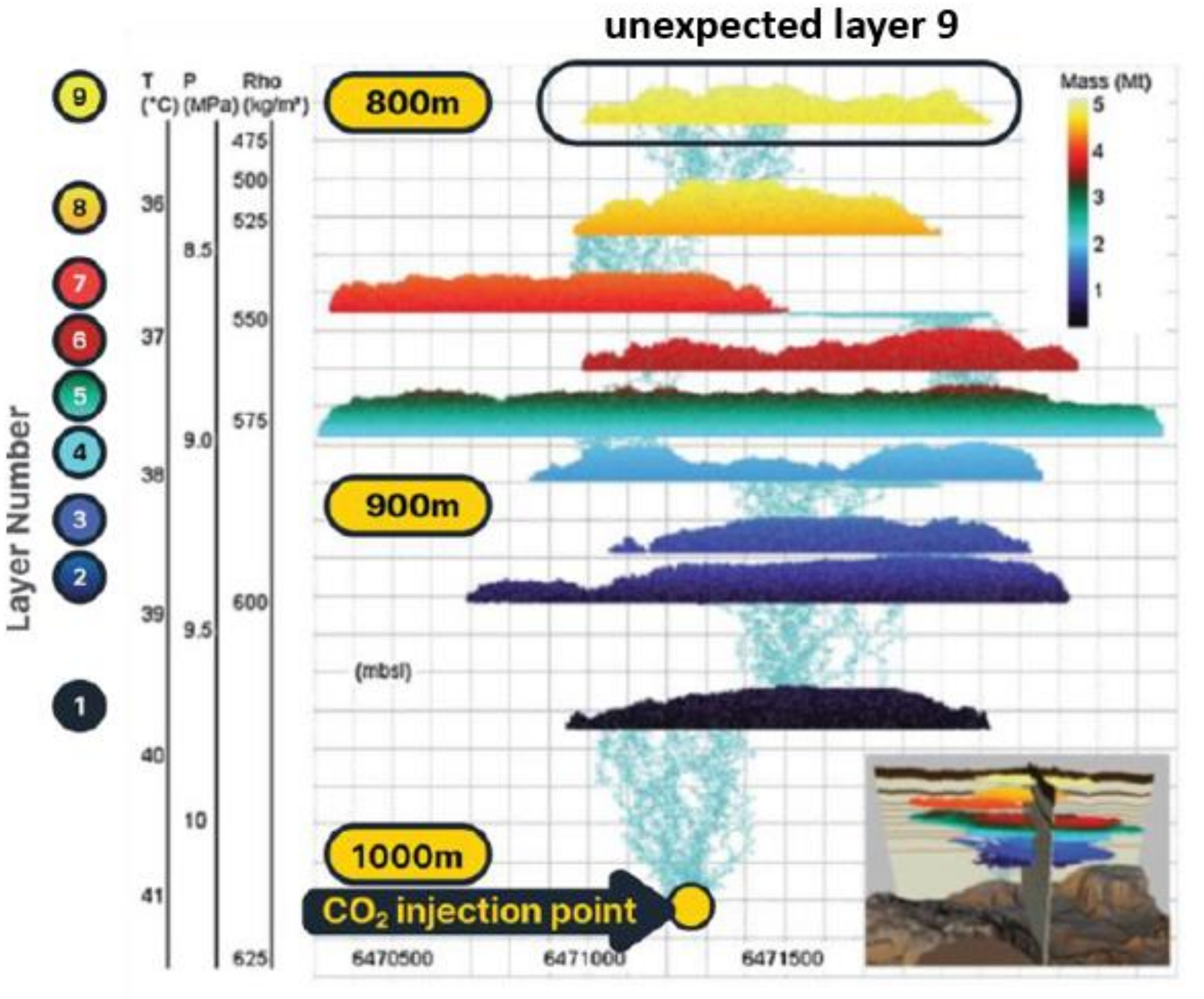
At Sleipner, approx. 250 km offshore from Norway in the North Sea, gas production has occurred since 1974 (IEEFA 2023; ZEP 2019). Carbon storage was introduced in 1996[45] when operators started injecting liquefied to supercritical[46] CO_2 into the saline, highly porous Utsira Formation aquifer (~1,000 m below the seafloor[47]) near the Sleipner Øst production platform (Furre et al. 2017). Immediately after it began, high sand flux caused injection problems, which were solved by re-perforation

45 Sleipner, which began in 1996, was the first offshore injection project (Furre et al. 2019).
46 CO_2 conditions are close to the triple point (Ringrose and Sæther (2020).
47 The water depth at Sleipner is approx. 80 m (Furre et al. 2019).

of the injection and installation of sand screen and gravel packs (Furre et al. 2019; Ringrose and Sæther 2020). Since 1997, CO_2 injection has been stable at approx. 0.9 Mt per year[48] (Furre et al. 2019). Pressure management and injectivity monitoring are conducted successfully at the well head, eliminating the need for the installation of downhole pressure gauges and in well monitoring[49].

However, a pre-operation 3D seismic baseline survey revealed a series of eight subsurface layers within the Utsira Formation, ranging between 1,050 m and 850 m below the seafloor, which were identified as suitable for permanent storage of CO_2 (Figure 20). Subsequently, operation was conducted through a single deviated well injecting CO_2 at levels of the lower base layer (Furre et al. 2019). Thereby, operators strove to percolate the gas into the higher layers above (Cavanagh and Haszeldine 2014).

Figure 20: Depth of Sleipner's nine CO_2 storage strata within the Utsira Formation



Source: Based on IEEFA (2023)

48 17.9 Mt of CO_2 had been injected by 2019 (Furre et al. 2019), meaning that it currently totals more than 20 Mt.

49 Furre et al. (2019) argue that well head pressure monitoring is sufficient, which is proven by smooth injection operation over time. However, there is also criticism as the lack of downhole sensors does not allow the temperature of CO_2 to be monitored, which is vital to understanding plume migration behaviour (IEEFA 2023). Operators would have to rely on the interpolation of surrounding borehole data, giving room for uncertainties.

Controversial contradictions arose with the results of the first 3D seismic survey after start of injection which was conducted after operation had occurred for three years (IEEFA 2023; ZEP 2019). 3D imaging indicated that CO_2 had started migrating as expected (Furre et al. 2017; Furre et al. 2019). However, the pace and distance at which the CO_2 had migrated within three years was surprising. Results showed that the gas had already percolated over 220 m in a shallower, previously unidentified ninth layer at a depth of about 800 m (Cavanagh and Haszeldine 2014). Moreover, accumulation of CO_2 in the newly discovered layer implied that migration had taken place much more quickly than assumed. Therefore, Cavanagh and Haszeldine (2014) suspected that the eight layers were far more fractured and/or thinner than previously thought.[50]

Concerns emerged and questions were raised about the migration of the plume and if containment could be maintained (IEEFA 2023). Operators reacted by introducing a comprehensive state-of-the-art monitoring: A series of repeated 3D seismic surveys every two years with 4D time-lapse seismic monitoring to monitor the movement of the CO2 plume and to learn more about the extent of the newly identified layer nine.

As operations progressed, CO_2 plume growth further accelerated and operators increased their efforts to understand the storage formation behaviour[51] (Furre et al. 2017; Ringrose et al. 2021; IEEFA 2023). Certainty about Sleipner's storage integrity[52] remained unknown for many years during operation and challenges in determining behaviour of plume migration in layer nine persisted (White et al. 2018b). Recently, time-lapse seismic data shows the clear tendency that the increasing fraction of CO_2 might be structurally trapped in layer eight and nine[53] (Furre et al. 2024).

IEEFA (2023) nonetheless emphasises the need for continual improvement of modelling and monitoring techniques and stresses the uncertainties that still remain in term of better addressing the risks and potential impacts of carbon storage. Furre et al. (2024) also acknowledge interpretation challenges[54] that developed with increasing volumes of CO_2 and further indicate an unusual CO_2 behaviour pattern[55] in the storage site. IEEFA (2023) concludes that despite the availability of a comprehensive seismic dataset, a state-of-the-art benchmark model and open research eager to produce large volumes of scientific models, there is still a fundamental challenge in assessing Sleipner's storage behaviour over years to decades.

However, MMV programmes at Sleipner were comprehensive, case specific and risk based, and therefore successful from start helping to set monitoring guidelines for future carbon storage projects (Furre et al. 2024; ZEP 2019).Time-lapse seismic imaging of about 10 seismic surveys since the start of injection gave valuable insights into the physics of the storage process. Moreover, the MMV programmes of the Sleipner project are broad and not confined to 3D time-lapse seismic surveys; gravimetric investigations, CSEM, sonar and chemical monitoring are also included (Furre and Eiken 2014; Furre et al. 2017; Ringrose and Sæther 2020). Therefore, Furre et al. (2024) see Sleipner as

[50] Cavanagh and Haszeldine (2014) introduced the theory that deglaciation of regional ice sheets had provoked hydro-fracturing the thin shales in between the target layers enabling fast CO_2 ascent via a multi-layered plume. A scenario that could also apply to other shallow CO_2 storage sites in the Northern North Sea or other Quaternary ice sheets affected areas.

[51] Operators responded by creating a new and more detailed model of the Sleipner storage site's geology. They also granted researchers open access to their seismic data (Sleipner Benchmark, 2011) allowing open research to model future storage build ups and boundary conditions (IEEFA 2023).

[52] Up to date, *Sleipner* has fulfilled its containment (IEEFA 2023). Nevertheless, the question of the extent of layer nine and if it exceeded the edge boundaries of the caprock or even the geographic limits of *Sleipner*'s operating license remained unknown for most of the operating period (White et al. 2018b).

[53] Layer nine is expected to be the last layer to be charged with CO_2 (Furre et al. 2024).

[54] As deeper anomalies are overlain by shallower anomalies in the seismic imaging, percolation of CO_2 into higher layers make it more difficult to interpret deeper reflections confidently (Furre et al. 2024).

[55] Furre et al. (2024) assume a unusual combination of vertical and lateral migration pathways to cause the different from any of the previously observed migration behaviour.

a unique and highly experimental storage site often referred to as a proxy[56] when it comes to monitoring examples that provide new insights into detailed reservoir architecture and CO_2 migration patterns. Nevertheless, actual reservoir behaviour did not achieve conformance with previous modelled predictions. While MMV programmes allowed for early identification of operational irregularities, questions arose as to whether the pre-injection site characterisation was sufficient (IEEFA 2023).

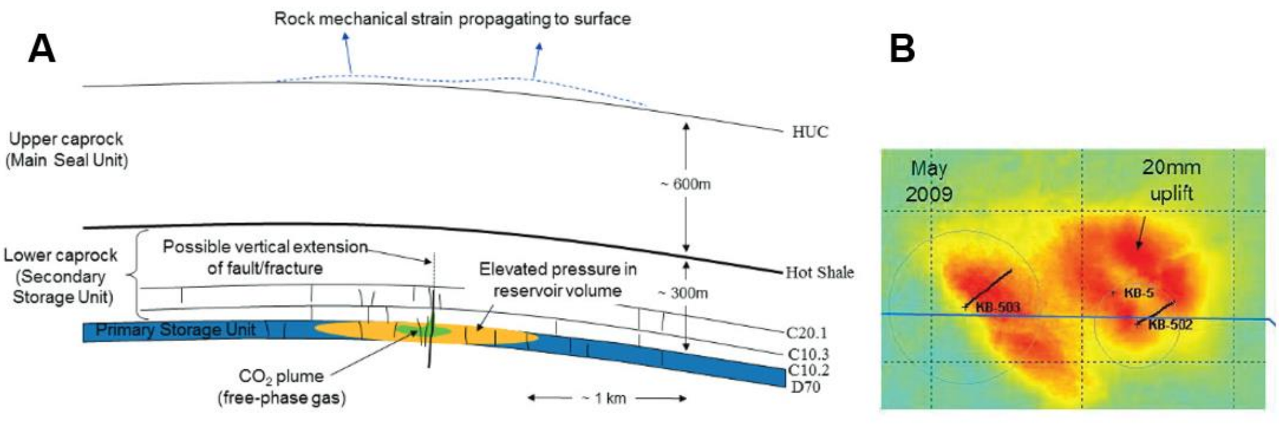
To date, there are no indicators that CO_2 has escaped from the storage site (Furre et al. 2019; Ringrose et al. 2021; Furre et al. 2024). The smallest detectable volume observed at Sleipner is about 10.5 kt of CO_2 on the first seismic repeat survey. Therefore, Furre et al. (2024) are confident they would be able to detect such volumes if the CO_2 had started to migrate into the overburden.

3.6.2 In Salah (Algeria)

The In Salah carbon storage project in Algeria was one of the pioneer projects in the world (ZEP 2019). At In Salah, CO_2 was sequestered from nearby gas production streams, compressed, transported, and then stored onshore in a 1.9 km deep anticline structure of a carboniferous sandstone (IPCC 2005; Ringrose et al. 2013b).

The In Salah project began operation in 2004 and was shut down in 2011, having experienced several operational irregularities since 2009 when CO_2 pressure in the reservoir increased significantly during injection[57]. Accompanied by several monitoring activities to assess the irregularities in the pressure management, the injection nevertheless continued into early 2011 until monitoring results implied that over-pressurisation in the reservoir had fractured the caprock containment strata (Ringrose et al. 2013b; IEEFA 2023; ZEP 2019). Interferometric synthetic aperture radar (InSAR) investigations confirmed that pressure had been strong enough to cause subsurface ground movement due vertical extension in the lower caprock approx. 950 m below the earth's surface. Moreover, rock mechanical strain had propagated to the surface, leading to a surface-level ground swell of 20-25 millimetres (Figure 21).

Figure 21: The In Salah CO_2 storage project



Source: Ringrose et al. (2013b). A: Sketch of the In Salah storage site and the issues around well KB-502. B: Subsurface deformation inferred from Interferometric Synthetic Aperture Radar (InSAR). InSAR data shows millimeter changes in ground elevation.

56 Furre et al. (2024) conclude that thin internal clay-rich barriers (mudstones) enhance distribution of CO_2 within the reservoir and have a positive effect on residual trapping and CO_2 dissolution into the in-situ brine.

57 At In-Salah, operators ultimately injected about 3.8 Mt of CO_2 between 2004 and 2011 (Ringrose et al. 2013b).

However, operators responded relatively quickly by adapting the injection rate to mitigate reservoir pressure from further damaging geological barrier structures. Ringrose et al. (2013a) therefore emphasises the proven value of monitoring technologies like InSAR, micro seismic monitoring and 3D/4D seismic surveys to successfully address pressure management. Nonetheless, operators were convinced enough to continue operations despite operational irregularities and the recorded subsurface ground movement.

Although seismic surveys clearly show that fractures had propagated upwards into the lower caprock, propagation is expected to not reach further into the upper caprock. Until the early 2010s, no leakage had been recorded and observations indicate that the CO_2 remains safely contained within the storage complex (Ringrose et al. 2013b). Despite the technical irregularities, the In Salah project tends, therefore, to be seen as an example of successful risk intervention that demonstrates the importance of comprehensive monitoring programmes for immediate remediation and mitigation of materialising risks and impacts (IPCC 2005; Ringrose et al. 2013b).

Yet, as IEEFA (2023) points out, a movement of such significant scale on the earth's surface could have easily caused damage to buildings and infrastructure in urban areas and operators were rather fortunate that the storage site lies under unoccupied desert land. Even if damage could have been mitigated, ground movement impact had already occurred. Consequently, questions arise as to whether continuing operations despite operational irregularities represents an appropriate example for future Carbon Storage projects.

3.6.3 Snøhvit (Norway)

The Snøhvit carbon storage project is part of the Hammerfest fossil gas production project and lies approx. 150 km offshore Norway in the Barents Sea (Hansen et al. 2013; ZEP 2019). Fossil gas is extracted from the Snøhvit gas field and transported via seabed pipeline to the onshore Hammerfest LNG plant. There, CO_2 is captured, compressed to a supercritical state, and transported back to the offshore injection well (White et al. 2018a; IEEFA 2023). As the injection well sits on the seafloor in water depths of 290-350 m, operators did not build an offshore platform due to the lack of technical feasibility. Instead, operators decided to install a well head (subsea template) affixed to the seafloor from which the CO_2 is injected into the reservoir, which is located at depths of between 2,300-2,500 m (Furre et al. 2019).

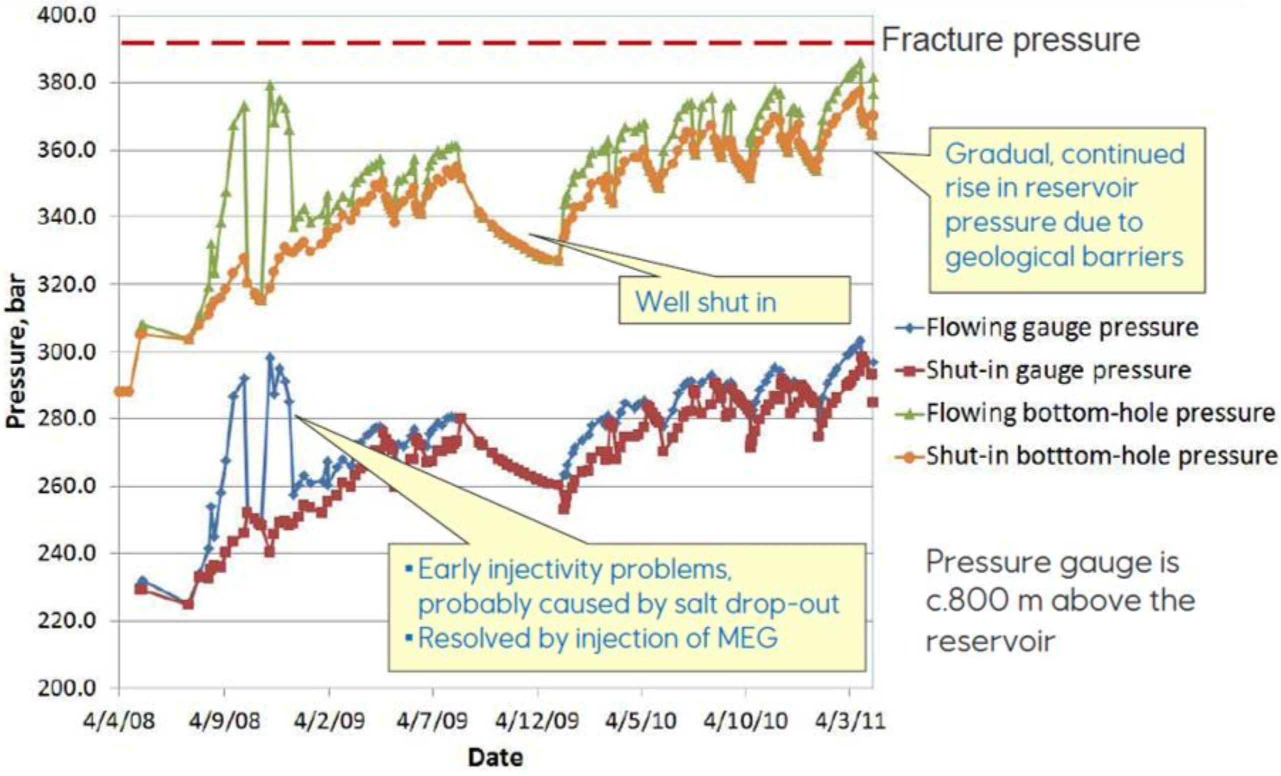
Initially, operators intended to store the CO_2 in the early to middle Jurassic Tubåen Formation, an approx. 100 m thick, markedly heterogenous sandstone reservoir with a base that lies around 2,600 m below the seafloor (White et al. 2018a). The Tubåen Formation is overlain by a second, initially uncared-for sandstone formation (Stø Formation) with an average thickness of 85 m.

Prior to injection, operators conducted a baseline 3D seismic survey to assess the Snøhvit storage site injectivity and capacity (White et al. 2018a). Storage site characterisation predicted the rocks to be porous enough to receive about 18 years of Snøhvit's CO_2 production[58] (IEEFA 2023).

Injection of CO_2 into the Tubåen reservoir began in 2008 with initial injection rates of about 0.7 Mtpa (IEEFA 2023). However, irregularities emerged early on as the installed downhole pressure gauge experienced strong pressure build-up shortly after injection began (Figure 22).

[58] Snøhvit's site performance characterisation predicted to deposit between 12.6 Mt to 14 Mt of CO_2 during operation. However, operators planned to find additional storage capacities of 8.4 Mt to 10 Mt of CO_2 simultaneously to the injection into the Tubåen reservoir (IEEFA 2023).

Figure 22: Snøhvit injection pressure history (Tubåen Formation)



Source: Ringrose and Sæther (2020)

Operators assumed salt precipitation in the near wellbore vicinity to have caused the initial reservoir pressure build-up. Following remediation measures that involved repeated treatments of Methyl Ethyl Glycol (MEG)[59] to resolve the effects of the salt drop-out, downhole pressure in the reservoir stabilised, but nevertheless continually approached the fracture pressure of the target formation in the subsequent years (Furre et al. 2019; Ringrose and Sæther 2020; IEEFA 2023).

In 2011, downhole pressure in the reservoir formation had reached levels threatening to exceed fracture pressure (Furre et al. 2019; Ringrose and Sæther 2020). Therefore, operators were forced to take immediate remedial measures by initiating an emergency well intervention (White et al. 2018a). Consequently, after just three years and approx. 1.4 Mt of injected CO_2, the operation was shut down and the formation had to be plugged and abandoned. Operators assumed that the deposition strata were having problems accepting the gas due to lower insufficient porosities of the reservoir rocks. Assuming that the reservoir rocks were not as receptive as pre-operation studies had indicated implies a significant lack of understanding during site performance characterisation (IEEFA 2023).

Subsequently, operators decided to switch to the shallower and more homogenous Stø Formation. This involved re-perforating the original well to inject into the shallower reservoir. Since then, injection

[59] MEG is a colourless, moderately viscous, miscible compound that is often injected directly into the wellheads (CSIRO 2016). Due to its miscibility and higher density, it is considered to disperse reasonably quickly in seawater when spilled. MEG is not expected to accumulate in seabed sediments and in the benthic ecosystem. Nevertheless, MEG could leak during the pipeline transport. In the event of leakage, the compound is not considered to bioaccumulate in aquatic organisms (Staples et al. 2001). The Centre for Environment, Fisheries and Aquaculture Sciences (CEFAS) rates MEG as a "non-CHARMable" compound with an offshore chemical notification scheme (OCNS) rating E, the lowest environmental risk, with no substitution warning (CEFAS 2024)). However, MEG has very high acute toxicity values and most aquatic organisms are assumed to tolerate gram per liter concentrations (Staples et al. 2001).

has occurred as expected without an indication of a significant increase in downhole pressures. Building on continuous and stable injection[60], a new injection well was drilled into the Stø Formation and operation has since been running without major problems reported.

Furre et al. (2019) discuss a comprehensive and successful MMV program that involved repeated time-lapse 3D seismic surveys[61]. Further, in-well monitoring via downhole pressure gauges revealed important insights for future carbon storage projects, such as pipeline transport in chromium stell pipes and operation of subsea injection wells.

To date, there are no indications of CO_2 having migrated from the primary storage unit (Furre et al. 2019; IEEFA 2023). However, IEEFA (2023) criticises, among other difficulties, that less than 50% of the projected CO_2 could have been stored and an extra capacity[62] of at least 11-14 Mt of CO_2 needs to be found to keep the Snøhvit gas field and Hammerfest LNG operational.

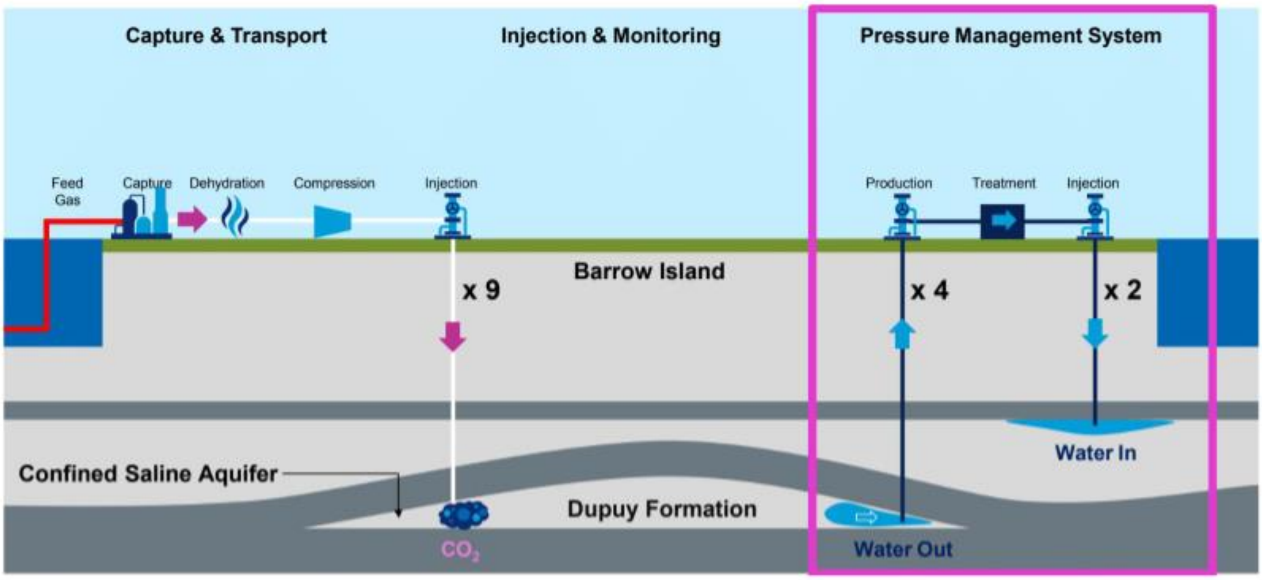
3.6.4 Gorgon (Australia)

The Gorgon[63] onshore carbon storage project on Barrow Island in Australia started to inject CO_2 into a confined saline aquifer (Dupuy Formation) in 2019 (Trupp et al. 2021). Operators initially aimed to inject 4 Mt per year (or >100 Mt over ~40 years) via nine injection wells overall, making Gorgon by far the largest carbon storage project to date (IEEFA 2022; ZEP 2019).

However, as the reservoir is confined to each side (Figure 13), to maintain reservoir pressure and integrity, a pressure management system was introduced. This system extracts brine from the reservoir to provide space for the injected CO_2 (Figure 23). After production, the extracted water is treated and reinjected into a neighbouring aquifer that is shallower (Gladman 2023).

60 By the beginning of 2019, a total of 5.8 M t CO_2 was injected at Snøhvit.
61 In 2012, operators conducted the biggest 3D seismic program surveying more than 84 km^2.
62 Stø Formation is assumed to accept between 8 Mt and 9 Mt of CO_2.
63 The Gorgon carbon storage project is part of the Gorgon offshore LNG project, which is one of the world’s largest LNG production sites in the world (IEEFA 2022).

Figure 23: Gorgon simplified flow diagram



Source: Gladman (2023)

Problems emerged soon after the start as the extracted water contained more solid particles than expected. These solids fouled the water injection wells hampering water injection. Thereby, pressure management failed as water extraction had to be reduced and less CO_2 could be injected into the reservoir. Actions to remediate pressure management irregularities involve the expansion of water injection wells and improvement of water treatment installations through better filters (Gladman 2023).

As a result, Gorgon underperformed its targets by about 50% for the first five years (2016-2021, IEEFA 2022). Such consequences and actions as those discussed above take time and are extremely costly. IEEFA (2022) suggests that a financial burden could be handed over to the Australian public after carbon storage closure.

Yet, in terms of carbon storage, Gorgon is a success when considering the current capacities of other carbon storage projects[64] (Gladman 2023). Moreover, CO_2 injection and reservoir performance are as expected and there is excellent conformance between CO_2 plume behaviour models and actual CO_2 growth. Nevertheless, Gladman (2023) indicates that remediation actions could have been addressed earlier if water extraction was conducted from the start of the CO_2 injection.

3.7 Summary and conclusions

Permanent storage of CO_2 in geological formations poses several risks, both technical and site-specific and political and value-based, such as public confidence in long-term monitoring. This summary highlights the complex and multifaceted risks associated with carbon storage and emphasises the importance of site-specific analysis, comprehensive risk management and the development of comprehensive and robust monitoring, measurement, and verification (MMV) programmes to guarantee storage integrity and long-term safety.

[64] As of May 2023, ~8 Mt of CO_2 have been injected (Gladman (2023).

Many of these risks are well known from the fossil gas and petroleum industry, but CO_2 storage also presents new challenges specific to carbon storage:

- Leakage: The greatest risk might be the uncontrolled release of CO_2, which can occur in a variety of ways and different areas, and therefore have different impacts, depending on the volume, duration, and form of the released CO_2.
- Lifespan risk profile: Risks exist throughout the entire carbon storage process chain, from transport to injection and storage, until the handover of the responsibility to state authorities. The CCS Directive assumes a lifetime of 50-70 years, with critical phases occurring during CO_2 transport and at the start of injection. The risks are highest during the operational period (5-50 years) due to rising reservoir pressures.
- Technical difficulties: Offshore storage projects such as Sleipner and Snøhvit have experienced unforeseen problems with reservoir and CO_2 behaviour during the injection processes, leading to operational irregularities and significant increases in cost. The results of carbon projects have demonstrated that the actual injectivity and behaviour of CO_2 in the reservoir during operations often exhibited significant discrepancies from the modelled predictions of pre-injection site performance characterisation.
- Local risks: These include risks associated with transport routes, injection wells and storage sites. These can affect the environment at the source of release and in the immediate vicinity.
- Global risks: Uncertainties about the permanence of geological CO_2 storage pose a threat to addressing the global climate crisis.

  Technologies such as EGR and EOR do not provide net-zero emissions solutions and use CO_2 storage as a smokescreen to mitigate global effort to phase out fossil fuels to justify fossil fuel expansion. This carries the fundamental risk of jeopardising public acceptance.

A comprehensive analysis of these key risks across the above phases and time frames of carbon storage projects leads to the following conclusions:

- The realisation of CO_2 storage projects is highly dependent on geological characteristics and the development of an appropriate transport infrastructure. Technical risks during transport, in particular those related to pipeline integrity and safety, need to be carefully considered to avoid adverse impacts on humans and the environment. The use of existing infrastructure, such as pipelines and wells, may be appealing for cost reasons but is unlikely to be effective. Existing infrastructure probably does not meet the specific requirements for CO_2 transport and injection, leading to potential failures and increased risks.
- Injection operations may comprise the most critical part of carbon storage projects. Misjudgement of geological environment, injectivity and capacity can lead to irregularities that cause damage to the reservoir rock formations and their seals. This poses fundamental risks to the storage integrity and safety. Risk analysis must be project- and site-specific.
- There is a broad consensus that the overall risk to humans of being exposed to dangerous levels of CO_2 in the atmosphere, even if the containment of carbon storage fails and stored CO_2 leaks to the surface, is comparatively very low. This is due to the rapid dispersal of CO_2, which is likely to affect only the immediate vicinity of the leak.
- It is extremely unlikely that major earthquakes will be induced by CO_2 storage operations. Historical data and studies suggest that the likelihood of significant seismic events due to CO_2 injection is very low, especially if proper site selection and injection practices are followed.

- Environmental impacts associated with sub-seabed carbon storage, even during the industrial ramp-up of offshore carbon storage in the European North Sea, are expected to be possible but rather small. This is due to the depth and isolation of the storage sites, combined with stringent monitoring and regulatory measures.
- Experimental results suggest that long-term moderate exposure to unfavourable living conditions is generally more harmful to biota than short-term major perturbations. The potential for mitigating adverse effects is contingent on the application of appropriate monitoring techniques. This highlights the importance of monitoring and managing long-term environmental conditions around storage sites.
- While carbon storage helps remove CO_2 from the atmosphere on a global scale, the offsetting emissions of other air pollutants could damage ecosystems on a local scale. It is important to consider these localised impacts in the broader context of the overall environmental benefits.
- Accurate site selection is essential to minimise environmental impacts. When assessing the impact of a potential leak, the cumulative and combined effects of a CO_2 leak should be considered, in addition to the pressures from other marine activities. For example, the North Sea is a target for significant CO_2 storage activities but is also subject to other activities and impacts such as trawling and the climate crisis (e.g. warming and ocean acidification). A meaningful environmental risk assessment for carbon storage requires comparison with other ongoing and potential impacts.
- Spatial planning should consider indirect impacts on the marine environment as carbon storage infrastructure adds up to overall maritime land consumption exposing already vulnerable environments to significant stress. Marine environments would benefit significantly from bundling and limiting human activities to certain areas, leaving others untouched to minimise environmental impacts. Effective protection measures may involve defining no-go areas and prioritising human activities.
- Comprehensive risk management is a prerequisite for carbon storage projects and involves containment risk analysis and monitoring, measurement, and verification programmes over the entire carbon storage project lifespan. Risk analysis must be project- and site-specific.
- Comprehensive site and performance characterisation prior to operation is key to mitigating impacts on the geological environment during carbon storage. A detailed understanding of the geological, hydrological and geomechanical characteristics of the storage site is essential to optimising injection operations and confirming storage volumes. Therefore, it is imperative to learn from past experiences as almost all carbon projects revealed unforeseen reservoir and CO_2 behaviour during operation. Such incidents often caused major operational deviations or damage to the storage complex. While this does not necessarily imply insufficient site and performance characterisation, it demonstrates the overall importance of comprehensive pre-injection studies. It is vital to understand that even the most rigorous efforts to characterise storage sites and their performance does not protect carbon storage projects from experiencing unforeseen reservoir and CO_2 behaviour during operation.
- The combination of containment risk analysis and monitoring, measurement, and verification programmes sets the basis for proving the conformance of actual CO_2 behavior with previous predictions, and containment through detection of leakages out of the storage complex to assure storage integrity.
- Risk management allows for early identification of operational irregularities and non-conformance reservoir behaviour and thus enable a subsequent response to prevent leakage-driven non-containment. It also helps to facilitate immediate remediation actions.

- Experiences gathered in the past: Sleipner and Snøhvit have demonstrated commercial carbon storage. Early injection problems at both Sleipner and Snøhvit were mitigated by well intervention. This demonstrates that initial technical difficulties can be effectively managed with flexible well design and planning. Geological and geochemical surprises are to be expected with CO_2 injection operations, but experience gathered with existing projects suggests these problems can be overcome by remedial action. Although direct learning effects from past carbon storage projects for future projects may be limited due to the uniqueness of each storage site, the experiences gained are crucial for the overall learning curve of all stakeholders in place.
- Following operation, it is imperative that stringent regulations are implemented for the closure and abandonment of storage sites. Operators must fulfil all handover criteria for the safe transfer of responsibility to state authorities.
- The post-operational period should not be neglected as projects often design CO_2 to migrate away from the injection zone. Moreover, operators accept that larger fractions of injected CO_2 will remain in a supercritical and mobile phase for tens to hundreds of years after operation.
- The question of carbon storage permanence is still a controversial one. To date, no carbon storage project has detected CO_2 leakage despite significant operation irregularities. However, assuming complete permanence and full containment of CO_2 for a technology that is still in its infancy, and therefore has not yet been proven to be permanent would be a highly risky proposition. This would particularly apply to stakeholders who draw on decade-old projects to ensure permanence for several thousands of years.
- Nevertheless, there is a broad scientific consensus, built on the confidence of natural storage processes, that containment and retention are long-term, lasting even for several millions of years. The IPCC contends that 99% of CO_2 is still stored geologically after 1,000 years. Carbon storage projects should be so designed that they rely on the effectiveness of several storage mechanisms. A high proportion of CO_2 stored by residual trapping, dissolution, and mineralisation early on is favourable. Well-known reservoir structures that rely on structural and stratigraphic trapping still appear to be very reliable and should be favoured over open system reservoirs.
- Early and transparent stakeholder involvement is undoubtedly beneficial to raise trust in carbon storage technologies.

In summary: The ramp-up of carbon storage should therefore start early but initially proceed slowly to allow for learning-by-doing. To ensure progress, detailed site surveys, environmental monitoring, and stringent regulations must be in place. This approach will help to identify and mitigate risks early, ensuring the safe and effective deployment of carbon storage technologies. While CCS holds significant promise for reducing atmospheric CO_2 levels, it must be approached with meticulous planning and proactive risk management to address the complex challenges that it presents.

4 Landscape of policy positions

The following sections provide an in-depth analysis of the political positions surrounding carbon storage across different stakeholder groups. The discussion begins with an assessment of the positions of the political groups in the European Parliament as stated in their manifestos for 2024 European Parliament elections (4.1). It is noted that there is a lack of focus on carbon storage in their manifestos although debates on the contribution of carbon storage to the EU's climate goals have become increasingly visible in the months leading up to the elections, especially with the completion of the NZIA and of the publication of the Industrial Carbon Management Strategy and the 2040 Climate Targets Communication. We then turn to the perspectives of industry associations (4.2), which provide more detailed insights on the potential of carbon storage. Both the perceived benefits and the associated risks are discussed. Key industry players and major CS projects are also examined (4.3) and the growing commercial interest in developing carbon storage infrastructure highlighted, particularly in sectors such as oil and gas. Finally, the study examines the positions of environmental NGOs (4.4), which emphasise the need to prioritise emission reductions over removals and warn of the environmental risks and economic costs associated with large-scale deployment of carbon storage. The final section (4.5) provides a summary of the study and the overall conclusions.

4.1 European Parliament groups

Regarding the state of the political discussion on European level, the manifestos published ahead of the European Elections 2024 by the most relevant European political parties, which conform the political groups of the European Parliament (EP), were analysed.[65] In general, very little information and mention of carbon storage was found in the manifestos. CCS technologies are of central importance to the EU Commission's 2040 Climate Target Impact Assessment, in which 200 Mt CO_2 are stored based on carbon capture processes (EC 2024f). In the light of this, it seems surprising that there is little information on the critical issues such as risks, energy demand, envisaged scale or concrete policy measures.

The European People's Party (EPP Group) does not mention carbon storage in its manifesto. However, in prior policy papers and resolutions they state that CCS technologies are helpful in further reducing emissions, which is especially necessary in coal-reliant regions, but they do not differentiate between emission reductions and removals (EPP 2018). Accordingly, they call for increased public and private investment in CC technologies and point specifically to DACCS and CCU, but do not mention carbon storage (EPP 2022). Similarly, the Progressive Alliance of Socialists and Democrats (S&D) does not mention CCS technologies in its 2024 Manifesto. It does, however, generally see them as a key sector for which public and private investment in research, innovation, and production needs to be increased (PES 2023).

For the Renew Europe Group, the manifesto of the Alliance of Liberals and Democrats for Europe (ALDE) is the only one that includes a specific reference to CCS technologies and also calls for investments. As a policy, they propose implementing a technology-neutral certification system for verified negative emissions, under which carbon storage would fall, leaving open if these certifications should then be included into the ETS or remain in a voluntary market.

The European Greens do not mention CCS in their manifesto but clearly state their position of limiting the geological storage of CO_2 to unavoidable industrial process emissions if carried out in an

65 The following manifestos were included in our analysis: ALDE (2024), ECR (2024), EDP (2024), EGP (2024), EL (2024), EPP (2024), PES (2024).

environmentally safe, sustainable and permanent manner. These emissions would amount to less than 100 Mt CO_2 in 2050. They are calling, for example, for a limit on the use of BECCS and favour nature restoration for climate mitigation and adaptation. In general, they suggest keeping emission reductions, land-based sequestration and technological removals strictly separate from each other from a policy perspective (Greens/EFA 2024).

In addition, the manifestos of the European Conservatives and Reformists (ECR), the European Left (EL) and the European Democratic Party (EDP) were assessed. However, no concrete position regarding carbon storage or CCS was found for these EP groups.

It should be noted that the permanence of carbon storage and other safety or environmental risks relating to carbon storage are only briefly touched on in the manifestos of the EP groups, because the manifestos aim at a broader narrative without too many details. They are not necessarily the place for addressing specific topics such as carbon storage.

4.2 Industry associations

In contrast to the political groups in the EP, the associations surveyed generally provide more information on CCS technologies, their use, role, risks and the necessary policies as they aim to promote the technology.[66] All associations who published their positions regarding CS state the critical role of it for the net zero targets. A few associations, specifically CCS Association, CCS Europe, Zero Emissions Platform (ZEP), and Direct Air Capture Coalition, envisage CS only being used in certain sectors. Some associations, namely the Deutscher Verband für negative Emissionen (DVNE) and CO2RE, focus on carbon dioxide removal (CDR), but also see its role as inevitable in order to meet the net zero targets.

The Carbon Capture Coalition (CCC) calls for federal policies that accelerate the deployment of technologies to capture, transport, and store CO_2 in oil and gas fields and in geologic formations (CCC 2023). CCS Europe also focuses on the permanent storage of CO_2 in geological formations and the necessity of developing strategies to deploy CC technologies.[67] In addition, the CCC remarks that CO_2 can be safely captured, transported and permanently stored in oil and gas fields and in geological formations. The Global CCS Institute shares the risk assessment of CCC. It evaluates the transportation of CO_2 as safe because it does not form flammable or explosive mixtures with air and, additionally, it sees CO_2 as not toxic to humans or wildlife when released in the atmosphere. The Global CCS Institute considers important risks of CCS to relate to financial/operational and political liability and states that there are cross-chain risks when using a traditional “full value chain” model. Like the CCC, the Global CCS Institute demands investment in CCS technologies through several mechanisms such as carbon taxes and direct or indirect subsidies. The institute defines the optimum storage of CO_2 until 2065 to be cumulatively 703 Gt CO_2, including a mix of fossil CCS, BECCS and DACCS. According to the institute, the minimum cumulative amount of CO_2 for meeting the net zero targets is 10 Gt CO_2 (GCCSI 2023). In comparison, the CCS Association assesses the potential of carbon capture technologies as very high since they can capture more than 95% of emitted CO_2.[68]

In contrast to the risk assessment of the CCC and the Global CCS Institute, the Negative Emissions Platform evaluates the risk of lack of permanence or reversibility as very important and therefore calls for clear rules on liability in the case of reversals. Additionally, accurate monitoring is highlighted

66 The following association have been included in the analysis: CCC (2023), CCSA (2024), CCSE (2024), Cembureau (2023), CEWEP (2024), DACC (2024), DVNE (2024), VDZ et al. (2024), ZEP (2024).

67 CCS Europe, Our Mission, https://www.ccs-europe.eu/our_mission.

68 CCS Association, The Value of CCUS, https://www.ccsassociation.org/discover-ccus/the-value-of-ccus/.

as very important. The policy suggestions of the Negative Emissions Platform focus on the support of development and use of negative emissions technologies (NETs), such as the inclusion of NETs in the ETS to widen the instruments and provide support for the technologies or the support of CO_2 transport and storage infrastructure (Elkerbout and Bryhn 2022). Likewise, the ZEP emphasises the urgent need to identify potential storage sites. Like the CCC and CCS Europe, it proposes the underground storage of CO_2, which it assesses as safe and permanent storage. For the reduction of emissions in the heating and transport sectors, the ZEP considers low-carbon hydrogen production enabled by CCS as a potential instrument. Furthermore, it suggests the use of captured CO_2 as a CCU raw material in industrial production processes (ZEP 2020).

The DVNE and CO2RE, whose focus is on CDR, mention similar points to the other associations. The DVNE highlights the necessity of investing major resources into CDR and states that all CDR methods need to have a removal capacity of 10 Gt up to 2050. In addition, it is necessary to include CDR in the climate strategies and promote the development and deployment of these methods and technologies.[69] CO2RE emphasises the risk of non-permanence, for example in the land sector, and calls for a monitoring, reporting and verification scheme and a certification scheme. According to CO2RE, the permanence of different storage methods should decide the future role of CRD in climate policies (Burke and Schenuit 2023).

The Direct Air Capture Coalition only focuses on DAC. To define the role and volume of DAC, it points out that the IPCC sees the need for 100 to 1,000 bn Gt of CDR in this century to limit global warming to 1.5°C. They point out that the existing analysis showed that carbon dioxide removals of between 1.3-29 Gt are needed in order to achieve the 1.5°C goal, with most analyses falling between 5 and 15 Gt.[70]

Cembureau concentrates exclusively on the cement sector. It also assesses the risk of non-permanence. It recommends a clear differentiation between CCS and the non-permanent forms of CCU to ensure that all emitted CO_2 is accounted for. With a view to carbon storage, Cembureau envisages the use of geological storage and of CO_2 in products by means of recycled plastic. It believes that CO_2 in chemicals should be regarded as permanent storage (Cembureau 2023).

CEWEP focuses on waste-to-energy applications. It promotes policies for enabling conditions. According to CEWEP, the carbon held in residual waste can be captured and permanently stored in deep geological storage. It could alternatively be used as a resource in other industries or as feedstock for new products, e.g. synthetic fuels. Annually, 60 to 70 Mt CO_2 can potentially be captured in Europe through the integration of CCS in waste-to-energy facilities. The energy mix substituted by waste-to-energy will be less carbon-intensive due to a higher penetration of renewables. The energy penalty of CCUS applications can be compensated by introducing flue gas condensation further heat recovery systems that use heat pumps and the higher energy outputs expected in the future in the European waste-to-energy sector (CEWEP 2024).

All in all, many associations have similar policy suggestions and similar visions of the roles and volumes of CS. Differences mainly arise in the assessment of risks, predominately the risk of non-permanence. While some believe certain methods like carbon storage in geological formations are safe and permanent, others call for policies and strategies that closely monitor the permanence of different methods. Nonetheless, the main take-away of the positions of the associations is that,

[69] DVNE, Deutschlands Weg zu Netto Null und darüber hinaus, https://dvne.org/
[70] Direct Air Capture Coalition, DAC FAQ, https://www.ccs-europe.eu/our_mission.

independently of the risk assessment, all see CS as an important instrument to be able to achieve net zero targets and that it should be invested in and deployed as soon as possible.

4.3 Companies or projects

The CCS market is evolving rapidly around the world, with several companies and projects offering carbon storage, CO_2 infrastructure for transport and processing and other technology providers emerging rapidly. While several hubs for these type of large-scale storage projects are forming around the globe, for example in the United States/Canada, Brazil or the Gulf States, the positions of central companies and projects in the European and German context will be reviewed in the following. In general, many of the emerging CCS projects are either co-financed or fully implemented by large oil and gas providers, like Total Energies, Shell or Equinor. Such providers are leveraging these initiatives to spearhead the advancement of CCS technologies, thereby aligning themselves with the evolving energy transition narrative, claiming to position themselves as leaders towards a sustainable future.[71]

Equinor, a state-owned Norwegian oil and gas company, has been one of the pioneers of carbon storage projects. Already in 1996, they undertook the injection of captured CO_2 into the Sleipner gas field. Similar projects in the Snøhvit gas field, the successful underground storage in the North Sea, followed. These projects, along with several collaborative research projects on environmental risks, will be used to demonstrate the safety of the method and to legitimise future similar projects (Equinor 2023).

The CS project Northern Lights will be operational in 2025, have an initial CO_2 capacity of 1,5-5 Mtpa and use the saline aquifer injection method. It will be the first project to deliver cross-border CO_2 transport and storage as a service through its open-source infrastructure to establish a commercial CCS market in Europe. Supported by large energy providers like Equinor, Shell and Total Energies, the project enables the storage of industrial emissions and accelerates the decarbonisation of European industry and CCS in general as a contribution to meet net-zero goals. Regarding the risk assessment of the project, it is stated that the technology is safe and permanent. The project description includes extensive risk analysis (e.g. CO_2 leaks, noise studies) but does not cover the impact on marine ecosystems. It concludes that no high environmental or safety risks are present and refers to performed EIAs (Equinor 2019). Similar saline aquifer injection CS projects are being developed in the North Sea (e.g. Havstjerne, Luna, Polaris) with different energy companies being involved (e.g. Wintershall DEA, Horisont Energi, Total Energies) and storage capacities of 2-7 Mtpa CO_2 each. Their position with regard to CCS is similar to those above: they see the technology as necessary in large scale for a sustainable future and relatively risk-free.

With the Smeaheia project, Equinor is planning the largest CS project in the region. It will be able to store up to 20 Mtpa CO_2 in the saline aquifer from 2028 onwards and aims to increase this volume.[72] In general, Equinor sees CS projects in empty gas fields or saline aquifers as the most secure and permanent option for meeting climate targets and calls for the use of large-scale CCS, especially for key industries like cement production and waste incineration. As a large oil and gas provider, they see CCS as an option for counterbalancing ongoing operations in oil and gas and for continuing the provision of a safe and stable energy supply and financial muscle for the energy transition (Equinor 2024a).

[71] While most carbon storage projects in the past aimed at enhancing oil recovery (EOR), all projects under construction or in development are aimed at carbon storage without EOR (GCCSI 2023).
[72] Equinor, Smeaheia, https://www.equinor.com/energy/smeaheia.

A different technology for CS is offered by the Icelandic company Carbfix: it dissolves CO_2 in water that then interacts with rock formations like basalts to form stable minerals. They claim that their method is less prone to CO_2 leakage due to the higher density of carbonated water compared to the surrounding water, is stable over millennia does not need long-term monitoring. The first project Silverstone will have a storage capacity of 0.15 Mtpa CO_2 from 2025 onwards, but the company claims their technology offers a storage capacity overall that is much greater than that needed to meet climate goals (Carbfix 2024).

The NOR-GE project, co-developed by Equinor and Wintershall DEA, is a major project for CO_2 transportation from Germany to the several CS sites being developed in the North Sea. It aims to transport 20-40 Mtpa CO_2 in 2032.[73] In general, they also see CCS as a low-cost, safe, and reliable opportunity for decarbonisation.

Another sector that has a great interest in the development of a commercial CCS market is the cement industry. This industry is increasingly investing in carbon capture infrastructure and creating partnerships with CS projects. Examples of these projects are the Brevik (in Norway) and GeZero (in Germany) projects of Heidelberg Materials, a German cement manufacturer. They see CCS as a relevant technology for reducing emissions not only in their sector, but also for steel production, the petrochemical sector and even coal- or oil-fired power plants.[74] The energy needs for the capture infrastructure will be solely generated based on renewable energy. Regarding the risks of CS, the storage of large amounts of CO_2 on the Norwegian continental shelf is assessed as absolutely safe; it is argued that to date, no CCS project has had to be stopped due to environmental concerns.[75] The German Association of Cement Manufacturers (VDZ), along with other industrial associations from, for example, the petrochemical and maritime transport sector, also defends CCS technologies as capable of making a great and necessary contribution towards decarbonisation, especially in Germany due to its great industrial basis and logistical infrastructure. To support the development of a commercial CCS market, they ask for political commitments to, and financial support of, carbon storage and transport, as well as clear targets for technical CO_2 removals and the use of negative emissions for offsetting (VDZ 2024).

Overall, the companies promoting CCS projects have a great interest in boosting a commercial CCS market and correspondingly see CS as safe, permanent, and reliable. While risk assessments tend to fall short (section 3.5), the safety of the methods is generally justified based on experiences from existing commercial and research projects and performed EIAs. In general, CCS is seen as the central strategy for many oil- and gas companies, which are strongly involved in CCS projects, for accelerating and contributing to the energy transition, while not having to completely stop their fossil fuel operations despite clear global and national commitments to phase out fossil fuels entirely.

4.4 NGOs

Reviewing the positions of environmental NGOs with a view to carbon storage, it becomes clear that, in contrast to most of the reviewed associations, environmental and climate protection NGOs generally hold a cautious to critical position on carbon storage and CCS technologies in general. Although they differ with respect to the envisaged role of carbon storage and CCS technologies, they

[73] Equinor, NOR-GE, https://www.equinor.de/co2-management/nor-ge.
[74] Heidelberg Materials, Brevik CCS, https://www.brevikccs.com/en.
[75] Heidelberg Materials, GeZero: on the path to Germany's first fully decarbonised cement plant, https://www.heidelbergmaterials.com/en/sustainability/we-decarbonize-the-construction-industry/ccus/gezero.

all point to possible, unforeseeable risks of carbon storage and stress that reductions should be strictly prioritised over removals.[76]

As one of the world's largest environmental networks with more than 170 NGOs, CAN-Europe stresses that CCS technologies must be focused on residual emissions, like industrial process emissions, and not deviate attention from emission reduction and from changing unsustainable production and consumption patterns. Carbon storage should only be used for residual emissions if there are no other more developed alternatives that contribute to the phase-out of fossil fuels, e.g. ecodesign, substitution, demand-side measures, etc., and if carbon storage is proven on a large scale, taking into account both the contribution to climate objectives and environmental and social acceptability. They point to possible risks associated with CS and emphasise the need to avoid public funding of CS and to exclude technologies like BECCS (CAN Europe 2020).

Carbon Market Watch (CMW) focuses its position on CDR and does not mention risks or policies specifically with regard to storage. They see removals as an important supplementary option to emissions reductions, but one that cannot replace the emissions reduction and that must intend storage to last for several centuries as a minimum. On a policy level, removal accounting and targets must, therefore, remain strictly separated from emissions, defined in a robust manner and include an analysis of co-benefits and associated risks (CMW 2021).

The World Wildlife Fund (WWF) limits the role of CCS to unavoidable emissions in certain industrial sectors that have no other decarbonisation options and, therefore, sees that CCS technologies must be developed to a limited extent. They point at associated risks, like premature escape of the stored CO_2 or groundwater pollution, and ask for extensive environmental impact assessments, monitoring, and inclusion of high accompanying costs (e.g. related to ecosystem damage) in cost-benefit analysis for CS projects (WWF 2023). Adopting a similar position, the German Association for Nature Protection (NABU) sees a possible role for CCS technologies in outbalancing unavoidable emissions, e.g. from the steel, cement, and aluminium industry and cites the need for negative emissions in Germany beyond the capacity of the natural sinks to meet the global 1.5°C target. At the same time, they call for caution and the need to minimise risks related to CCS, emphasizing the transport and storage processes, tailor its deployment to defossilisation, renewable energy use and call for inclusive and participatory governance structures (NABU 2024).

Bellona views CCS as essential for reducing industrial CO_2 emissions, particularly in sectors that cannot easily switch to decarbonised fuels (Bellona; E3G 2023). They stress the need for robust support mechanisms, strategic planning, and a strong regulatory framework to ensure successful CCS deployment. Bellona also highlights the importance of addressing regional disparities in CO_2 network development and supports CCS in waste incineration to further reduce emissions. Overall, they believe CCS is crucial for achieving net-zero targets and decarbonising industry.

Greenpeace Germany adopts a more critical position towards CCS technologies, seeing them as a "false solution with harmful consequences for nature and climate" (Greenpeace 2024) that should not play a role in the climate architecture of Germany. They see high risks that its high energy demand will be satisfied by fossil fuels and thereby prevent the transition away from fossil based to a circular economy and point at several risks for natural ecosystems (e.g. earthquakes, water pollution, destruction of natural landscapes) (Greenpeace 2024). Friends of the Earth Germany (BUND) also argues that CCS should not play a role in Germany's climate architecture and urges the industry to reduce emissions instead. It points to the risk that CC technologies might even produce an overall positive emission balance over their whole life cycle due to its high energy use. With carbon storage

[76] The analysis covers positions of Bellona, BUND, CAN-E, CMW, Greenpeace and WWF.

in empty gas fields, the injection can cause new cracks in the rock or even trigger earthquakes. They therefore call for no subsidies for CCS, no licenses for carbon storage at sea and for stronger marine protection instead.

In general, NGOs emphasise that emission reductions should always take precedence over removals. Several groups emphasise that CS should only be used for residual, unavoidable emissions and stress the need to avoid distracting from the necessity of emission reductions. They also point to potential risks such as leakage and high costs, argue for a strict policy framework and oppose subsidies. Other groups insist on a clear separation between removal and emission targets and emphasise long-term storage and robust accounting. Some groups cautiously support CS for sectors with unavoidable emissions but stress the need for risk mitigation and the use of renewable energy in CS operations. In contrast, Greenpeace and BUND take a more critical stance, arguing that CCS could perpetuate fossil fuel dependence and pose environmental risks such as earthquakes and ecosystem damage, calling instead for stricter emissions reductions for such technologies.

4.5 Conclusions

The assessment reveals differences and commonalities among the stakeholder groups assessed. While most EP groups do not address carbon storage in detail, some groups see carbon storage technologies as key areas for investment.

In contrast to the EP groups, industry associations provide more detailed insights into the potential of carbon storage, outlining both the benefits and the risks. They all agree on the critical role of carbon storage in achieving net zero targets. However, they differ in their assessment of the risks, with some seeing certain methods as safe and permanent and others calling for policies and strategies to closely monitor the permanence of different methods.

Several companies, particularly in the oil and gas sector, are investing in carbon storage projects, supported by different degrees of public funding. They generally see carbon storage as a safe and reliable decarbonisation method. However, their risk assessments tend to be less comprehensive and often justify the safety of the processes on the basis of experience from existing projects and environmental impact assessments.

NGOs are generally sceptical about or critical of carbon storage and CCS technologies. They emphasise that emission reductions should take precedence over removals and point to potential risks such as leakage and high costs. Some groups are cautiously supportive of CS for sectors with unavoidable emissions but stress the need for risk mitigation and the use of renewable energy in CS operations.

In summary, while there is almost a consensus that some levels of carbon storage will be needed on the path to a climate-neutral economy, views diverge widely on the extent of this carbon storage and on the chain of priorities and means to achieve climate neutrality. The perceived risks and strategies for managing these risks vary considerably between different stakeholder groups. This highlights the need for a balanced and well-informed approach to carbon storage policy and implementation.

5 Policy design

This chapter analyses the current governance mechanisms for carbon transportation and storage at international, European, and national levels. It highlights key regulations such as the United Nations Convention on the Law of the Sea (UNCLOS), the London Convention and Protocol, and various European directives including the CCS and ETS Directives and the Net Zero Industry Act (5.1). The chapter discusses the procedural requirements for CO_2 storage facilities, the composition of CO_2 streams (5.2), and the transport of CO_2 by pipelines, ships, trains, and trucks (5.3). It also addresses site selection criteria (5.4), storage permits (5.5), and the operational phase of carbon storage (5.6), emphasising the importance of environmental protection and regulatory compliance. Additionally, it explores the governance of leakage and the liability, particularly through the ETS Directive, and the financial securities required to cover potential risks associated with carbon storage (5.8). The chapter concludes with recommendations for improving transparency, external control, and financial security measures to ensure the safe and effective implementation of carbon storage projects (5.9).

5.1 Overview of important current governance mechanism

The most important governance mechanisms regarding carbon transportation and storage are:

- on an international level: The United Nations Convention on the Law of the Sea (UNCLOS 1982), the London Convention (London Convention 1972, Annex I) and the London Protocol (IMO 1996)
- on a European level: the Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive 2009), the Environmental Impact Assessment Directive (2011/92/EU), the Environmental Liability Directive (ELD 2004), the Net Zero Industry Act (NZIA 2024)

On a national level, there can be a national law that offers, for example, additional protection for the environment and implementing acts of the above mentioned directives. For the storage of carbon, the CCS Directive sets new procedural requirements throughout the life chain of CO_2 storage facilities (exploration, operation, closure), and requirements regarding geological formations, and changed the EU water and waste legislation. Directives always need to be implemented by the Member States, but some directives, like the CCS Directive, offer more options for implementation than others. For example, Member States are able to opt-out of CCS altogether or designate certain sites. Thus, when considering if and where carbon storage is possible in a specific Member State, the national implementation acts are very important. As an example of national implementation, brief references will be made to the German Federal Carbon Storage Act (KSpG 2012) and its proposed revision (BMWK 2024b).

The Net Zero Industry Act (NZIA 2024) encompasses both the transport infrastructure and carbon capture and storage (Art. 3.1, 4.1, Annex). By 30 December 2024, the Member States need to establish single points of contact for permit-granting (Art. 6), make information accessible online (Art. 7) and provide assistance to accelerate implementation (Art. 8). The duration of the permitting process is limited to 18 months (Art. 9.2), excluding impact assessments necessary due to the EIA Directive (Art. 9.4), though this process is also accelerated (Art. 10) (Kannenberg 2024).

5.2 CO_2 stream composition

According to Art. 12.1 CCS Directive and Annex I London Protocol the carbon transported and stored must consist “overwhelmingly of carbon dioxide”. Additionally, “no waste or other matter may be added” for the purpose of disposing it. The CO_2 stream may contain incidental substances; those substances are associated with the CO_2 emission’s source, the capture or injection process.

Furthermore, substances may be added in order to monitor and verify the migration of CO_2 (EC 2024d). The concentrations of all incidental and added substances shall be below levels that would:

a) “adversely affect the integrity of the storage site or the relevant transport infrastructure;

b) pose a significant risk to the environment or human health; or

c) breach the requirements of applicable Community legislation.”

Further clarifications of these terms can be found in the European Commission’s updated non-binding Guidance Document (EC 2024d). The Guidance refers to various standards without expressing a preference. A uniform standard may unnecessarily increase the energy use for the purification and thus costs. However, the lack of a common standard is not helpful for a level playing field and does not encourage the use of the ‘best’ standard as the diversity of standards can be a barrier for a larger CO_2 network when different operators apply different standards (section 3.1.1). The development of a more harmonised approach that applies to all CO_2 transport and storage activities may facilitate the development of that technology while also reducing technical and leakage risks which stem from the potential confusion which standard is applicable.

5.3 Transport

5.3.1 By pipelines

Transport by pipelines is covered to some extent by the CCS Directive and national CCS Law. A risk assessment is necessary, as is an Environmental Impact Assessment for pipelines over 800 mm and a length of more than 40 km (2011/92/EU, Annex I). According to Art. 24 CCS Directive, transboundary pipelines within the EU must jointly meet the requirements of both countries – another reason why a common standard is useful. In Germany, there are currently problems if a pipeline is used for CCS and for CCU, but the new proposal suggests using the same standards (BMWK 2024b). Furthermore, some stakeholders are in favour (DVGW 2024) and some are against using the same standards as for as fossil gas pipelines since the risk of fire/inflammation differs (Altrock et al. 2022).

According to the Net Zero Industry Act, Member States “shall make all reasonable efforts to develop the necessary CO_2 transport infrastructure” and “take the necessary measures to enable access to CO_2 transport networks and to storage sites for the purposes of geological storage of the produced and captured CO_2” (Art. 22.1, 22. 2 NZIA). They shall coordinate cross-border transport and they can ask the Commission for support, who then will establish CCS Regional Groupings (Art. 22.3). The 2022 revision of the Trans-European Networks for Energy (Ten-E) regulation (EU 2022) includes CO_2 transport and storage infrastructure between EU member states and with neighbouring third countries.

5.3.2 By ship, train or truck

The CCS Directive and the German Federal Carbon Storage Act do not apply to transport by ship, train or truck. Applicable regulations can be found in international agreements and national law that regulate the transport of hazardous goods (Altrock et al. 2022). Regulation (EC) 1013/2006 on shipments of waste (EU 2006) does not apply (Art. 3.3) The Ten-E regulation does not apply to transport via ship, train or truck. It only refers to carbon storage in its preamble and proposes to “strengthen synergies between the transport and energy sector in the efforts to decarbonise the Union’s economy, maritime ports could also play a role in transporting of carbon dioxide through pipelines or other modes of transport".[77]

5.3.3 Transporting across borders for storage under the sea

According to Art. 6.1 London Protocol forbids an export of "wastes and other matter to other countries for dumping or incineration at sea" which included storage under the sea. A 2009 amendment to allow transportation still lacks sufficient signatures, but a compromise in 2019 allows for bilateral agreements (Altrock et al. 2022) as currently formed by Denmark, Belgium, the Netherlands, Sweden with Norway and by Sweden and Denmark (Čavčić 2024).

5.4 Site selection

According to Art. 4.1 CCS Directive, Member States may choose to allow CCS, limit it to certain areas or opt out of CCS. If CCS is (partially) allowed, MS need to assess their storage capacity (Art. 4.2). Annex I provides extensive criteria how storages sites need to be assessed. Further information can be found in a recently published guidance document by the European Commission (EC 2024d). According to the preamble, "Member States should, in selecting storage sites, take account of their geological characteristics, for example seismicity, in the most objective and effective way possible" to ensure "CO_2 will be completely and permanently contained" (Preamble CCS Directive at 19).

5.4.1 Conditions for storage under the sea

UNCLOS permits states to exploit the sea outside of their territorial waters if it is still within 200 nautical miles (exclusive economic zone, EEZ) or on their Continental Shelf. There are environmental obligations specified in the London Convention and in the London Protocol. Most European countries are parties to the London Protocol (IMO 2019). The London Protocol's Annex I was amended to explicitly allow for "carbon dioxide streams from carbon dioxide capture processes for sequestration", but only in sub-sea-bed geological formations. Storage in the water column is therefore not permitted (Stoll and Lehmann 2008; Janssen 2024). The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR 1992) has similar regulations for CCS as the London Protocol, while the Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM 1974) lacks such provisions (Janssen 2024).

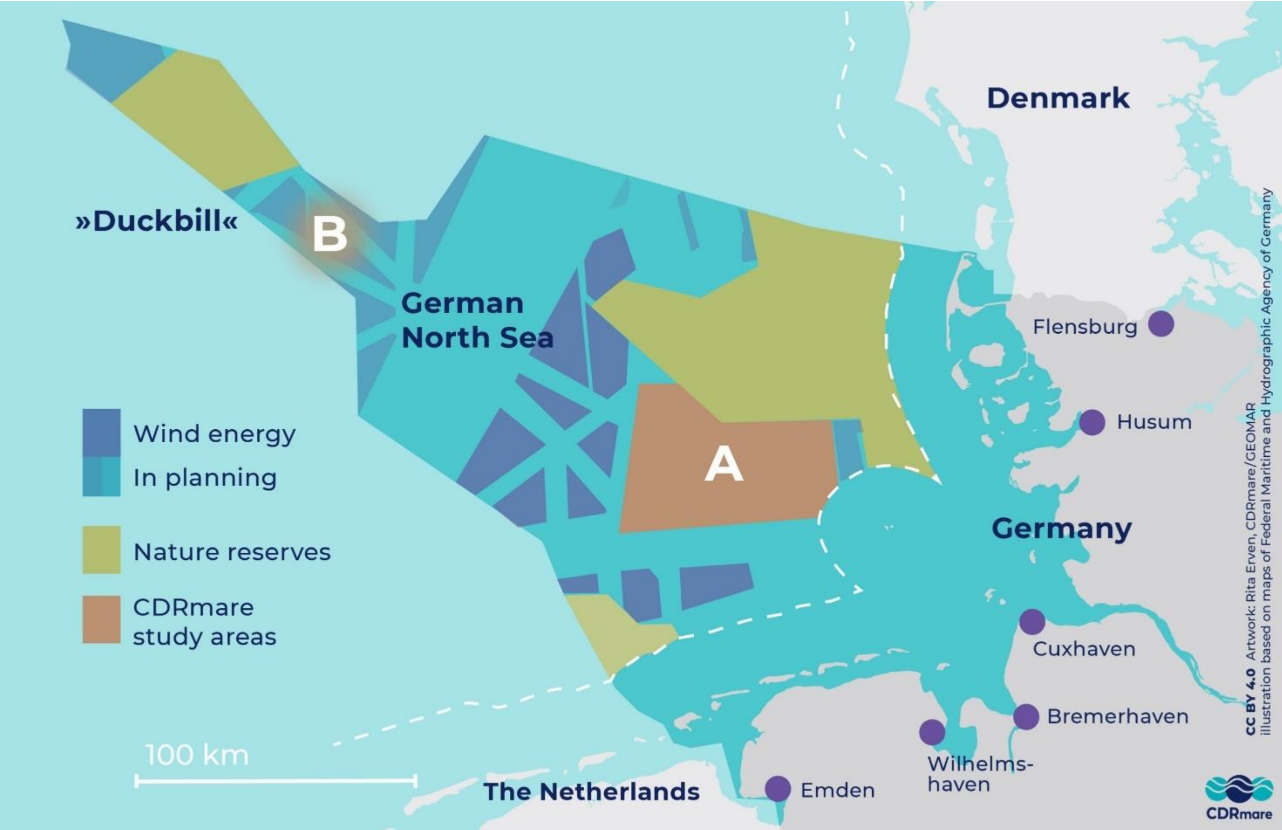
5.4.2 Example of a national application

The German Federal Carbon Storage Act is currently under review. Applications for storage permits were only possible up to the end of 2016, and as long as the respective federal state did not opt-out of carbon storage – which all relevant states did (BMWi 2018). The new proposal from May 2024 would make applications possible again with no limit on the amount (BMWK 2024b). Storage in the exclusive economic zone (EEZ) – which is under federal control – is permitted; federal states can opt-in for their territories. For offshore storage in the EEZ, there is a special protection for marine protected areas, e.g. no storage is allowed under marine protected areas and the injection site must be at least 8 km away. Furthermore, negative consequences for offshore wind energy and hydrogen

[77] European Parliament (2024): Trans-European transport network, recital 54, https://www.europarl.europa.eu/doceo/document/TA-9-2024-0317_EN.html.

production should be ruled out. Germany's marine planning does not designate areas for carbon storage, but for many other uses.

Figure 24: Sketch of the German North Sea



Source: CDRmare (2024)

A designation of such areas, similar to the designation for wind turbines, is therefore essential (Janssen 2024), particularly to prevent environmental risks beyond CO_2 leakage because these risks can usually only be addressed through a comprehensive and thorough assessment before establishing carbon storage infrastructures (section 3.4).

5.5 Storage permits

According to the CCS Directive, Member States can require that exploration permits are necessary before applying for storage permits (Art. 5). Storage is only possible if a storage permit is issued by a Member State (Art. 6.1). The European Commission reviews draft storage permits and issues an opinion (Art. 10.1). The Member State needs to explain if and why it defers from the Commission's opinion (Art. 10.2). The CCS Directive set out a number of conditions for the permission process, including criteria regarding the operator's background (Art. 8.1 b), carbon stream criteria (Art. 12), individual monitoring plan (Art. 13 + Annex II) and reporting (Art. 14) by the operator. The storage permit may only be granted if "all relevant requirements of this Directive and of other relevant Community legislation are met" (Art 8.1 a), if there is more than one storage site in the hydraulic unit, "the potential pressure interactions are such that both sites can simultaneously meet the requirements of this Directive" (Art. 8.1 c). Sites may only be selected "if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist" (Art. 4.4). The new proposal for Germany's Federal Carbon Storage Act already contains certain conditions on how to protect porpoises, further conditions how to protect the environment may be established in a delegated act. Art. 11 CCS Directive lays down how to address changes, reviews, updates and withdrawals of storage permits.

According to Art. 9 CCS Directive, the following information need to be included in the storage permit:

- “the requirements for storage operation, the total quantity of CO_2 authorised to be geologically stored, the reservoir pressure limits, and the maximum injection rates and pressures”;
- “the requirements for the composition of the CO_2 stream and the CO_2 stream acceptance procedure pursuant to Article 12, and, if necessary, further requirements for injection and storage in particular to prevent significant irregularities”;
- “the approved monitoring plan, the obligation to implement the plan and requirements for updating it pursuant to Article 13 as well as the reporting requirements pursuant to Article 14”;
- “the requirement to notify the competent authority in the event of leakages or significant irregularities, the approved corrective measures plan and the obligation to implement the corrective measures plan in the event of leakages or significant irregularities pursuant to Article 16”;
- “the conditions for closure and the approved provisional post-closure plan referred to in Article 17”;
- “any provisions on changes, review, updating and withdrawal of the storage permit pursuant to Article 11”;
- “the requirement to establish and maintain the financial security or any other equivalent pursuant to Article 19”.

5.6 Operational phase

During the operational phase, the operator has to conduct monitoring according to his or her individual monitoring plans. The monitoring plans need to be established according to the requirements in Annex II and “in accordance with the guidelines established pursuant to Article 14 and Article 23(2) of Directive 2003/87/EC” (Art. 13.2), which are now set out in the Monitoring and Reporting Regulation 2018/2066/EU, Annex IV, Section 23 (EC 2024d). The Commission’s updated CCS guidelines contain information on the approach, scope, and format of monitoring plans and on implementation, reporting and performance management. They need to be updated at least every 5 years (Art. 13.2). At least once a year the operator needs to report the following:

- his or her monitoring results, “including information on the monitoring technology employed”;
- “the quantities and properties of the CO_2 streams delivered and injected, including composition of those streams, in the reporting period, registered pursuant to Article 12(3)(b)”;
- “proof of the putting in place and maintenance of the financial security pursuant to Article 19 and Article 9(9)”
- “any other information the competent authority considers relevant for the purposes of assessing compliance with storage permit conditions and increasing the knowledge of CO_2 behaviour in the storage site”.

Member States need to organise a system of routine and non-routine inspections (Art. 15). Routine inspections need to be at least once a year until three years after closure and every five years until transfer of responsibility to the competent authority has occurred (Art. 15.1), Art. 15.4 regulates when non-routine inspections have to be carried out.

Compared to other European legislation, e.g. Directive 2013/30 on safety of offshore oil and gas operations (Offshore Directive 2013), the CCS Directive sets less requirements regarding the operational phase. Unlike for oil and gas installations in the sea, the CCS Directive does not mandate a:

- confidential reporting system of safety concerns;
- competent national authority with no conflict of interests;
- participation and extensive transparency requirements for the public (though it mandates the publication of inspection reports, Art. 11.5).

Art. 16 describes measures in the case of leakages or significant irregularities. Member States must ensure that the operators immediately notify the competent authority and takes necessary corrective measures, including those for protecting human health, in the event of leakages or significant irregularities. These actions should at least follow a corrective measures plan that was originally approved with the permit. The competent authority can also mandate additional or alternative corrective actions and may implement measures itself if the operator fails to do so. Costs incurred by the competent authority for these actions can be recovered from the operator, including through financial security mechanisms. The European Commission’s guidance document contains further information on the definitions of those terms and when and how corrective measures need to be taken (EC 2024d). Corrective measures focus on human health while the Environmental Liability Directive focuses on the prevention of environmental damages; thus, two different systems may apply.

5.7 Information for the public and public participation

According to Art. 26 CCS Directive “the Member States shall make available to the public environmental information relating to the geological storage of CO_2 in accordance with the applicable Community legislation.” The CCS Directive contains no further clauses regarding public participation and information, except regarding the inspection reports in Art. 11.5 which “shall be publicly available in accordance with relevant Community legislation within two months of the inspection.” The most important Community legislation is the Directive on public access to environmental information (2003/4/EC), which implements the obligations of the 1998 Aarhus Convention on access to information. According to Art. 3.1 of that Directive, public authorities must make available environmental information held by or for them to any applicant at his or her request and without his having to state an interest, there are only limited grounds on which the request can be refused (Art. 4).

The CCS Directive contains no special regulations regarding public participation – unlike the Offshore Directive. The Offshore Directive mandates that if no public participation is mandated by Community legislation, the public authorities still have to inform and allow comments from the public (Art. 5.2). Community legislation that mandates public participation are the Environmental Impact Assessment (EIA) Directive (2011/92/EU) and the Strategic Environmental Assessment (SEA) Directive (2001/42/EC). Carbon storage sites fall under the EIA Directive (Annex I Nr. 22), as do pipelines with a diameter of more than 800 mm and a length of more than 40 km for the purposes of geological storage, including associated booster stations (Annex I Nr. 16b). Member States can have additional legislation that requires participation of the public.

5.8 Leakage and liability

5.8.1 Emissions Trading System Directive

The Directive establishing a scheme for greenhouse gas emission allowance trading (ETS Directive 2003) puts a price on CO_2 emissions. If installations use CCS to store the emissions permanently, these installations do not need to surrender allowances for the stored emissions (Article 12 of the ETS Directive) provided that the storage site has a permit according to the CCS Directive (Section 5.8.2). This provides an incentive to pursue CCS if the total cost of CCS is lower than the expected allowance price. With this approach the responsibility for the CO_2 emissions is transferred to the operators of carbon storage sites. The installation initially producing the emissions is no longer responsible for the CO_2 emissions. In return, all elements of the CCS chain are covered by the ETS. This includes capture plants, all modes of transport and storage sites. The different elements of the CCS chain are included in the ETS as separate activities. According to Annex 1 of the ETS Directive, transport and geological storage of CO_2 is covered by the scope of the ETS Directive. If CO_2 is released during transport, for example, allowances need to be surrendered to cover the emissions by the transport provider. The same holds if CO_2 is released from a capture plant or a storage site. This creates an incentive to avoid leakages because these leakages are a cost element for the operator of the transport system or the storage site. As long as emissions from the storage site are monitored (which is stipulated by the ETS Directive) and sufficient financial securities are in place (section 5.8.2), risks regarding CO_2 leakage are adequately addressed. It should be noted that monitoring of emissions from installations "traditionally" covered by the ETS is different from monitoring emissions from the CCS process chain. Traditionally, CO_2 emissions are calculated in the ETS by multiplying quantities of fuel used with (standard) emission factors (e.g. for a gas fired power plant). For CCS, continuous emission measurement systems (CEMS) will be important to measure CO_2 flows. To monitor emissions from the CCS chain, the Monitoring and Reporting Guidelines differentiate between fugitive emissions, vented emissions, leakage events and "normal" combustion emissions (EC 2024e).

Until now, the ETS has not covered no CCS storage sites. The Northern Lights project reports emissions in the ETS under category 20 (combustion installations). The first Norwegian CCS projects store CO_2 from natural gas production (when the CO_2 content in natural gas is above 2.5% it needs to be reduced according to the "natural gas sales specification" (Mazzetti et al. 2014)). This CO_2 stream is not covered by the ETS as the CO_2 emissions are not produced by combustion. Therefore, experiences gathered with the first CCS projects covered by the ETS will provide insights that can be taken into account to improve the monitoring system at a later stage.

Currently, the ETS Directive only creates incentives for carbon capture and storage for non-biogenic CO_2 emissions (e.g. from fossil fuels, non-sustainable biomass or from industrial processes). As most emissions from biomass are considered to be zero-rated according to Article 14 ETS Directive, there is not currently an incentive to implement CCS projects with biogenic CO_2 emissions. According to Article 30 (4a) ETS Directive, the European Commission shall present a report and proposal until July 2026 on "how negative emissions … could be accounted for … including safeguards to ensure that such removals are not offsetting necessary emissions reductions in accordance with Union climate targets".

There are various options for creating incentives for CCS with biogenic CO_2 emissions:

- In principle, biogenic emissions could no longer counted as zero (Article 14 ETS Directive).

- Indirect financing of projects providing negative emissions (indirect linking) via auctioning revenues. Sweden recently started financing BioCCS projects (EC 2024a).
- Allowing the use of credits from industrial removal projects in the ETS.

If wood-based BioCCS is pursued, it needs to be taken into account that there is the risk of reducing the contribution of other carbon sinks such as carbon stored in forests (Concito 2024; Fehrenbach et al. 2022). The best option to address this problem is to no longer count biogenic emissions as zero. This means that operators would have to surrender allowances for all biomass uses in the ETS when the CO_2 from biomass use is released into the atmosphere. When CCS is applied in this way, CO_2 from biomass will not be released into the atmosphere, with the result that no allowances need to be surrendered. This creates an incentive for CCS as CO_2 certificates no longer have to be surrendered for the combustion of biomass when the CO_2 emissions are captured and permanently stored.

5.8.2 Carbon Capture and Storage Directive

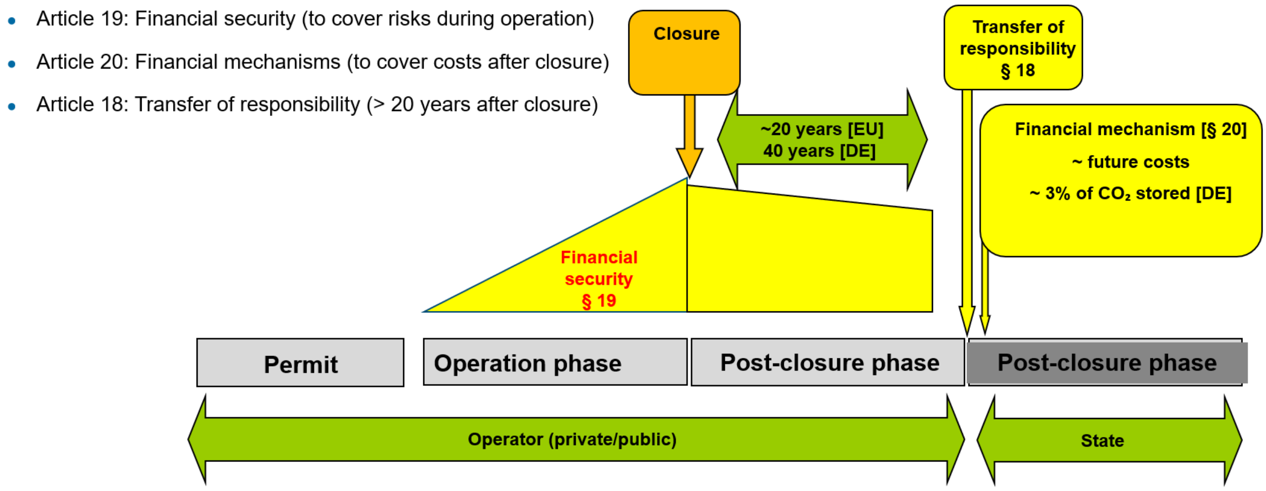
With a view to CO_2, the main requirements are regulated in the ETS Directive. The Directive on geological storage of carbon dioxide (CCS Directive 2009) contains general provisions for a financial security to cover costs during operation (Article 19 CCS Directive), the closure and the long-term responsibility for a carbon dioxide storage site (Article 18 and Article 20 CCS Directive). These provisions are important so as to be able cover any costs that arise from the surrendering of CO_2 allowances in the case of CO_2 leakage from the storage site (Figure 25). The CCS Directive leaves the definition of details to the Member States or their competent authorities. Some further explanations can be found in the European Commission's updated Guidance Document (EC 2024b):

- The amounts should be sufficient to cover any obligations stemming from the storage permit (using a cost risk analysis multiplying estimated costs with the probability). At the same time, they should not hinder investment in storage sites.
- The financial security should include different components, e.g. a component for monitoring, a component for corrective measures, one for the potential surrender of allowances and one related to closure and post-closure.
- One key question in this context is the nature of the security and how it is protected against the operator's bankruptcy. The guidance document describes different options for the financial security (e.g. an insurance product). Among many others, the guidance document also includes the option of using EU emissions allowances (EUAs).

In Germany, this is regulated in § 30 KSpG. In Germany, the financial security can be provided by an insurance or by the deposition of securities. Internal reserves are not allowed. This is very positive given the negative experiences gathered with internal reserves. In the case of lignite mining, for instance, there is the risk that the internal reserves will not be available once the open pit mines need to be rehabilitated. The amount of the financial security is to be determined by the competent authority (§ 30 KSpG). The fundamental question is how high this security should be set. There is a risk that the competent authority will set the security too low.[78] It is therefore positive that the European Commission's updated non-binding guidance document provides options in this respect.

[78] In the case of the hard coal mining industry in Germany, the perpetuity costs were estimated to be at least € 13 billion, while RAG's provisions amounted only to € 5 billion (KPMG 2006).

Figure 25: Liability in the CCS Directive



Source: Authors' own compilation

Article 18 and Article 20 of the CCS Directive regulate the long-term responsibility for a carbon dioxide storage site. Once the storage site is closed and certain prerequisites are met, it is possible that the operator transfers the responsibility to the government. According to the CCS Directive, a minimum period of 20 years needs to have elapsed before the transfer is possible. One prerequisite for the transfer of responsibility is a financial contribution by the operator. According to the CCS Directive, the financial contribution should finance, for example, the future costs of monitoring. Again, the CCS Directive leaves the definition of details to the Member States. Further guidance is provided by the European Commission's updated Guidance Document (chapter 4.3 in EC 2024b). The financial contribution should cover those costs that are certain to occur and costs that might occur with a probability weighting. In Germany, the minimum period is 40 years. In addition to the financial security, a financial contribution amounting to 3% of the value of the CO_2 stored in a given year has to be built up (§ 30 (4) KSpG).

5.9 Conclusions

The CCS Directive establishes a framework for carbon storage and some aspects of carbon transport via pipelines, not via other means of transportation. The latter are regulated by the general transport of hazardous good laws. Overall, the regulatory approach of the CCS Directive prescribes what needs to be taken into account, but in a few cases does not set standards. Implementation is carried out by Member States, which may lead to differences. On the other hand, as it is a technology with limited practical experience gathered in long term projects, a learning-by-doing approach needs to be taken. Some terms of the CCS Directive often need further clarification in order to be implemented. For example, when do incidental and added substances pass the threshold of a significant risk to the environment or human health? Often these terms are already used in other European legislation and the Commission's updated guidance documents offer further clarification. Nevertheless, taking the example of carbon purity, a uniform interpretation of an adequate standard would be useful, especially for cross-border transport.

Regarding storage under the sea with carbon from other countries, bilateral agreements are needed to comply with the requirements of the London Protocol.

With regard to site selection, no-go areas are recommended, such as the exclusion of marine protected areas currently proposed in Germany. As there are many competing interests in the North Sea, comprehensive and careful spatial planning is needed to ensure the safe implementation of carbon storage projects, to prevent environmental risks beyond CO_2 leakage, which can usually only be addressed with a comprehensive and thorough assessment prior to the construction of carbon storage infrastructure. This spatial planning should be more closely coordinated with countries bordering the North Sea and Baltic Sea to designate coherent zones for the different uses such as marine protection, wind farms, carbon storage.[79]

The CCS Directive contains systems of external control, such as the review of the Member States' permits on the Member States - European Commission level, or the yearly reporting and the systems of inspections on the Member States - operator level. Trust in the operation of carbon storage could be increased by adding further requirements for external control, such as an involvement of independent third-party verifiers in the monitoring process which are selected and paid by the competent national authority rather than the operators to avoid collusion or prevent conflicts of interests.

A system for confidential reporting of safety concerns similar to those for oil and gas extraction facilities should be established. Furthermore, it should be discussed whether an increase of transparency is necessary and possible by including similar provisions as in Art. 24, Annex IX of the Offshore Directive (2013/30/EU). This would automatically make any information regarding major incidents available, and not only inspections reports and environmental information regarding the carbon storage (Art. 11.5, 26 CCS Directive).

The ETS Directive and the CCS Directive provide comprehensive governance for CO_2 storage with provisions for detailed monitoring of leakage during transport and at the storage sites. Since CO_2 transport entities and storage site operators are covered by the ETS Directive, they need to surrender allowances for potential leakage. In this way, they have an intrinsic incentive to avoid leakage, particularly since allowance prices are projected to increase.

For the time after transfer of their responsibility for the storage site to the government, operators have to build up financial security. Currently the security can be established in any form, including such which involve higher risks of non-availability at the time of the responsibility transfer. Here more stringent requirements should be established across the EU to ensure that these securities are also available in the case of the operator's bankruptcy. Due to the lack of long-term experience with CO_2 storage, it is difficult to project the extent to which the securities will cover the future cost of continued monitoring and of potential leakage. Therefore, these requirements need to be reviewed on a regular basis to address the experiences gained. In this review, it should be scrutinised whether the current value of 3% of the CO_2 value stored each year is adequate and whether ETS allowances as security for future costs could address potentially increasing per tonne cost of carbon leakage.

Given the fact that Germany is likely to extend the operational period from 20 years (as required as a minimum in the CCS Directive) to 40 years, it can be questioned whether 20 years is actually appropriate. It should thus be scrutinised whether geological or other conditions in Germany require

[79] Ott argues that purely national planning of offshore wind and marine protected areas leads to sub-optimal results, such as higher costs due to shading of wind turbines and fragmentation of protected areas. Coordinated planning across the North Sea could open up further optimisation potentials. However, all potential uses, including carbon storage, should be included in such planning, which should be coordinated with all countries bordering the North Sea and Baltic Sea. (Tagesspiegel Background, 29/08/2024, https://background.tagesspiegel.de/energie-und-klima/briefing/windenergie-und-meeresschutzgebiete-nordseeweit-zusammen-denken-und-umsetzen.

a longer operational period or whether it would be advisable for a longer period to apply across the EU.

6 Bird's eye view of challenges and options

While the analysis of the existing policies revealed that there is already a comprehensive governance structure in place which addresses many of the envisaged risks, several issues were identified in terms of how the governance structure should be improved or complemented to further reduce the potential risks. However, carbon storage remains contentious in many European countries (Otto et al. 2022). Many deem carbon storage as a new technology with little practical experience gathered to date. The lack of transparency on the extent to which and where the technology will be implemented has also contributed to these concerns. However, other relatively new technologies are not associated with similar concerns. Therefore, it seems appropriate to assess the issue from a different, higher perspective and examine more general challenges with respect to the governance of CO_2 storage.

This chapter discusses more fundamental challenges with a view to identifying options for addressing them in the longer term. Section 6.1 discusses challenges arising from lack of confidence, experience with other long-term risks and the application of the polluter pays principle, particularly in relation to the negative emissions required to address overshoot scenarios. The extent to which different levels of government involvement in the carbon storage process chain would help to address or mitigate these challenges is considered in section 6.2, before conclusions are drawn from the previous considerations in section 6.3.

6.1 Governance challenges

The more fundamental governance challenges can be summarised as a lack of confidence in the technology based on experience with the expected operators, scepticism about long-term responsibilities based on experience with other technologies and, finally, challenges due to limited perspectives on how to finance carbon storage in the longer term.

Lack of confidence

Geological storage of CO_2 is a highly complex industrial technology that, unlike renewable energy, can only be implemented on a large scale. The expertise required for geological storage of CO_2 is largely located in the existing oil and gas industry, making it almost impossible to implement carbon storage without involving that industry. However, this industry has been a major contributor to climate change and has made substantial profits from business models that have triggered and exacerbated the climate crisis. This raises critical questions for many stakeholders: Can these companies be trusted to help solve the climate crisis, and should they be allowed to profit from solving the very problem they helped create?

Experience with other long-term risks

The history of managing long-term industrial risks shows a pattern whereby the burden is often shifted from operators to governments. In Germany, for example, the so-called eternity costs of coal mining exceeded the provisions of the hard coal mine operator by more than 50% (KPMG 2006). The costs not covered by these provisions will need to be covered from public budgets In Germany; responsibility for nuclear waste disposal and risk provisioning has been transferred to governments (BMJ 2017). There is also the question of whether governments have to intervene in cases of inadequate risk provisions, such as in lignite mining (Fiedler and Schrems 2019). This pattern suggests that, in the long term, the risks associated with carbon storage are likely to fall on governments, regardless of the initial liability of the operator. The CCS Directive stipulates that responsibility can only be transferred to the state after 20 years of operation. In Germany this period was extended to

40 years for German storage sites. However, if responsibility does eventually pass to national governments, it may be worth considering whether greater government involvement from the outset could address some of the challenges related to lack of trust or transfer of responsibility.

Polluter Pays Principle

The long-term demand for CO_2 storage is driven by the need to offset residual emissions to ensure and maintain carbon neutrality and, particularly in the second half of this century, by negative emissions to address overshoot. For pathways that overshoot 1.5°C of global warming, carbon dioxide removal (CDR) will need to exceed residual CO_2 emissions later in the century to stay below 1.5°C by 2100 (Figure 1, p. 11).

Larger overshoots will require larger amounts of CDR, highlighting the importance of robust CO_2 storage options.[80] As overshoot continues to increase both in likelihood and magnitude (Bossy et al. 2024), it is increasingly likely that the demand for negative emissions to address overshoot will significantly exceed the demand for CDR to offset remaining emissions.

This would have important implications for financing the costs of CDR and carbon storage. While the costs of offsetting residual emissions should be borne by the operators of the facilities or activities that cause those residual emissions, according to the polluter pays principle (PPP), it is less clear who could bear the cost of the amounts of negative emissions required. The remaining emitters should not be charged because they already bear the cost of their residual emissions. According to the PPP, the costs should be charged to those who caused the overshoot in the past, including the fossil energy industry. However, retroactive charging for past activities is legally difficult and practically unfeasible as it will be very difficult to allocate costs to individual past polluters.

As with other long-term industrial risks, these costs will very likely have to be borne by society as a whole. They would therefore have to be financed by a specific levy on, for example, certain natural resources or from the state budget, making the government the main purchaser of CDR and carbon storage, initially to facilitate the development of the technology and, in the longer term, to ensure that negative emissions are actually achieved. While the cost of offsetting residual emissions from processes such as agriculture, cement and waste incineration must be borne by the emitters under the PPP, a significant proportion of future demand for carbon storage is likely to be financed as a public good either from government budgets or through specific levies. It therefore seems appropriate to consider whether government should play a different role in the carbon storage process chain.

6.2 Varying degree of government involvement

Fattouh et al. (2024) have assessed the diverging degrees of involvements of governments in the CCS process chain and identified a spectrum of degrees reaching from minimal to full government control:

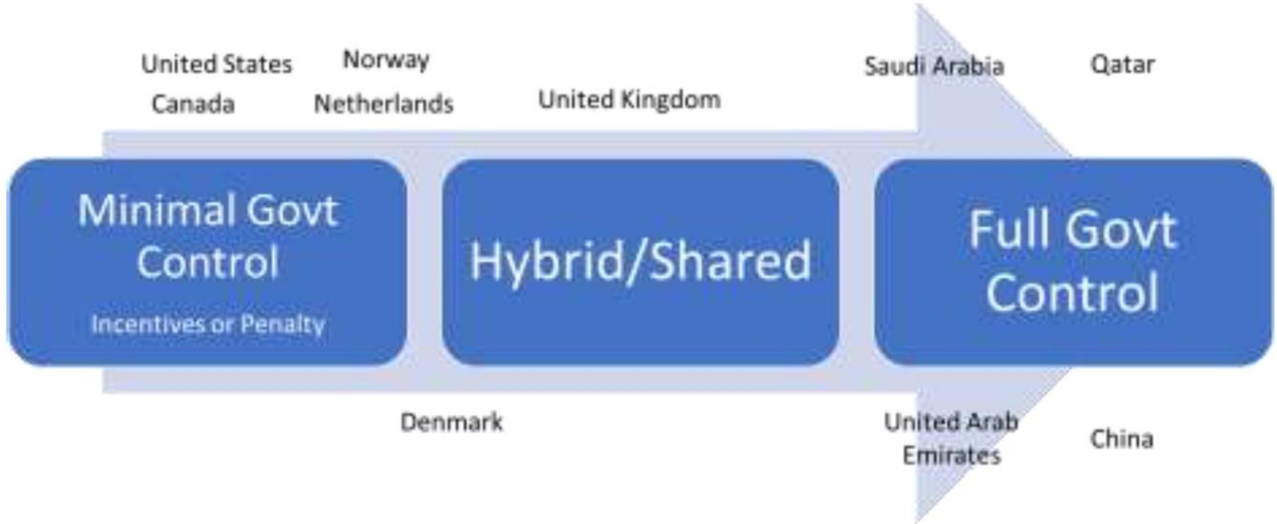
- **Minimal**: Using incentives and/or penalties to influence and nudge the private sector to invest in CCS projects without taking ownership of any segment in the supply chain;
- **Hybrid/Shared**: For capital-intensive activities with uncertain revenue streams, governments may share costs and risks with the private sector;

[80] “Pathways that overshoot 1.5°C of global warming rely on CDR exceeding residual CO_2 emissions later in the century to return to below 1.5°C by 2100, with **larger overshoots requiring greater amounts of CDR** (Figure SPM.3b) (high confidence).” (IPCC 2018, p. 31).

- **Full**: Countries leverage their state-owned and/or national oil companies to invest in and potentially operate CCS projects.

They also allocate the countries analysed within this spectrum (Figure 26).

Figure 26: Varying degree of government involvement in CCS



Source: Fattouh et al. (2024)

While OPEC countries and China tend towards the full government control, the USA and Canda follow a minimal involvement approach. European countries are in the middle of spectrum, falling either in the Hybrid/Shared category or between the Minimal and Hybrid/Shared.

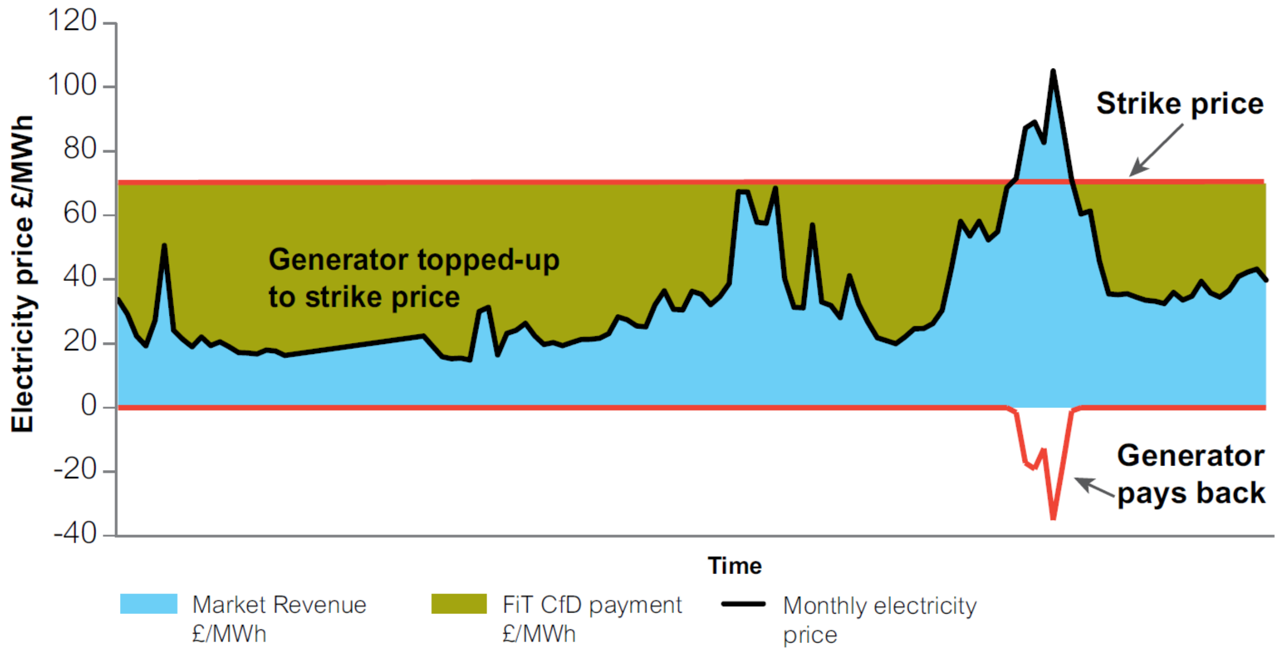
The government involvement varies in several dimensions (Fattouh et al. 2024):

- Process chain: Full chain, partial chain;
- Ownership: State/public, private, public-private partnership;
- Financing: Government, private:

Full government control of carbon storage is only applied in China and Arab countries (Fattouh et al. 2024) and is unlikely to be applied in market-based democracies such as European Member States. However, the range of potential involvement described above shows that it is worth considering a number of questions related to the EU's overall governance approach in order to address the challenges outlined above and to further improve the overall governance approach:

- Should the EU or national governments therefore bear the risks of carbon storage from the outset?
- Would establishing an EU or national bodies for the governance of CO_2 storage further reduce risk and increase confidence in and acceptance of carbon storage?
- For what activities (operation of transport and storage facilities) and with what responsibilities will private companies, including those from the established oil and gas industry, be involved?
- Should the volume of geological CO_2 storage be partly subsidised through contracts for difference (Figure 27) in a competitive bidding process, as similarly already applied in the ETS innovation fund?

Figure 27: Contracts for Difference



Source: DECC (2011)

Note: Contracts for Difference (CfD) provide subsidies to investors in a way which ensures **efficient use of the subsidies while eliminating windfall profits** and mitigating price risks for investors at the same time (UBA 2023a, pp. 165-167).

Elliott (2023) suggests that the UK should create a dedicated body to manage CDR, as responsibility is currently spread across government departments, which can hinder the efficient development of the technologies. A dedicated government body would facilitate the necessary scale-up and help build the expertise needed to monitor and regulate these complex technologies and processes. The proposed Office for Carbon Removal should establish clear definitions of legitimate residual emissions, allocate CDR volumes among residual and negative emissions appropriately, enforce mandatory standards to prevent greenwashing, support the scaling up of less developed and more costly options, implement rules to restrict the use of CDR where there is a high risk of reversal, and have the power to investigate and intervene to prevent environmental damage.

Similarly, a European CO_2 Storage Body (ECSB) could be established. Its role in ensuring effective and sustainable carbon storage would need to be thoroughly discussed. However, it could, among other things, be responsible for determining the amounts of CO_2 to be stored, in line with demand projections for residual and negative emissions. This body could also be responsible for managing the budget needed to finance permanent CO_2 storage for negative emissions, ensuring that funds are allocated efficiently and effectively. In addition, the selection of appropriate storage sites could be a key responsibility, requiring thorough assessments to identify sites that are both geologically suitable and environmentally safe.

In addition to these logistical tasks, the CO_2 storage body could play a crucial role in overseeing monitoring and verification processes. This would include reviewing and approving monitoring plans to ensure compliance with regulatory standards. The body would also accredit third-party entities responsible for monitoring operators, ensuring that these entities meet high standards of accuracy and reliability. It could also be discussed whether the authority should manage the monitoring of storage sites in its entirety. On the one hand, this could reduce monitoring costs and increase confidence in the reliability of monitoring and thus in carbon storage in general. On the other hand, storage operators will need immediate access to monitoring data to ensure the safe operation of storage sites, so appropriate information gateways will need to be established. In addition, the management of Contracts for Difference (CfDs) would be essential to provide financial stability and incentives for CO_2 storage projects, helping to mitigate risk and encourage investment in this critical area.

A number of issues still need to be addressed with regard to establishing and operating an ESCB. These include but are not limited to whether a single European authority or several national authorities should oversee the process. In addition, it needs to be decided whether the risks associated with CO_2 transport should be included in the regulatory framework. Another critical issue is who should be responsible for monitoring of storage sites – the operators themselves or a central body. Covering the costs of carbon storage for negative emissions is also an important issue, with potential sources including charges on private entities or allocations from general government budgets. Identifying the volume of residual emissions from sectors such as agriculture, cement and waste incineration is essential, as is designing an effective bidding process for CfDs to incentivise investment in efficient carbon storage projects.

6.3 Conclusions

The long-term challenges of managing carbon storage are significant and should not be overlooked. Addressing these challenges requires careful consideration of the level of government involvement. Greater government involvement could mitigate many of these challenges by increasing confidence and acceptance through effective risk management, e.g. how the European Central Bank manages inflation risks. Governments can also directly manage demand for carbon storage as setting targets is a core function of government. In addition, potential profits from carbon storage would remain with the government rather than with private companies, ensuring that the public interest is prioritised. This approach would also ensure consistency of responsibility over time, avoiding the pitfalls of shifting responsibility.

Despite the potential benefits, several important questions remain and will need to be carefully addressed. These include determining the appropriate level of government involvement managing the risks associated with the different steps of the carbon storage process chain and whether the responsibility for monitoring storage sites should be changed. Funding mechanisms for carbon storage will also need to be clarified, whether through levies on private entities or allocations from government budgets. However, it is worth considering greater involvement by the European Commission or national governments to ensure effective and sustainable governance of carbon storage.

7 Conclusions and recommendations

All technologies harbour certain risks for society and the environment, not to mention the unpredictable and far greater risks of climate change. Technologies to reduce greenhouse gas emissions such as renewable energy generation, energy storage or smart grids (abatement technologies) are generally associated with lower risks than established technologies such as fossil power generation, installations of the chemical industry or nuclear power plants (incumbent technologies). As carbon storage is a technology with which relatively little practical experience has been gathered, the risks of carbon storage, as measured by the risk premiums charged to operators by insurances, are higher than some of the abatement technologies, but tend to be closer to the abatement technologies than to the incumbent technologies. In this sense, carbon storage can be considered a lower-risk technology. However, there may still be risks which should be further addressed. Therefore, this study has identified risk issues and suggests areas in which improvements in the governance of carbon storage should be considered to enhance not only the overall safety of carbon storage but also the environmental sustainability of the technology:

- **Regulatory framework and standards:** The CCS Directive offers a foundation for its Member States, considering individual national circumstances where appropriate. Confidence in the operation of carbon storage could be enhanced by the inclusion of independent third-party oversight and by establishing procedures for the confidential reporting of irregularities. Different standards for the purity of CO_2 fluxes required for transport or storage facilities may create legal uncertainty. Member States could benefit by establishing a set of common standards across the EU, which would help create a level playing field and foster cross-border cooperation. The lack of standardised regulations may result in inefficiencies and increased costs for operators who must navigate different legal landscapes, which potentially pose the risks of operational irregularities due to unregulated requirements.
- **Technical and operational challenges:** Operational irregularities during injection and the use of existing infrastructure from fossil gas and petroleum industry pose significant risks. Offshore storage projects such as Sleipner and Snøvhit have experienced unforeseen problems with CO_2 behaviour during injection, leading to operational irregularities and significant cost increases. Proper site selection and injection practices are critical to mitigate these risks and make progress along the learning curve. The use of existing infrastructure, such as pipelines and wells, is in principle attractive for cost reasons but should not be considered because existing infrastructure carries higher risks as it does not always meet the specific requirements for CO_2 transport and injection. However, as Ringrose et al. (2021) put it: “The major challenges for CCS scale-up are not geological but are about financial incentives and business drivers. Public perception factors also play an important role in both resisting or encouraging CCS as a climate mitigation measure.”
- **Monitoring and risk management:** Effective pre-injection site performance characterisation and comprehensive monitoring during the injection phase and beyond are critical to mitigate environmental risks. The involvement of an independent third-party to overlook pre-injection site characterisation, the permitting process and operation of the storage sites could increase transparency and thus the public acceptance of carbon storage. Real-time monitoring systems and robust mechanisms for reporting and addressing irregularities are essential to mitigate the risks of leakage and other operational irregularities.
- **Environmental impacts:** The environmental impacts associated with sub-seabed carbon storage are likely to be relatively small but should not be neglected. Therefore, rigorous site selection and environmental criteria before and strict monitoring during operations should be an unconditional prerequisite to minimise potential environmental hazards. Above, indirect impacts on the marine environment due to carbon storage should be considered in the wider context of human activities

and infrastructure development. Thereby, an environmental impact assessment can also consider potential indirect effects, such as noise pollution from increased shipping traffic at offshore storage sites. Research suggests that while short-term spills may have reversible effects on local ecosystems, long-term leakage may provoke irreversible damage. Therefore, thorough investigation and continuous monitoring of potential flaws, such as legacy wells, is essential. Conclusively, the environmental impact of carbon storage projects must be carefully minimised to avoid unintended consequences.

- **Human safety:** For humans, the overall risk of drawing damage from CO_2 exposure is comparatively low due to the generally rapid dispersal of CO_2, which is likely to affect only the immediate vicinity of the leak. Historical data and studies suggest that the likelihood of significant seismic events from CO_2 injection is very low, especially if proper site selection and injection practices are followed. Nevertheless, avoiding urban areas as far as possible is generally sensible to minimise risks for human safety.
- **Post-closure responsibility**: Studies indicate a high long-term storage capacity of geological storage sites, providing confidence in the permanence of CO_2 storage. Clear handover criteria, guidelines, and standards are needed for the transfer of responsibility after closure. The EU framework requires a minimum of 20 years (40 years in Germany) before the state authorities take over responsibility, provided full containment and permanent storage can be demonstrated. Reliable financial security measures must be in place to ensure that operators cover the costs of any necessary remediation during the post-closure phase. This includes comprehensive post-closure plans and possible European Commission's guidance to standardise procedures across EU Member States.
- **Policy landscape:** The CCS Directive provides a comprehensive governance framework for CO_2 storage. Greater government involvement could mitigate the societal, rather than technical, challenges of carbon storage by increasing confidence and acceptance through effective risk management. Governments can also directly manage the demand for carbon storage, ensuring that volumes match the demand for residual and negative emissions. Financing the costs of negative emissions may require much larger financial contributions from government budgets than currently envisaged. This approach would ensure consistency of responsibility over time and avoid the pitfalls of shifting responsibility from operation companies to governments.
- **Revision of the governance:** It is essential to continuously monitor and anticipate evolving technologies and their potential risks and opportunities accordingly. This includes the need for updated regulations on transboundary transport and site selection. Strengthening existing and developing new legislations to address emerging challenges is essential. Policymakers must proactively manage the evolving needs of carbon storage to ensure its long-term viability.

Building on these conclusions, this study recommends the following governance improvements that should be pursued to reduce the risks associated with carbon storage and ensure not only the general safety but also the the environmental sustainability of the technology.

- **Standards for the purity of CO_2 streams:** Initiate a process to agree on a set of common EU-wide standards for CO_2 purity, taking into account the different requirements of each process step and technology, to ensure consistent best practice in terms of risk and cost, while minimising regulatory ambiguity. This helps to create a level playing field and encourage cross-border cooperation. Standardised rules reduce inefficiencies, lower costs for operators and facilitate the development of carbon storage capacity and reduce risks posed by unregulated transport conditions.
- **Enhanced monitoring process:** Establish independent third-party verifiers, selected and paid for by the competent authorities, to oversee the monitoring of carbon storage projects and establish

procedures for confidential reporting of irregularities, as already exists for oil and gas extraction facilities, to increase transparency and confidence in the carbon storage process. Additional independent monitoring could also help building public confidence in the safety and reliability of carbon storage projects. Real-time monitoring systems and robust mechanisms to identify and mitigate operational irregularities are essential.

- **Expanded environmental impact assessments:** Consider indirect effects during environmental impact assessments for all CO_2 storage projects. These assessments should strongly regard noise pollution, increased vessel traffic and other indirect effects. Ongoing monitoring of these impacts is necessary to minimise environmental risks effectively.
- **Integrated spatial planning:** Define No-go areas as part of site selection criteria, e.g., the exclusion of marine protection areas currently discussed in Germany. As land consumption is already high in the North Sea, comprehensive and careful spatial planning is needed to ensure the safe implementation of carbon storage projects. Thereby, thorough assessment of different land uses prevents creating risks, such as land use conflicts risks that often come at the expense of environmental protection. Proper site selection and injection practices are critical to avoid operational irregularities and reduce risks.
- **Environmental criteria and monitoring:** Apply rigorous site selection and environmental criteria that include both direct and indirect impacts and establish stringent monitoring during the operation of storage sites to manage environmental risks effectively. The environmental impacts of carbon storage projects must be carefully managed to avoid unintended consequences. In addition, a system for confidential reporting of safety concerns similar to those for oil and gas extraction facilities should be established.
- **Post-closure liability:** Ensure that financial provisions are in place to cover remediation costs during the post-closure phase. Operators should be required to build up financial provisions to guarantee compensations even in the event of bankruptcy. The European Commission's new guidance on financial security and financial contributions is helpful in this regard. It includes comprehensive post-closure plans and additional guidance to standardise requirements across EU Member States. Financial liability requirements should be regularly reviewed to ensure adequate coverage of future costs.
- **Government involvement:** Initiate processes to examine whether enhanced government involvement can deliver effective and sustainable governance. Greater government involvement can mitigate fundamental societal challenges by building trust and acceptance through effective risk management. Governments can also directly manage the demand for carbon storage, ensuring that volumes are in line with requirements to achieve and maintain carbon neutrality.
- **Regularly review policies:** Mind the learning curve. Despite more than 20 years of experience from large-scale demonstration projects, the carbon storage is still at the beginning of its industrial development. Generally, it is to be expected that industrial ramp-up will lead to a better assessment of risks. It is possible that some risks might not be as relevant as initially thought. The ramp up might also reveal new risks and already identified risks could increase in accordance with deployment and rising storage capacity demand. It is therefore imperative to develop forward-looking policies that address newly identified risks associated with CO_2 storage. Policymakers need to proactively address the evolving needs of carbon storage. This includes updated regulations on transboundary transport and the selection of storage sites in environmentally sensitive areas.

While reducing greenhouse gas emissions remains the overall priority at both the overall and sectoral levels for achieving carbon neutrality, implementing these recommendations contributes to ensuring safe and sustainable carbon storage in geological formations, helping to offset residual and achieve negative emissions. Thereby, carbon storage could play a major role to achieve and maintain carbon neutrality in the second half of this century.

8 References

2001/42/EC: European Union. DIRECTIVE 2001/42/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment, 2001/42/EC. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32001L0042, last accessed on 10 Sep 2024.

2003/4/EC: European Union. DIRECTIVE 2003/4/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 28 January 2003 on public access to environmental information and repealing Council Directive 90/313/EEC, 2003/4/EC. Online available at https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:041:0026:0032:EN:PDF, last accessed on 10 Sep 2024.

2011/92/EU: EU. Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment (codification), 2011/92/EU. Source of information: OJ L 26, 28.1.2012, p. 1–21. Online available at https://eur-lex.europa.eu/legal-content/DE/TXT/?uri=celex:32011L0092.

Abrahamsen, K. (2012): The ship as an underwater noise source. In: *Proc. Mtgs. Acoust.* 17 (1). DOI: 10.1121/1.4772953.

Acuna, C. (2023): The Northern Lights: How we built arobust monitoring and responseplan, Phase 1 monitoringplan. IEAGHG International Workshop on Offshore Geologic CO2 Storage. Aberdeen, 2023.

Alcalde, J.; Flude, S.; Wilkinson, M.; Johnson, G.; Edlmann, K.; Bond, C. E.; Scott, V.; Gilfillan, S. M. V.; Ogaya, X.; Haszeldine, R. S. (2018): Estimating geological CO2 storage security to deliver on climate mitigation. In: *Nat Commun* 9 (1), pp. 1–13. DOI: 10.1038/s41467-018-04423-1.

ALDE - Aliance of Liberals and Democrats for Europe (2024): Your Europe, Your Freedom, Delivering change for you, Aliance of Liberals and Democrats for Europe, last accessed on 8 Sep 2024.

Altrock, M.; Däuper, O.; Kliem, C.; Braun, F.; Hausmann, N. (2022): Rechtliche Rahmenbedingungen für Carbon Capture and Storage (CCS) in Deutschland im Auftrag der Bellona Europa AISBL, 6 Apr 2022.

Anders, S.; Liebe, U.; Meyerhoff, J. (2024): Cross-border CO2 transport decreases public acceptance of carbon capture and storage. In: *Nat. Clim. Chang. DOI:* 10.1038/s41558-024-02023-0.

Becattini, V.; Gabrielli, P.; Antonini, C.; Campos, J.; Acquilino, A.; Sansavini, G.; Mazzotti, M. (2022): Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout. In: *International Journal of Greenhouse Gas Control* 117, p. 103635. DOI: 10.1016/j.ijggc.2022.103635.

BEIS - UK Department for Business, Energy & Industrial Strategy (2023). Deep Geological Storage of CO2 on the UK Continental Shelf, Containment Certainty. UK Department for Business, Energy & Industrial Strategy, 2023.

Bellona; E3G (2023): Carbon Capture and Storage Ladder, Assessing the Climate Value of CCS Applications in Europe, Bellona; E3G. Online available at https://network.bellona.org/content/uploads/sites/3/2023/07/CCSL_briefing.pdf, last accessed on 10 Sep 2024.

BGR - Bundesanstalt für Geowissenschaften und Rohstoffe (2015): Rütters, H.; Bettge, D.; Eggers, R.; Kather, A.; Lempp, C., Lubenau, U. CO2-Reinheit für die Abscheidung und Lagerung (COORAL) – Synthese, Synthesebericht. Bundesanstalt für Geowissenschaften und Rohstoffe. Bundesministerium für Wirtschaft und Klimaschutz (ed.). Hannover, 2015.

BGR - Bundesanstalt für Geowissenschaften und Rohstoffe (2024): Rütters, H.;Löschke, S. CO2-Speicherung im Meeresgebiet – Nutzungskonflikte und Einbeziehung in die Meeresraumplanung?, Bericht zum Fachworkshop des Forschungsverbundes GEOSTOR der Forschungsmission CDRmare am 11. Oktober 2023 im Geozentrum Hannover. Bundesanstalt für Geowissenschaften und Rohstoffe, 2024.

BGS - British Geological Survey (2014): Pearce, J.; Blackford, J.; Beaubien, S.; Foekema, E.; Gemeni, V.; Gwosdz, S.; Jones, D.; Kirk, K, Lions, J.; Metcalfe, R.; Smith, C.; Steven, K.; West, J.; Ziogou, F. A guide to potentical impacts of leakage from CO2 storage (RISCS). Specific Targeted Research Project (240837). British Geological Survey, 2014. Online available at www.riscs-co2.eu.

BMJ - Bundesministeriums der Justiz (2017): Ein Service des Bundesministeriums der Justiz sowie des Bundesamts für Justiz – www.gesetze-im-internet.de - Seite 1 von 9 - Gesetz zur Errichtung eines Fonds zur Finanzierung der kerntechnischen Entsorgung (Entsorgungsfondsgesetz - EntsorgFondsG). Online available at https://www.gesetze-im-internet.de/entsorgfondsg/EntsorgFondsG.pdf, last accessed on 18 Aug 2024.

BMWi - Bundeswirtschaftsministerium (ed.) (2018). Evaluierungsbericht der Bundesregierung über die Anwendung des Kohlendioxid- Speicherungsgesetzes sowie die Erfahrungen zur CCS-Technologie (19/6891), 21 Dec 2018.

BMWK - Bundesministerium für Wirtschaft und Klimaschutz (2022): Evaluierungsbericht der Bundesregierung zum Kohlendioxid-Speicherungsgesetz (KSpG). Online available at https://www.bmwk.de/Redaktion/DE/Downloads/Energiedaten/evaluierungsbericht-bundesregierung-kspg.pdf?__blob=publicationFile&v=1, last accessed on 18 Sep 2023.

BMWK - Bundesministerium für Wirtschaft und Klimaschutz (2024a). Entwurf eines Ersten Gesetzes zur Änderung des Kohlendioxid-Speicherungsgesetzes, Referentenentwurf des Bundesministeriums für Wirtschaft und Klimaschutz. Bundesministerium für Wirtschaft und Klimaschutz, 2024.

BMWK - Bundesministerium für Wirtschaft und Klimaschutz (2024b). Entwurf eines Ersten Gesetzes zur Änderung des Kohlendioxid-Speicherungsgesetzes, Referentenentwurf des Bundesministeriums für Wirtschaft und Klimaschutz. Bundesministerium für Wirtschaft und Klimaschutz, 2024. Online available at https://www.bmwk.de/Redaktion/DE/Downloads/Gesetz/20240226-referentenentwurf-cms.pdf?__blob=publicationFile&v=10.

Bond, S. (2024): Ship Design for CO_2 Transportation. Online available at https://wwwcdn.imo.org/localresources/en/About/Events/Documents/Science%20Day%20Symposium%202024/5.%20ABS%20Europe_Sean%20Bond_Science%20Day_2024_MS.pdf, last accessed on 3 Sep 2024.

Bossy, T.; Gasser, T.; Tanaka, K.; Ciais, P. (2024): On the chances of staying below the 1.5°C warming target. In: *Cell Reports Sustainability* 1 (7), p. 100127. DOI: 10.1016/j.crsus.2024.100127.

Braun, C. (2017): Not in My Backyard: CCS Sites and Public Perception of CCS. In: *Risk analysis : an official publication of the Society for Risk Analysis* 37 (12), pp. 2264–2275. DOI: 10.1111/risa.12793.

Burke, J.; Schenuit, F. (2023): Governing permanence of Carbon Dioxide Removal: a typology of policy measures, CO2RE. Online available at https://co2re.org/wp-content/uploads/2023/11/CO2RE_Report_CDR_Permanence-FINAL-v7.pdf, last accessed on 23 Apr 2024.

Cames, M.; Chaudry, S.; Keimeyer, F.; Sutter; Jürgen; Vittorelli, L. von; Hasegawa, R.; Schilling, J. (2022): Current Situation and Ongoing Projects on Carbon Capture and Storage and Carbon Capture and Utilization in Germany and Japan, Factsheet, Oeko-Institut; ECOS. Online available at https://www.ecos.eu/files/content/downloads/publikationen/BMU_CCS%20&%20CCU.pdf.

Cames, M.; Chaudry, S.; Sutter, J. (2021): Wie ökologisch und sozial verträglich sind CCS, BECCS und CCU Technologien?, Oeko-Institut. Online available at https://www.nabu.de/imperia/md/content/nabude/klimaschutz/221027_studie_ccuccus.pdf.

CAN Europe (2020): CAN Europe’s position on Carbon Capture and Storage and/or Use (CSCU), CAN Europe. Online available at https://caneurope.org/position-carbon-capture-storage/, last accessed on 23 May 2024.

Carbfix (2024): How it works, Carbfix. Online available at https://www.carbfix.com/how-it-works, last updated on 17 Aug 2024, last accessed on 17 Aug 2024.

Catapult - Catapult Offshore Renewable Energy (2021): Robertson, S.;McAreavey, J. CCUS & Offshore Wind Overlap Study Report, Report Findings and Recommendations. In collaboration with Net Zero Technology Centre, The Crown Estate. Catapult Offshore Renewable Energy, 2021.

CATF - Clean Air Task Force (2023): Baltac, S.; Pusceddu, E.; O'Sullivan, C.; Galbraith-Olive, H.; Henderson, C. Unlocking Europe's CO2 Storage Potential, Analysis of Optimal CO2 Storage in Europe. Technical Appendix. Clean Air Task Force, 2023.

Cavanagh, A. J.;Haszeldine, R. S. (2014): The Sleipner storage site: Capillary flow modeling of a layered CO2 plume requires fractured shale barriers within the Utsira Formation. In: *International Journal of Greenhouse Gas Control* 21, pp. 101–112. DOI: 10.1016/j.ijggc.2013.11.017.

Čavčić, M. (2024): Five European countries open their doors to cross-border CO2 storage. Online available at https://www.offshore-energy.biz/five-european-countries-open-their-doors-to-cross-border-co2-storage/.

CCC - Carbon Capture Coalition (2023): About the Carbon Capture Coalition, Carbon Capture Coalition. Online available at https://carboncapturecoalition.org/wp-content/uploads/2023/03/About-us-Fact-Sheet-draft-2-28.pdf, last accessed on 24 May 2024.

CCS Directive (2009): European Union. Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006, CCS Directive. In: *OJ L*, pp. 114–135. Online available at http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0031&from=EN, last accessed on 15 Aug 2014.

CCSA - CCS Association (2024): The Value of CCUS, CCS Association. Online available at https://www.ccsassociation.org/discover-ccus/the-value-of-ccus/, last accessed on 8 Sep 2024.

CCSE - CCS Europe (2024): Our Mission, CCS Europe. Online available at https://www.ccs-europe.eu/our_mission, last accessed on 8 Sep 2024.

CDRmare (2024): Infografics, CDRmare. Online available at https://cdrmare.de/en/infographics/, last accessed on 17 Aug 2024.

CDRmare (ed.) (2023). Chancen und Hürden der marinen geologischen CO_2-Speicherung, Policy Brief (CDRmare Research Mission), 2023.

CEFAS - Centre for Environment, Fisheries and Aquaculture Sciences (2024): Offshore Chemical Notification Scheme (OCNS), Centre for Environment, Fisheries and Aquaculture Sciences. Online available at https://www.cefas.co.uk/data-and-publications/ocns/, last updated on 14 Aug 2024.

Cembureau - The European Cement Association (2023): Permanence of CO_2 Storage in Products, The European Cement Association. Online available at https://cembureau.eu/media/nzxdwckc/231026-cembureau-position-on-permanence-of-co2-storage-in-products.pdf, last accessed on 23 Apr 2024.

CEWEP - Confedereation of European Waste-to-Energy Plants (2024): Waste-to-Energy: Energising your waste, Confedereation of European Waste-to-Energy Plants. Online available at https://www.cewep.eu/wp-content/uploads/2018/07/Interactive-presentation-2018-New-slides.pdf, last accessed on 23 Apr 2024.

Chen, E. Y.-S. (2021): Often Overlooked: Understanding and Meeting the Current Challenges of Marine Invertebrate Conservation. In: *Front. Mar. Sci.* 8. DOI: 10.3389/fmars.2021.690704.

CIEL - Center for International Environment Law (ed.) (2023). Deep Trouble - The risk of offshore Carbon Capture and Storage, 2023.

Clark, D. E.; Oelkers, E. H.; Gunnarsson, I.; Sigfússon, B.; Snæbjörnsdóttir, S. Ó.; Aradóttir, E. S.; Gíslason, S. R. (2020): CarbFix2: CO2 and H2S mineralization during 3.5 years of continuous injection into basaltic rocks at more than 250 °C. In: *Geochimica et Cosmochimica Acta* 279, pp. 45–66. DOI: 10.1016/j.gca.2020.03.039.

CMW - Carbon Market Watch (2021): Respecting the laws of physics - principles for carbon dioxide removal accounting, Carbon Market Watch. Online available at https://carbonmarketwatch.org/wp-content/uploads/2021/12/Respecting-the-laws-of-physics-Dec2021.pdf, last accessed on 23 May 2024.

CO2GeoNet - Eurpäisches Exzellenznetzwerk CO2GeoNet (ed.) (2010). Geologische CO2-Speicherung - Was ist das eigentlich?, 2010. Online available at https://www.bgr.bund.de/DE/Themen/Nutzung_tieferer_Untergrund_CO2Speicherung/Downloads/CO2Geonet-broschuere.pdf;jsessionid=1C6BE279340C3DE3B5D0E1C8A9200EA1.internet011?__blob=publicationFile&v=2.

CO2GeoNet - The European Network of Excellence on the Geological Storage of CO2 (2013). State-of-the-Art of Monitoring Methods to evaluate Co2 Storage Site Performance. The European Network of Excellence on the Geological Storage of CO2, 2013.

Concito (2024). Towards a sustainable deployment of BioCCS in the EU. Concito, May 2024. Online available at https://concito.dk/files/media/document/Towards%20a%20sustainable%20deployment%20of%20BioCCS%20in%20the%20EU.pdf, last accessed on 9 Aug 2024.

CSIRO - Commonwealth Scientific and Industrial Research Organisation (2016): Hook, S. E.;Revill, A. T. Understanding the Environmental Risks of Unplanned Discharges – the Australian Context: Non-Hydrocarbon Chemicals (Document No. 1128_01_001/2_RevD). Commonwealth Scientific and Industrial Research Organisation. Australien Energy Producers (ed.), 2016. Online available at https://www.appea.com.au/wp-content/uploads/2017/08/APPEAWhitePaper_non_Hydrocarbons_Rev0.pdf.

DACC - Direct Air Capture Coalition (2024): Frequently Asked Questions, Direct Air Capture Coalition. Online available at https://daccoalition.org/faq/, last accessed on 8 Sep 2024.

DECC - Department of Energy & Climate Change (2011). Planning our electric future, A white paper for secure, affordable and low-carbon electricity. Department of Energy & Climate Change, 2011. Online available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48129/2176-emr-white-paper.pdf, last accessed on 23 Mar 2023.

Duncan, I.;Wang, H. (2014): Evaluating the likelihood of pipeline failures for future offshore CO2 sequestration projects. In: *International Journal of Greenhouse Gas Control* 24, pp. 124–138. DOI: 10.1016/j.ijggc.2014.02.004.

Dütschke, E.; Alsheimer, S.; Bertoldo, R.; Bagci, A.; Delicado, A.; Gonçalves, L.; Kappler, L.; López-Asensio, S.; Mays, C.; Oltra, C.; Poumadère, M.; Prades, A.; Preuß, S. et al. (2022): Community Acceptance: Findings from community profiles and first local survey. In collaboration with Fraunhofer-Gesellschaft, 2022.

DVGW - Deutscher Verein des Gas- und Wasserfaches (2024): Stellungnahme vom 21. März 2024 zum Entwurf eines Ersten Gesetzes zur Änderung des Kohlendioxid-Speicherungsgesetzes und zu den Eckpunkten der Bundesregierung für eine Carbon Management-Strategie, 21 Mar 2024. Online available at https://www.dvgw.de/medien/dvgw/verein/aktuelles/stellungnahmen/dvgw-stellungnahme-carbon-management-strategie.pdf.

DVNE - Deutscher Verband für Negative Emissionen (2024): Deutschlands Weg zu Netto Null und darüber hinaus, Deutscher Verband für Negative Emissionen. Online available at https://dvne.org/, last accessed on 8 Sep 2024.

EC - EU Commission (2024a). Commission approves €3 billion Swedish State aid scheme to support the roll-out of biogenic carbon dioxide capture and storage. EU Commission, 2 Jul 2024. Online available at https://ec.europa.eu/commission/presscorner/detail/en/ip_24_3583, last accessed on 9 Aug 2024.

EC - EU Commission (2024b). Guidance document 4: Financial security and financial contribution. EU Commission, July 2024. Online available at https://climate.ec.europa.eu/document/download/9a6b221d-642e-499e-a5a0-298ce1068b21_en?filename=ccs-implementation_gd4_en.pdf, last accessed on 9 Aug 2024.

EC - European Commission (2009). Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide, CO2 Storage Life Cycle Risk Management Framework. Guidance Document 1. European Commission, 2009.

EC - European Commission (2012). Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC Text with EEA relevance (32012L0018). European Commission, 2012. Online available at https://eur-lex.europa.eu/eli/dir/2012/18/oj.

EC - European Commission (2024c). Communication from the Comission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Towards an ambitious Industrial Carbon Management for the EU. European Commission. Strasbourg, France, 2024.

EC - European Commission (2024d). Guidance document 2, Characterisation of the storage complex, CO2 stream composition, monitoring and corrective measures. European Commission, 2024. Online available at https://climate.ec.europa.eu/document/download/6f19cb98-b791-466d-8f3c-32c5bb12be2d_en?filename=ccs-implementation_gd2_en.pdf.

EC - European Commission (2024e): Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601/2012. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02018R2066-20240101, last accessed on 15 Jul 2024.

EC - European Commission (ed.) (2023). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act). Brussels, 16 Mar 2023. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0161, last accessed on 8 Feb 2024.

EC - European Commission (ed.) (2024f). Impact Assessment Report, Accompanying the document "Communication from the Commission to the EU. Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society" (SWD(2024) 63 final). Strasbourg, 2024. Online available at https://climate.ec.europa.eu/document/download/768bc81f-5f48-48e3-b4d4-e02ba09faca1_en?filename=2040%20Climate%20Target%20Impact%20Assessment_en_0.pdf, last accessed on 20 Feb 2024.

ECO2 - Sub-seabed CO2 Storage: Impact on Marine Ecosystems (2014a). Potential impact of CCS leakage on marine communities, Deliverable 4.1 (265847). Sub-seabed CO2 Storage: Impact on Marine Ecosystems, 2014.

ECO2 - Sub-seabed CO2 Storage: Impact on Marine Ecosystems (2014b): Morgan, E.; Hauton, C.; Schade, H.; Melzner, F.; Guilini, K.; Vanreusel, A.; Meyer, S.; Ramette, A.; Dupont, S.; Widdicombe, S. The response and potential adaptation of marine species to CO2 exposure associated with different potential CO2 leakage scenarios, Deliverable Number D4.2 (265847). Sub-seabed CO2 Storage: Impact on Marine Ecosystems, 2014.

ECO2 - Sub-seabed CO2 Storage: Impact on Marine Ecosystems (2014c): Queirós, A. M.; Norling, K.; Amaro, T.; Nunes, J.; Cummings, D.; Yakushev, E.; Sorensen, K.; Harris, C.; Woodward, M.; Danocaro, R.; Rastelli, E.; Alve, E.; Vittor, C. de et al. Best Practice Guidance for Environmental Risk Assessment for offshore CO2 geological storage. Deliverable Number D14.1 (European Union Seventh Framework Programme (FP7/2007-2013), EU grant agreement no 265847). Sub-seabed CO2 Storage: Impact on Marine Ecosystems, 2014.

ECO2 - Sub-seabed CO2 Storage: Impact on Marine Ecosystems (2019). ECO2 Final Publishable Summary Report (265847). Sub-seabed CO2 Storage: Impact on Marine Ecosystems, 2019. Online available at https://www.eco2-project.eu/ECO2(265847)%20Final%20Publishable%20Summary%20Report.pdf.

ECR - European Conservatives and Reformists Group (2024): Manifesto, European Conservatives and Reformists Group. Online available at https://drive.usercontent.google.com/download?id=1GWy-8gar-JEV8pSRpSZBOlOo3wxBPp06p&export=download, last accessed on 8 Sep 2024.

EDP - European Democratic Party (2024): Reinventing Europe, European Democratic Party, last accessed on 8 Sep 2024.

EEA - European Environment Agency (2011). Air pollution impacts from carbon capture and storage (CCS). European Environment Agency, 2011. Online available at https://www.eea.europa.eu/publications/carbon-capture-and-storage, last accessed on 13 Jun 2024.

EGP - European Greens (2024): Courage to Change, European Green Manifsto 2024, European Greens. Online available at https://www.datocms-assets.com/87481/1713876249-manifesto_2024.pdf, last accessed on 8 Sep 2024.

EL - EuropeanLEFT (2024): European Elections Manifesto 2024, EuropeanLEFT, last accessed on 8 Sep 2024.

ELD (2004): EU. Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage, ELD. Source of information: OJ L 143, 30.4.2004, p. 56–75. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32004L0035.

Elkerbout, M.; Bryhn, J. (2022): Carbon Removals on the Road to Net Zero, Exploring EU policy options for negative emissions, Centre for European Policy Studies. Online available at https://cdn.ceps.eu/wp-content/uploads/2022/03/CEPS-PI2022-08_Carbon-removals-on-the-road-to-net-zero.pdf, last accessed on 23 Apr 2024.

Elliott, J. (2023): The case for a UK Office for Carbon Removal, green alliance. Online available at https://green-alliance.org.uk/wp-content/uploads/2023/06/Office_for_carbon_removal.pdf, last accessed on 17 Aug 2024.

Energinet (ed.) (2023): Energinet. General Terms and Conditions for Gas Transport - Version 23.0, 2023. Online available at https://en.energinet.dk/media/b03fklth/general-terms-and-conditions-for-gas-transport-23-0_legally-binding-english-version.pdf.

EPP - European Peoples Party (2018): A Sustainable Europe, Policy Paper 3, November 2018. Online available at https://www.epp.eu/files/uploads/2018/11/Policy-Paper-3_Helsinki-1-1.pdf.

EPP - European Peoples Party (2022): EPP leading the sustainable transition towards a climate-neutral future, June 2022. Online available at https://www.epp.eu/files/uploads/2022/06/FINAL-6.pdf, last accessed on 23 Apr 2024.

EPP - European People’s Party Group (2024): Our Europe, a safe and good home for the people. EPP 2024 Minifesto, European People’s Party Group. Online available at https://www.epp.eu/files/uploads/2024/03/Manifesto_2024.pdf, last accessed on 8 Sep 2024.

Equinor (2019). Northern Lights Project Concept report (RE-PM673-00001). Equinor, 2019.

Equinor (2023): Carbon Management – Ambitionierter Klimaschutz und Stärkung des Industriestandorts Deutschland, Equinor. Online available at https://cdn.equinor.com/files/h61q9gi9/germany/86dee1c339108130618c203823d51d94fa1006d4.pdf?Carbon-Management-Position-Equinor-in-Deutschland.pdf, last updated on Oktober 2023, last accessed on 23 May 2024.

Equinor (2024a): Carbon capture and storage, making net zero possible, Equinor. Online available at https://www.equinor.com/energy/carbon-capture-utilisation-and-storage, last accessed on 8 Sep 2024.

Equinor (2024b): CCS: Carbon capture and storage — making net zero possible, Equinor. Online available at https://www.equinor.com/energy/carbon-capture-utilisation-and-storage, last updated on 2 Apr 2024.

Equinor (ed.) (2022). Northern Lights JV DA, Søknad om tillatelse til injisering og lagring av CO2 i lagringskomplekset (Doc. No.: NLJV-ISP-0001), 2022.

ESABCC - European Scientific Advisory Board on Climate Change (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. European Scientific Advisory Board on Climate Change, 2023. Online available at https://climate-advisory-board.europa.eu/reports-and-publications/scientific-advice-for-the-determination-of-an-eu-wide-2040, last accessed on 11 Aug 2023.

ETS Directive (2003): European Union. Directive on establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC, ETS Directive. In: *Official Journal of the European Union* (L 275). Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32003L0087.

EU - European Union (2022): REGULATION (EU) 2022/869 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2022 on guidelines for trans-European energy infrastructure. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R0869, last accessed on 10 Sep 2024.

EU (2006): Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste. Online available at https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:32006R1013.

Fattouh, B.; Muslemani, H.; Jewad, R. (2024): Capture carbon, capture value, An overview of CCS business models, The Oxford Institute for Energy Studies. Online available at https://www.oxfordenergy.org/wpcms/wp-content/uploads/2024/02/CM08-Capture-Carbon-Capture-Value_Final.pdf.

Fehrenbach, H.; Bischoff, M.; Böttcher, H.; Reise, J.; Hennenberg, K. J. (2022): The missing limb: Including impacts of biomass extraction on forest carbon stocks in greenhouse gas balances of wood use. In: *Forests* 13, pp. 1–14. DOI: 10.3390/f13030365.

Fink, M.;Ratter, B. (2024): Blurring societal acceptance by lack of knowledge—insights from a German coastal population study on blue carbon. In: *Front. Clim.* 6. DOI: 10.3389/fclim.2024.1283712.

Fraunhofer ISI - Fraunhofer-Institut für System- und Innovationsforschung ISI (2015). Chancen für und Grenzen der Akzeptanz von CCS in Deutschland, „CCS-Chancen“. In collaboration with Wuppertal Institut für Klima, Umwelt, Energie GmbH (Wuppertal Institut) and Forschungszentrum Jülich. Fraunhofer-Institut für System- und Innovationsforschung ISI, 2015.

Furre, A.-K.; Eiken, O.; Alnes, H.; Vevatne, J. N.; Kiær, A. F. (2017): 20 Years of Monitoring CO2-injection at Sleipner. In: *Energy Procedia* 114, pp. 3916–3926. DOI: 10.1016/j.egypro.2017.03.1523.

Furre, A.-K.; Meneguolo, R.; Pinturier, L.; Bakke, K. (2020): Planning deep subsurface CO2 storage monitoring for the Norwegian full-scale CCS project. In: *First Break* 38 (10), pp. 55–60. DOI: 10.3997/1365-2397.fb2020074.

Furre, A.-K.; Meneguolo, R.; Ringrose, P.; Kassold, S. (2019): Building confidence in CCS: From Sleipner to the Northern Lights Project. In: *First Break* 37 (7), pp. 81–87. DOI: 10.3997/1365-2397.n0038.

Furre, A.-K.; Warchoł, M. J.; Alnes, H.; Pontén, A. S. M. (2024): Sleipner 26 years: how well-established subsurface monitoring work processes have contributed to successful offshore CO 2 injection. In: *Geoenergy* 2 (1). DOI: 10.1144/geoenergy2024-015.

Furre, A.-K.;Eiken, O. (2014): Dual sensor streamer technology used in Sleipner CO 2 injection monitoring. In: *Geophysical Prospecting* 62 (5), pp. 1075–1088. DOI: 10.1111/1365-2478.12120.

GCCSI - Global CCS Institute (2019): Havercroft, I. Lessions and Perceptions: Adopting a Commercial Approach to CCSS Liability (Thought Leadership Report). Global CCS Institute, 2019.

GCCSI - Global CCS Institute (2023): Scaling up through 2030, Global Status of CCS 2023, Global CCS Institute. Online available at https://www.globalccsinstitute.com/wp-content/uploads/2024/01/Global-Status-of-CCS-Report-1.pdf, last accessed on 24 May 2024.

GCCSI - Global CCS Institute (ed.) (2021a): Kearns, D.; Liu, H.; Consoli, C. Technology Readiness and Costs of CCS, 2021.

GCCSI - Global CCS Institute (ed.) (2021b): Tamme, E. Carbon remocal with CCS technologies, 2021.

GEOMAR - Helmholtz-Centre for Ocean Research Kiel (2020): Peterson, S.; Haeckel, M.; Steffen, J. Mineral Resources of the Deep Sea, Formation, Potential and Risks. Helmholtz-Centre for Ocean Research Kiel, 2020. Online available at https://www.geomar.de/fileadmin/content/entdecken/Print/pdfs_en/resources_brochure_2020_en_web.pdf.

GEUS - Geological Survey of Denmark and Greenland (2021): Anthonsen, K. L.;Christensen, N. P. EU Geological CO2 storage summary, Prepared by the Geological Survey of Denmark and Greenland for Clean Air Task Force. DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2021/34. Geological Survey of Denmark and Greenland. Danisch Ministry of Climate, Energy and Utilities (ed.), 2021.

Gladman, I. (2023): Asia-Pacific CCS Overview & Gorgon – 'Not a CCS problem'. CCUS Conference 2023 - GESGB & SPE, 2023.

Greenpeace (2024): CCS: Breites Umweltbündnis warnt vor gefährlichem Irrweg, Greenpeace. Online available at https://www.greenpeace.de/publikationen/Pressemitteilung_CCS.pdf, last accessed on 23 May 2024.

Greens/EFA - Greens/European Free Alliance (2024): Greens/EFA demands EU Post-2030 Climate Targets, Letter to the European Commission, Greens/European Free Alliance. Online available at https://www.greens-efa.eu/en/article/letter/ambitious-post-2030-union-climate-targets, last accessed on 23 May 2024.

Haase, C. (2015): Hydrogeochemische Modellierung der CO_2-Speicherung und -Leckage in geologischen Formationen, Unsicherheiten verursacht durch thermodynamische Datenbanken und numerische Codes. Dissertation, Christian-Albrecht-Universität zu Kiel. Kiel, 2015.

Hafez, A.;Fateen, S. (2016): CO2 Transport and Storage Technologies (In: Carbon Dioxide Capture, ISBN: 978-1-63485-321-7), 2016. Online available at https://www.researchgate.net/publication/304251602_CO2_Transport_and_Storage_Technologies, last accessed on 14 May 2024.

Hansen, O.; Gilding, D.; Nazarian, B.; Osdal, B.; Ringrose, P.; Kristoffersen, J.-B.; Eiken, O.; Hansen, H. (2013): Snøhvit: The History of Injecting and Storing 1 Mt CO2 in the Fluvial Tubåen Fm. In: *Energy Procedia* 37, pp. 3565–3573. DOI: 10.1016/j.egypro.2013.06.249.

HELCOM (1974): Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area. Online available at https://helcom.fi/about-us/convention/.

HSE - Health and Safety Executive of UK government (2011): Harper, P.; Wilday, J.; Bilio, M. Assessment of the major hazard potential of carbon dioxide. Health and Safety Executive of UK government, 2011.

IEA - International Energy Agency (ed.) (2004). Prospects for CO2 Capture and Storage (Energy Technology Analysis). Paris, France, 2004.

IEA - International Energy Agency (ed.) (2022). CO2 Storage Resources and their Development, IEA CCUS Handbook. Paris, France, 2022.

IEAGHG - International Energy Agency Greenhouse Gas R&D Programme (2011). Effects of Impurities on Geological Storage of CO2 (04). International Energy Agency Greenhouse Gas R&D Programme, 2011.

IEAGHG - International Energy Agency Greenhouse Gas R&D Programme (2014). Assessment of Emerging CO2 Capture Technologies and their Potential to Reducs Costs, Report: 2014/TR4. International Energy

Agency Greenhouse Gas R&D Programme, 2014. Online available at https://ieaghg.org/docs/General_Docs/Reports/2014-TR4.pdf.

IEEFA - Institute for Energy Economics and Financial Analysis (2022): Robertson, B.;Mousavian, M. Gorgon Carbon Capture and Storage: The Sting in the Tail. Institute for Energy Economics and Financial Analysis, 2022.

IEEFA - Institute for Energy Economics and Financial Analysis (2023): Hauber, G. Norways's Sleipner and Snøhvit CCS: Industry models or cautionary tales?, Unexpected surbsurface geology developments in the two projects call into question the world's offshore CO2 storage ambitions. Institute for Energy Economics and Financial Analysis, 2023.

IMO - International Maritime Organization (1996): London Protocol. Online available at https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx.

IPCC - Intergovernmental Panel on Climate Change (ed.) (2005): Metz, B.; Davidson, O.; Coninck, H. de; Loos, M.; Meyer, L. IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2005.

IPCC (2022): Climate change 2022, Mitigation of climate change. In collaboration with Shukla, P. R.; Skea, J.; Slade, R.; Fradera, R.; Pathak, M. et al. Geneva: IPCC. Online available at https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf, last accessed on 24 Aug 2023.

ISO - International Organization for Standardization (2016). ISO 27913:2016, Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems (1. edition). International Organization for Standardization, 2016. Online available at https://www.iso.org/standard/64235.html.

Janssen, G. (2024): Drum plane, wer sich ewig bindet – CCS in der Meeresraumordnung. In: *Zeitschrift für Europäisches Umwelt- und Planungsrecht*, pp. 165–179. Online available at https://eurup.lexxion.eu/article/EURUP/2024/2/6.

Kannenberg, L. (2024): Carbon Capture and Storage – rechtliche und klimapolitische Entwicklungen auf Ebene der EU. In: *ZUR*, pp. 396–405.

Knopf, S. (2023): CO2-Speicherpotenzial und -kapazitäten. 2. Dialogveranstaltung CMS: Fachworkshop CO2-Speicherung. Bundesanstalt für Geowissenschaften und Rohstoffe, 2023.

Koornneef, J.; Spruijt, M.; Molag, M.; Ramírez, A.; Turkenburg, W.; Faaij, A. (2010): Quantitative risk assessment of CO2 transport by pipelines—A review of uncertainties and their impacts. In: *Journal of Hazardous Materials* 177 (1), pp. 12–27. DOI: 10.1016/j.jhazmat.2009.11.068.

KPMG (2006): Bewertung der Stillsetzungskosten, Alt- und Ewigkeitslasten des Steinkohlenbergbaus der RAG Aktiengesellschaft Essen, KPMG. Online available at https://media.frag-den-staat.de/files/foi/83231/Anlage2KPMG-Gutachten.PDF.

KSpG (2012): Bundesregierung. Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid (Kohlendioxid-Speicherungsgesetz), KSpG.

Kühn, M. (2011): CO2-Speicherung, Chancen und Risiken. In: *Chem. Unserer Zeit* (45), 2011, pp. 126–138.

Lary, L. de; Loschetter, A.; Bouc, O.; Rohmer, J.; Oldenburg, C. M. (2012): Assessing health impacts of CO2 leakage from a geological storage site into buildings: Role of attenuation in the unsaturated zone and building foundation. In: *International Journal of Greenhouse Gas Control* 9, pp. 322–333. DOI: 10.1016/j.ijggc.2012.04.011.

Li, S.; Zhang, Y.; Lin, Q.; Li, Y.; Liang, X. (2022): Topography modelling for potentially leaked CO2 diffusion and its application in human health risk assessment for carbon capture, utilisation, and storage engineering in China. In: *International Journal of Greenhouse Gas Control* 119, p. 103714. DOI: 10.1016/j.ijggc.2022.103714.

London Convention (1972): International Maritime Organization. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, London Convention. Online available at https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx.

Mahjour, S.;Faroughi, S. (2023): Risks and uncertainties in carbon capture, transport, and stor-age projects: A comprehensive review. (Gas Science and Engineering, 119 (21923) 205117), 2023. Online available at https://doi.org/10.1016/j.jgsce.2023.205117, last accessed on 15 Jun 2024.

Marston, P. M. (2013): Pressure profiles for CO 2 -EOR and CCS: Implications for regulatory frameworks. In: *Greenhouse Gases* 3 (3), pp. 165–168. DOI: 10.1002/ghg.1348.

Masson-Delmotte, V.; Zhai, P.; Pörtner, H.-O.; Roberts, D.; Skea, J.; Shukla, P. R. et al. (ed.) (2018): Global Warming of 1.5° C, An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, Intergovernmental Panel on Climate Change. Geneva: IPCC. Online available at https://www.researchgate.net/profile/Peter-Marcotullio/publication/330090901_Sustainable_development_poverty_eradication_and_reducing_inequalities_In_Global_warming_of_15C_An_IPCC_Special_Report/links/6386062b48124c2bc68128da/Sustainable-development-poverty-eradication-and-reducing-inequalities-In-Global-warming-of-15C-An-IPCC-Special-Report.pdf.

May, F. (2024): Geotechnische Implikationen rechtlicher Rahmenbedingungen für die Erkundung und Überwachung von CO2-Speichern unter dem Meeresboden, GEOSTOR/BGR. Online available at https://cdrmare.de/wp-content/uploads/2024/07/Geostor_AP5.2_V04_29042024.pdf, last accessed on 9 Sep 2024.

Mazzetti, M. J.; Eldrup, N.; Skagestan, R.; Mathiesen, A. (2014): CO2 from Natural Gas Sweetening to Kick-Start EOR in the North Sea (NORDICCS Technical Report, D1.1.1402), December 2014. Online available at https://www.sintef.no/globalassets/sintef-energi/nordiccs/d1.1.1402-co2-form-natural-gas-sweetening-to-kick-start-eor-in-the-north-sea_web.pdf, last accessed on 10 Sep 2024.

McCauley, R. D.; Day, R. D.; Swadling, K. M.; Fitzgibbon, Q. P.; Watson, R. A.; Semmens, J. M. (2017): Widely used marine seismic survey air gun operations negatively impact zooplankton. In: *Nature Ecology & Evolution* 1 (7), p. 195. DOI: 10.1038/s41559-017-0195.

McLean, D. J.; Bond, T.; Partridge, J. C.; Rouse, S.; Love, M. S. (2020): The impact of oil and gas infrastructure in marine ecosystems: a global vision for informing decommissioning decisions. In: *The APPEA Journal* 60 (2), pp. 476–479. DOI: 10.1071/AJ19153.

McLean, D. L.; Ferreira, L. C.; Benthuysen, J. A.; Miller, K. J.; Schlappy, M.-L.; Ajemian, M. J.; Berry, O.; Birchenough, S. N.; Todd, B.; Boschetti, F.; Bull, A. S.; Claisse, J. T.; Condie, S. A. et al. (2022): Influence of offshore oil and gas structures on seascape ecological connectivity. In: *Global Change Biology* 28 (11), pp. 3515–3536. DOI: 10.1111/gcb.16134.

MEACP - Ministry of Economic Affairs and Climate Policy, Netherlands (2022). Safety Study CCS and Offshore Wind Farms, Project Technical Outline (F195696-002). Ministry of Economic Affairs and Climate Policy, Netherlands. Fugro (ed.), 2022.

Meneguolo, R.; Thompson, N.; Acuna, C.; Furre, A.-K.; Milovanova, E. (2024): Subsurface maturation in a saline aquifer CCS project development. Experience from the Northern Lights project, offshore Norway. In: *Geoenergy* 2 (1). DOI: 10.1144/geoenergy2024-013.

NABU - Naturschutzbund Deutschland (2022). NABU-Standpunkt CCU und CCS in der Industrie, Können diese Technologien einen wirksamen Beitrag zur Bekämp-fung der Klimakrise leisten?. Naturschutzbund Deutschland, 2022.

NABU - Naturschutzbund Deutschland (2024): Carbon Management-Strategie und KSpTG, Stellungnahme des NABU-Bundesverbands, Naturschutzbund Deutschland, last accessed on 10 Sep 2024.

NearCO2 - Participation & Communication near CO2 Capture and Storage Operations (2011). Engagement and communication strategies for CCS projects:, Gaps between current and desired practices and exemplary strategies Author(s): Deliverable 3.1. Participation & Communication near CO2 Capture and Storage Operations, 2011.

Neele, F.; Kler, R. de; Nienoord; Brownsort, P.; Belfroid, S.; Peters, L.; van Wijhe, D. (2017): CO2 transport by ship: the way forward in Europe. 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 (Energy Procedia, 114 (2017) 6824 – 6834), 2017.

Neupert, M.;Hilgenstock, A. (2022): CO2-Transport in Leitungen – nach welchen Regeln?, Dekarbonisierung, Speicher, CCS, CCU, CO2-Leitungen, CO2-Transport, Regelwer (Dekarbonisierung), 2022. Online available at https://gwf-gas.de/wp-content/uploads/2022/03/GE_03_2022_fb_Neupert.pdf.

North Sea Energy (2024): Projectatlas. North Sea Energy (ed.). Online available at https://northseaenergy.projectatlas.app/atlas/make-your-own-map/visibility?map=55.57687,5.22964,4.78,0,0, last accessed on 8 May 2024.

NZIA (2024): EU. Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724, NZIA. Source of information: OJ L, 2024/1735, 28.6.2024. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1735.

Oeko-Institut (ed.) (2023): Cames, M.; Mader, C.; Hermann, A.; Köhler, A. R.; Malinverno, N.; Möller, M.; Niesen, B.; Som, C.; Wäger, P. Chancen und Risiken von Methoden zur Entnahme und Speicherung von CO2 aus der Atmosphäre, Empfehlungen aufgrund der Analyse des Wissensstandes und einer systematischen Befragung von Fachleuten in der Schweiz (TA-SWISS 80/2023), 2023.

Offshore Directive (2013): European Union. Directive 2013/30/EU of the European Parliament and of the Council of 12 June 2013 on safety of offshore oil and gas operations and amending Directive 2004/35/EC, Offshore Directive. Online available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02013L0030-20210101.

Onyebuchi, V. E.; Kolios, A.; Hanak, D. P.; Biliyok, C.; Manovic, V. (2018): A systematic review of key challenges of CO2 transport via pipelines. In: *Renewable and Sustainable Energy Reviews* 81, pp. 2563–2583. DOI: 10.1016/j.rser.2017.06.064.

OSPAR (1992): Convention for the Protection of the Marine Environment of the North-East Atlantic. Online available at https://www.ospar.org/site/assets/files/1169/ospar_convention.pdf.

Otto, D.; Sprenkeling, M.; Peuchen, R.; Nordø, Å. D.; Mendrinos, D.; Karytsas, S.; Veland, S.; Polyzou, O.; Lien, M.; Heggelund, Y.; Gross, M.; Piek, P.; Puts, H. (2022): On the Organisation of Translation—An Inter- and Transdisciplinary Approach to Developing Design Options for CO2 Storage Monitoring Systems. In: *Energies* 15 (15). DOI: 10.3390/en15155678.

PES - Party of European Socialists (2024): The Europe we want, Social, democratic, sustainble, Party of European Socialists, last accessed on 8 Sep 2024.

Prognos; Oeko-Institut; Wuppertal Institut - Wuppertal Institut für Klima, Umwelt, Energie (2021): Dambeck, H.; Ess, F.; Falkenberg, H.; Kemmler, A.; Kirchner, A.; Kreidelmeyer, S.; Lübbers, S.; Piégsa, A.; Scheffer, S.; Spillmann, T.; Thamling, N.; Wünsch, A.; Wünsch, M. et al. Klimaneutrales Deutschland 2045, Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Langfassung im Auftrag von Stiftung Klimaneutralität, Agora Energiewende und Agora Verkehrswende. Prognos; Oeko-Institut; Wuppertal Institut für Klima, Umwelt, Energie, 2021. Online available at https://www.agora-verkehrswende.de/fileadmin/Projekte/2021/KNDE_2045_Langfassung/Klimaneutrales_Deutschland_2045_Langfassung.pdf, last accessed on 30 May 2022.

Razak, A. A.; M Saaid, I.; Husein, N.; Zaidin, M. F.; Mohamad Sabil, K. (2023): Physical and chemical effect of impurities in carbon capture, utilisation and storage (J. Pet. Explor. Prod. Technol. 1–12.), 2023. Online available at https://doi.org/10.1007/s13202-023-01616-3.

Rinaldi, A. P.; Rutqvist, J.; Vilarrasa, V. (2019): Deep Fracture Zone Reactivation During CO2 Storage at In Salah (Algeria) – A Review of Recent Modeling Studies. In: Ferrari, A. and Laloui, L. (ed.): Energy Geotechnics. SEG-2018. International Symposium on Energy Geotechnics. 1st ed. 2019. Cham: Springer International Publishing; Imprint: Springer (Springer Series in Geomechanics and Geoengineering), pp. 394–401. Online available at https://link.springer.com/chapter/10.1007/978-3-319-99670-7_49.

Ringrose, P. S.; Furre, A.-K.; Gilfillan, S. M. V.; Krevor, S.; Landrø, M.; Leslie, R.; Meckel, T.; Nazarian, B.; Zahid, A. (2021): Storage of Carbon Dioxide in Saline Aquifers: Physicochemical Processes, Key Constraints, and Scale-Up Potential. In: *Annual Review of Chemical and Biomolecular Engineering* 12 (Volume 12, 2021), pp. 471–494. DOI: 10.1146/annurev-chembioeng-093020-091447.

Ringrose, P. S.; Furre, A.-K.; Hansen, O. R. (2013a): Offshore Monitoring Lessons Learned: Sleipner and Snøhvit Storage Projects. USDoE/NETL Carbon Storage R&D Project Review Meeting. Pittsburgh, USA, 2013.

Ringrose, P. S.; Mathieson, A. S.; Wright, I. W.; Selama, F.; Hansen, O.; Bissell, R.; Saoula, N.; Midgley, J. (2013b): The In Salah CO2 Storage Project: Lessons Learned and Knowledge Transfer. In: *Energy Procedia* 37, pp. 6226–6236. DOI: 10.1016/j.egypro.2013.06.551.

Ringrose, P. S.;Sæther, Ø. (2020): CO2 injection operations: Insights from Sleipner and Snøhvit. Carbon Capture Utilisation and Storage Conference – Virtual Event. Aberdeen, 2020.

Roberts, J. J.; Wood, R. A.; Haszeldine, R. S. (2011): Assessing the health risks of natural CO2 seeps in Italy. In: *Proceedings of the National Academy of Sciences of the United States of America* 108 (40), pp. 16545–16548. DOI: 10.1073/pnas.1018590108.

Roberts, J. J.;Stalker, L. (2020): What have we learnt about CO2 leakage from CO2 release field experiments, and what are the gaps for the future? In: *Earth-Science Reviews* 209, p. 102939. DOI: 10.1016/j.earscirev.2019.102939.

RohrFLtgV (2002): Bundesministeriums der Justiz. Verordnung über Rohrfernleitungsanlagen (Rohrfernleitungsverordnung), RohrFLtgV. Online available at https://www.gesetze-im-internet.de/rohrfltgv/RohrFLtgV.pdf, last accessed on 3 Sep 2024.

Simonsen, K. R.; Hansen, D. S.; Pedersen, S. (2023): Challenges in CO2 transportation: Trends and perspectives (in Renewable and Sustainable Energy Reviews · November 2023), 2023.

Sivle, L. D.; Vereide, E. H.; Jong, K. de; Forland, T. N.; Dalen, J.; Wehde, H. (2021): Effects of Sound from Seismic Surveys on Fish Reproduction, the Management Case from Norway. In: *Journal of Marine Science and Engineering* 9 (4), p. 436. DOI: 10.3390/jmse9040436.

Snæbjörnsdóttir, S. Ó.; Sigfússon, B.; Marieni, C.; Goldberg, D.; Gislason, S. R.; Oelkers, E. H. (2020): Carbon dioxide storage through mineral carbonation. In: *Nat Rev Earth Environ* 1 (2), pp. 90–102. DOI: 10.1038/s43017-019-0011-8.

Solé, M.; Kaifu, K.; Mooney, T. A.; Nedelec, S. L.; Olivier, F.; Radford, A. N.; Vazzana, M.; Wale, M. A.; Semmens, J. M.; Simpson, S. D.; Buscaino, G.; Hawkins, A.; Aguilar de Soto, N. et al. (2023): Marine invertebrates and noise. In: *Front. Mar. Sci.* 10. DOI: 10.3389/fmars.2023.1129057.

Song, Y.; Jun, S.; Na, Y.; Kim, K.; Jang, Y.; Wang, J. (2023): Geomechanical challenges during geological CO2 storage: A review. In: *Chemical Engineering Journal* 456, p. 140968. DOI: 10.1016/j.cej.2022.140968.

Staples, C. A.; Williams, J. B.; Craig, G. R.; Roberts, K. M. (2001): Fate, effects and potential environmental risks of ethylene glycol: a review. In: *Chemosphere* 43 (3), pp. 377–383. DOI: 10.1016/s0045-6535(00)00148-x.

Stoll, P.-T.;Lehmann, F. (2008): Die Speicherung von CO 2 im Meeresuntergrund – die völkerrechtliche Sicht. In: *ZUR*, pp. 281–286.

Suzuki, T.; Toriumi, M.; Sakemi, T.; Masui, N.; Yano, S.; Fujita, H.; Furukawa, H. (2013): Conceptual Design of CO2 Transportation System for CCS (Energy Procedia, 37 (2013) 2989 – 2996), 2013.

SWP - Stiftung Wissenschaft und Politik (2024): Voelsen, D. Maritime kritische Infrastrukturen. Stiftung Wissenschaft und Politik, 2024.

Szizybalski, A.; Kollersberger, T.; Möller, F.; Martens, S.; Liebscher, A.; Kühn, M. (2014): Communication Supporting the Research on CO2 Storage at the Ketzin Pilot Site, Germany – A Status Report after Ten Years of Public Outreach. In: *Energy Procedia* 51, pp. 274–280. DOI: 10.1016/j.egypro.2014.07.032.

Themann, D.;Brunnengräber, A. (2021): Using socio-technical analogues as an additional experience horizon for nuclear waste management A comparison of wind farms, fracking, carbon capture and storage (CCS) with a deep-geological nuclear waste disposal (DGD). In: *Utilities Policy* (70), 2021, 101181, 11 S.

Trupp, M.; Ryan, S.; Barranco Mendoza, I.; Leon, D.; Scoby-Smith, L. (2021): Developing the world's largest CO2 Injection System – a history of the Gorgon Carbon Dioxide Injection System.

UBA - Umweltbundesamt (2006). Technische Abscheidung und Speicherung von CO2 - nur eine Übergangslösung, Positionspapier des Umweltbundesamtes zu möglichen Auswirkungen, Potenzialen und Anforderungen. Umweltbundesamt, 2006. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3074.pdf.

UBA - Umweltbundesamt (2019). Wege in eine ressourcenschonende Treibhausgasneutralität, RESCUE-Studie (Climate Change, 2019/36). Umweltbundesamt, 2019. Online available at https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/rescue_studie_cc_36-2019_wege_in_eine_ressourcenschonende_treibhausgasneutralitaet_auflage2_juni-2021.pdf, last accessed on 17 Sep 2021.

UBA - Umweltbundesamt (2023a): Cames, M.; Graichen, J.; Kasten, P.; Kühnel, S.; Faber, J.; Nelissen, D.; Scheelhaase, J.; Grimme, W.; Maertens, S. Climate protection in aviation and maritime transport: Roadmaps for achieving the climate goal (Climate Change, 26/2023). Umweltbundesamt, 2023. Online available at https://www.umweltbundesamt.de/publikationen/climate-protection-in-aviation-maritime-transport, last accessed on 18 Oct 2023.

UBA - Umweltbundesamt (ed.) (2008a). CO2-Abscheidung und Speicherung im Meeresgrund, Meeresökologische und geologische Anforderungen für deren langfristige Sicherheit sowie Ausgestaltung des rechtlichen Rahmens, 2008.

UBA - Umweltbundesamt (ed.) (2008b). CO2-Abscheidung und Speicherung im Meeresgrund, Meeresökologische und geologische Anforderungen für deren langfristige Sicherheit sowie Ausgestaltung des rechtlichen Rahmens, 2008.

UBA - Umweltbundesamt (ed.) (2023b). Carbon Capture and Storage, Diskussionsbeitrag zur Integration in die nationalen Klimaschutzstrategien, 2023.

UNCLOS (1982): United Nations. United Nations Convention on the Law of the Sea, UNCLOS. Online available at https://treaties.un.org/Pages/ViewDetailsIII.aspx?src=TREATY&mtdsg_no=XXI-6&chapter=21&Temp=mtdsg3&clang=_en.

Upham, P.;Roberts, T. (2011): Public perceptions of CCS in context: Results of NearCO2 focus groups in the UK, Belgium, the Netherlands, Germany, Spain and Poland. In: *Energy Procedia* 4, pp. 6338–6344. DOI: 10.1016/j.egypro.2011.02.650.

VDZ - Verein Deutscher Zementwerke (ed.) (2024). Anforderungen an eine CO2-Infrastruktur in Deutschland, Voraussetzungen für Klimaneutralität in den Sektoren Zement, Kalk und Abfallverbrennung. Düsseldorf, 2024. Online available at https://www.vdz-online.de/fileadmin/wissensportal/publikationen/zementindustrie/VDZ-Studie_CO2-Infrastruktur-Deutschland.pdf, last accessed on 16 Apr 2024.

VDZ et al. (2024): Eine nationale Carbon-Management-Strategie zur Umsetzung von industriellen CCS- und CCU-Projekten in Deutschland und Europa. Online available at https://www.vdz-online.de/fileadmin/wissensportal/publikationen/zementindustrie/Positionspapier_Carbon-Management-Strategie.pdf, last accessed on 8 Sep 2024.

Vereide, E. H.; Mihaljevic, M.; Browman, H. I.; Fields, D. M.; Agersted, M. D.; Titelman, J.; Jong, K. de (2023): Effects of airgun discharges used in seismic surveys on development and mortality in nauplii of the copepod Acartia tonsa. In: *Environmental pollution (Barking, Essex : 1987)* 327, p. 121469. DOI: 10.1016/j.envpol.2023.121469.

Vereide, E. H.; Vereide; Khodabandeloo, B.; Jong, K. de (2024): The copepod Acartia sp. is more sensitive to a rapid pressure drop associated with seismic airguns than Calanus sp. In: *Marine Ecology Progress Series* 730, pp. 15–30. DOI: 10.3354/meps14515.

Vereide, E. H.;Kühn, S. (2023): Effects of Anthropogenic Noise on Marine Zooplankton. In: Effects of Noise on Aquatic Life: Springer International Publishing, pp. 1–24. Online available at https://link.springer.com/referenceworkentry/10.1007/978-3-031-10417-6_63-1.

Vielstädte, L.; Linke, P.; Schmidt, M.; Sommer, S.; Haeckel, M.; Braack, M.; Wallmann, K. (2019): Footprint and detectability of a well leaking CO2 in the Central North Sea: Implications from a field experiment and numerical modelling. In: *International Journal of Greenhouse Gas Control* (84), 2019, pp. 190–203.

Vilarrasa, V. (2016): The role of the stress regime on microseismicity induced by overpressure and cooling in geologic carbon storage. In: *Geofluids* 16 (5), pp. 941–953. DOI: 10.1111/gfl.12197.

Vilarrasa, V.;Carrera, J. (2015): Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO2 could leak. In: *Proceedings of the National Academy of Sciences of the United States of America* 112 (19), pp. 5938–5943. DOI: 10.1073/pnas.1413284112.

Wallmann, K. (13.03.24): CCS und CO_2 -Speicherung in der Deutschen Nordsee: Chancen und Risiken. CO_2 unterirdisch speichern: Chancen und Risiken einer kontrovers diskutierten Klimatechnologie. Hosted by: CDRterra. Hannover, 13.03.24. Online available at https://cdrterra.de/news/co%e2%82%82-unterirdisch-speichern-chancen-und-risiken-einer-kontrovers-diskutierten-klimatechnologie.

Wallmann, K. (2023): CCS (Carbon Capture and Storage): CO2-Speicherung unter der Nordsee. (Version 1. Auflage). In: Lozán, J. L.; Graßl, H.; Breckle, S.-W.; Kasang, D. and Quante, M. (ed.): Warnsignal Klima: hilft Technik gegen die Erderwärmung? Climate Engineering in der Diskussion ; wissenschaftliche Fakten. Hamburg: Wissenschaftliche Auswertungen (Warnsignal Klima), pp. 120–125.

Wang, H.; Chen, J.; Li, Q. (2019): A Review of Pipeline Transportation Technology of Carbon Dioxide (IOP Conference Series: Earth and Environmental Science, 310 032033), 2019. Online available at https://iopscience.iop.org/article/10.1088/1755-1315/310/3/032033, last accessed on 14 May 2024.

White, J. A.;Foxall, W. (2016): Assessing induced seismicity risk at CO2 storage projects: Recent progress and remaining challenges. In: *International Journal of Greenhouse Gas Control* 49, pp. 413–424. DOI: 10.1016/j.ijggc.2016.03.021.

White, J. C.; Williams, G.; Chadwick, A. (2018a): Seismic amplitude analysis provides new insights into CO2 plume morphology at the Snøhvit CO2 injection operation. In: *International Journal of Greenhouse Gas Control* 79, pp. 313–322. DOI: 10.1016/j.ijggc.2018.05.024.

White, J. C.; Williams, G.; Chadwick, A.; Furre, A.-K.; Kiær, A. (2018b): Sleipner: The ongoing challenge to determine the thickness of a thin CO2 layer. In: *International Journal of Greenhouse Gas Control* 69, pp. 81–95. DOI: 10.1016/j.ijggc.2017.10.006.

Wuppertal Institut - Wuppertal Institut für Klima, Umwelt, Energie (2023): Witte, K.; Große-Kreul, F.; Reichmann, A.; Weber, N.; Altstadt, L. Akzeptanz von industriellem CCS in Nordrhein-Westfalen : Empfehlungen für Politik und Industrie (Wuppertaler Impulse zur Nachhaltigkeit, 11). Wuppertal Institut für Klima, Umwelt, Energie, 2023.

Wuppertal Institut - Wuppertal Institut für Klima, Umwelt, Energie GmbH (2007): Fischedick, M.; Esken, A.; Luhmann, H.-J.; Schrüwer, D.; Supersberger, N. Geologische CO2-Speicherung als klimapolitische

Handlungsoption, Technologie, Konzepte, Perspektiven (Wuppertal Spezial, 35). Wuppertal Institut für Klima, Umwelt, Energie GmbH, 2007.

WWF - World Wide Fund For Nature (2023): European Commission's public consultation on Industrial CArbon Management - Carbon, Capture, Utilisation & Stroage deployment, WWF European Policy Office response (August 2023), World Wide Fund For Nature. Online available at https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13848-Industrial-carbon-management-carbon-capture-utilisation-and-storage-deployment/F3435423_en, last accessed on 10 Sep 2024.

ZEP - Zero Emissions Platform (2019): CO_2 Storage Safety in the North Sea, Implications of the CO2 Storage Directive, Zero Emissions Platform. Online available at https://zeroemissionsplatform.eu/wp-content/uploads/ZEP-Report-CO2-Storage-Safety-in-NS.pdf, last accessed on 9 Sep 2024.

ZEP - Zero Emissions Platform (2020): A new long-term strategy for Europe's industrial future, Zero Emissions Platform. Online available at https://zeroemissionsplatform.eu/zep-position-paper-a-new-long-term-strategy-for-europes-industrial-future/#, last accessed on 24 May 2024.

ZEP - Zero Emissions Platform (2024): Why CCS, Zero Emissions Platform. Online available at https://zeroemissionsplatform.eu/about-ccs-ccu/why-ccs/, last accessed on 8 Sep 2024.

Zhou, Q.; Birkholzer, J. T.; Tsang, C.-F.; Rutqvist, J. (2008): A method for quick assessment of CO2 storage capacity in closed and semi-closed saline formations. In: *International Journal of Greenhouse Gas Control* 2 (4), pp. 626–639. DOI: 10.1016/j.ijggc.2008.02.004.

Zweigel, P.; Vebenstad, K.; Vazquez Anzola, D.; Lidstone, A. (2021): Containment Risk Assessment of the Northern Lights Aurora CO2 Storage Site.