

BELLONA

CO₂- STORAGE

How can CO₂ be stored underground and what are the risks?



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CO₂-Storage: A summary

For effective and safe CO₂ storage for the purpose of Carbon Capture and Storage (CCS), several considerations come into play. Firstly, selecting an appropriate reservoir is paramount, one that minimises the risk of CO₂ leakage and is strategically located near existing or planned CO₂ transport infrastructure to reduce costs. Ideally, this reservoir should exhibit high porosity and permeability, ensuring a large storage capacity and efficient injection rates. Enhancing storage security involves multiple layers of cap rocks and increasing storage depth. Additionally, a detailed geomechanical assessment of the site is necessary to ensure proper reservoir management, mitigate the risk of compromising the cap rock, and inducing seismic activity. Open-access monitoring and verification mechanisms are crucial not only to guarantee that the CO₂ is permanently stored but also to facilitate industry knowledge-sharing and build public confidence in CCS technology. Operators need to evaluate the impact of old wells and faults that traverse the cap rock, as they could jeopardise containment. A competent authority with fit-for-purpose regulation is needed to ensure risks are handled in a responsible way, and at the same time facilitating efficient storing and industry growth. Lastly, regions with a history of significant seismic activity require particularly careful consideration in CCS implementation.

CO₂-Storage: An overview

Why do we need it?

Carbon Capture and Storage (CCS), where CO₂ is captured, transported, and permanently stored, constitutes an indispensable component of the strategy for curbing CO₂ emissions and mitigating the severe consequences of climate change (IPCC, 2005). Anthropogenic emissions have been pinpointed as the primary drivers of climate change, elevating atmospheric CO₂ levels from 280 ppm in the 1800s to over 422 ppm in 2023 (NASA, 2023). Consequently, global mean temperatures have already increased by 1°C from pre-industrial levels (IPCC, 2018). To adhere to the Paris Agreement's target to keep the global average temperature increase to well below 2°C, substantial emission reductions are imperative (IPCC, 2018).

Energy-intensive industries stand as some of the largest CO₂ emitters and can achieve significant emission reductions through CCS. Certain industries, such as cement production and waste-to-energy, currently lack viable alternatives to CCS for emissions reduction. Cement production alone accounts for approximately 8% of global CO₂ emissions, making emissions reductions in this sector vital for attaining the Paris Agreement targets (Olivier, Janssens-Maenhout, Muntean, & Peters, 2016). Thus, the need for CCS is crucial, particularly in sectors like cement and waste-to-energy, and in addition CCS offers the most cost-effective means to reduce emissions in several energy-intensive industries (IPCC, 2023; Bellona & E3G, 2023).

In most projections for future emission pathways to stay below 2°C of warming, there is also an explicit need to remove carbon from the atmosphere, commonly called "negative emissions" (IPCC, 2023). A frequently mentioned strategy for achieving the necessary negative emissions is Bioenergy with CCS (BECCS) (IPCC, 2023). BECCS, or more broadly, Bio-CCS, commonly involves the combustion or processing of biomass (or biofuel) for energy production or serving as a reducing agent in metals production. Subsequently, CCS is applied to capture the resulting emissions.

The climate benefit is based on the assumption that biomass is carbon-neutral and can then be seen as a net transfer of CO₂ from the atmosphere to the underground storage, with the benefit of a non-fossil energy source. It is, however, important to take the whole process into account when determining the amount of carbon removed (Tanzer & Ramírez, 2019). Other strategies of potential carbon removal include Direct Air Capture and Storage, but this is currently a relatively expensive and energy intensive application of CCS (IEA, 2023)).

What is it?

To prevent captured CO₂ from entering the atmosphere, it needs to be permanently stored. This is normally done deep underground, in places where the CO₂ is naturally prevented from reaching the surface again. In a similar way as oil and gas have been trapped underground for millions of years, the same type of traps can be used to store CO₂. Instead of drilling wells to extract trapped oil and gas, wells can be drilled to inject CO₂. With decades of experience and knowledge from the oil and gas industry, this is a proven method, and hundreds of millions of tons of CO₂ have already been stored safely and permanently underground over the last decades, with no reported leaks (Aminu et al., 2017).

How do we store it?

Basic version:

First, we need a place to store the CO₂; a reservoir. This reservoir should have a large storage capacity and allow for high daily injection rates. Second, we need a trap to prevent the CO₂ from reaching the surface again. This is normally a cap rock overlying the reservoir in a shape that prevents the CO₂ from migrating upwards. The CO₂ cannot flow through the cap rock, and the cap rock acts as a seal over the reservoir. Lastly, we need a well in the reservoir to pump down the CO₂ (see figure 1 for an illustration of how to store CO₂ in the subsurface).

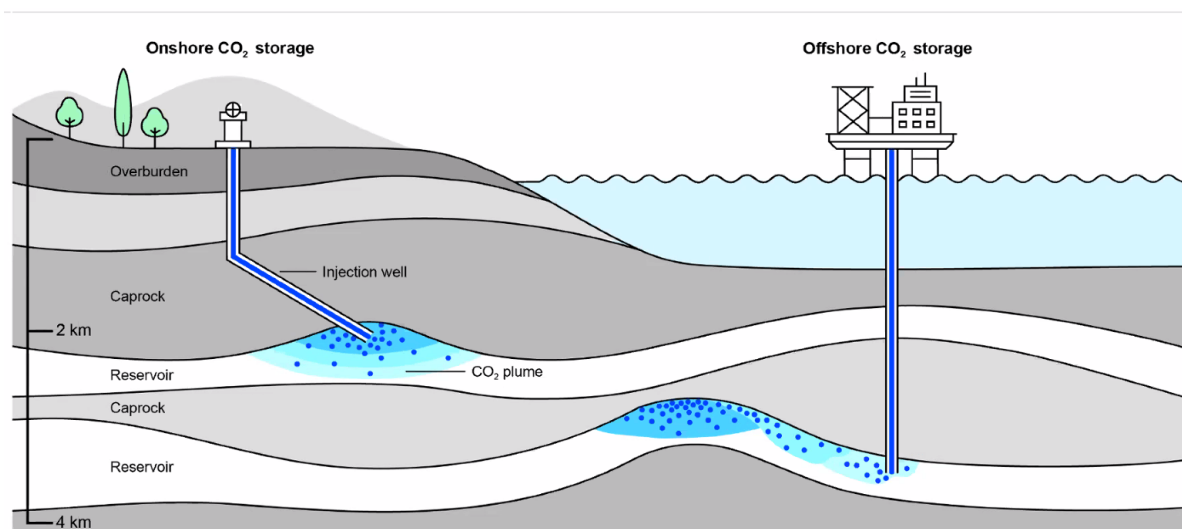


Figure 1: Overview of geological storage options for CO₂. The grey and striped rock represents a cap rock, that in several locations illustrates how the injected CO₂ is prevented from flowing towards the surface (Figure courtesy of IEA).

Detailed version:

The reservoir:

It is a common misconception that we inject CO₂ into a large cavern of space underground. In reality, it is injected into a rock, like sandstone, with a large number of tiny pores which in total offer a lot of space. The percentage of pore space in the rock is called porosity¹ and is normally around 30% in quality reservoir rocks. One can, however, not access all this space, so when calculating storage capacity, it is often estimated that 4-8% of the total reservoir pore volume can be accessed safely (Halland, 2014). Luckily many of these reservoirs are gigantic and still offer plenty of space. To be able to access as much of the reservoir as possible, with high injection rates, the CO₂ needs to flow easily into the reservoir. Therefore, a reservoir of high porosity and high permeability² is desired (see figure 2 for an illustration). In addition, depths greater than approximately 800 meters are desired to have a reservoir pressure and temperature where the CO₂ is in a supercritical phase. In the supercritical phase, which occurs at high temperature and high pressures, the CO₂ takes up substantially less space than in a gaseous phase.

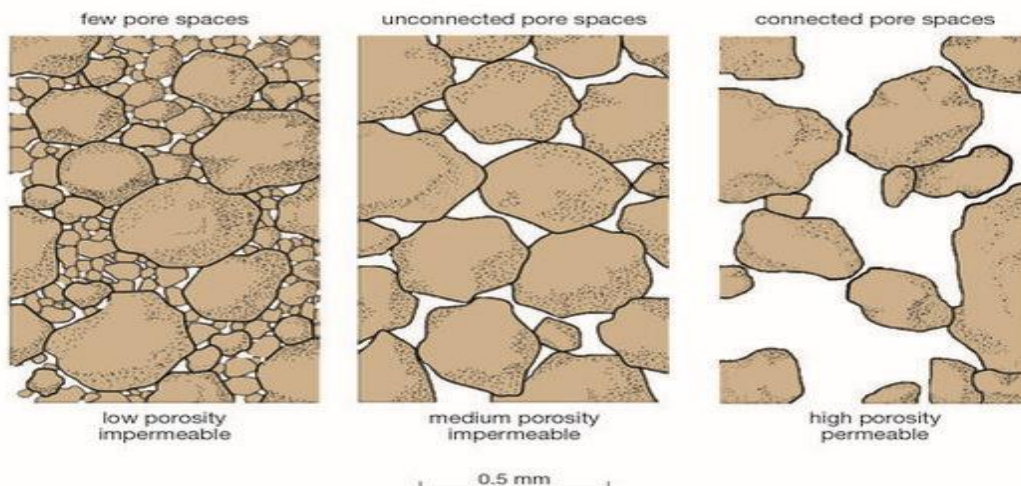


Figure 2 illustrates compositions of rock grains and pore space compatible with different porosities and permeabilities.

¹ **Porosity:** A measure of the volume of pore space in a rock, relative to the total rock volume.

² **Permeability:** A measure of how easily a fluid can flow through a rock.

The cap rock:

As the CO₂ is less dense than the fluids already present in the reservoir, it will tend to move upwards due to buoyancy³ forces. For it not to reach the surface, we need a seal above the reservoir in such a shape that it stops the CO₂ from moving upwards towards the surface. These seals are normally what we call a cap rock. The cap rock is of low permeability, meaning it is difficult for the CO₂ to flow through it.

The well:

To reach these underground storage sites trapping the CO₂ in various ways, a well is needed. This is already standard procedure in the oil and gas industry, and with small adjustments made to facilitate for CO₂ flow, it is a technology which is readily available. If the wells are poorly designed, they can, however, provide an escape route back to the surface, and should therefore be treated with care and a high level of quality assurance.

In figure 1, an illustration of reservoirs, with overlying cap rock(s) and penetrated by wells, can be seen. The injected CO₂ (blue) is prevented from moving upwards by an overlying cap rock, similar to the way oil would be prevented from moving towards the surface.

Secondary trapping mechanisms

The structural trapping of CO₂ by an overlying cap rock should be a prerequisite for any storage site, but with time other trapping mechanisms can come into effect. See figure 3 for illustrations of the different trapping mechanisms.

Residual trapping: As CO₂ flows through the reservoir, it displaces the pre-existing water. As it continues its movement, the water gradually reoccupies the space, and certain portions of the CO₂ become entrapped in small bubbles within the pore spaces. The bubbles are trapped there due to forces acting between the surface of the CO₂ bubble and the solid reservoir rock, known as capillary forces, resulting in what is termed residual trapping.

Solubility trapping: When the injected CO₂ comes in contact with the reservoir fluid it will start to dissolve until an equilibrium is reached. The fluid will increase in density as CO₂ dissolves and starts to sink. This process is normally quite slow, and it can take thousands of years for the CO₂ to be completely dissolved (Zhang & Song, 2014). It has, however, been shown in several modelling

³ **Buoyancy:** When something light is submerged in something heavy, it will float upwards. Like helium balloons towards the sky, and air bubbles in water towards the surface. CO₂ is less dense than the fluids normally found underground and will therefore tend to float back up towards the surface.

studies that diffusion of CO₂ into brine can increase storage capacity and may reduce the chance of migration of CO₂ to the surface (Aminu et al., 2017).

Mineral trapping: Mineral trapping occurs if the CO₂ reacts with the formation minerals or organic matter, and precipitates into a solid. This is a permanent trapping, but often only happens on very large time scales of thousands of years. In some specific conditions it can happen quite quickly, for example when dissolved CO₂ in water is injected into young basalt formations, as the Carbfix project in Iceland is an example of.

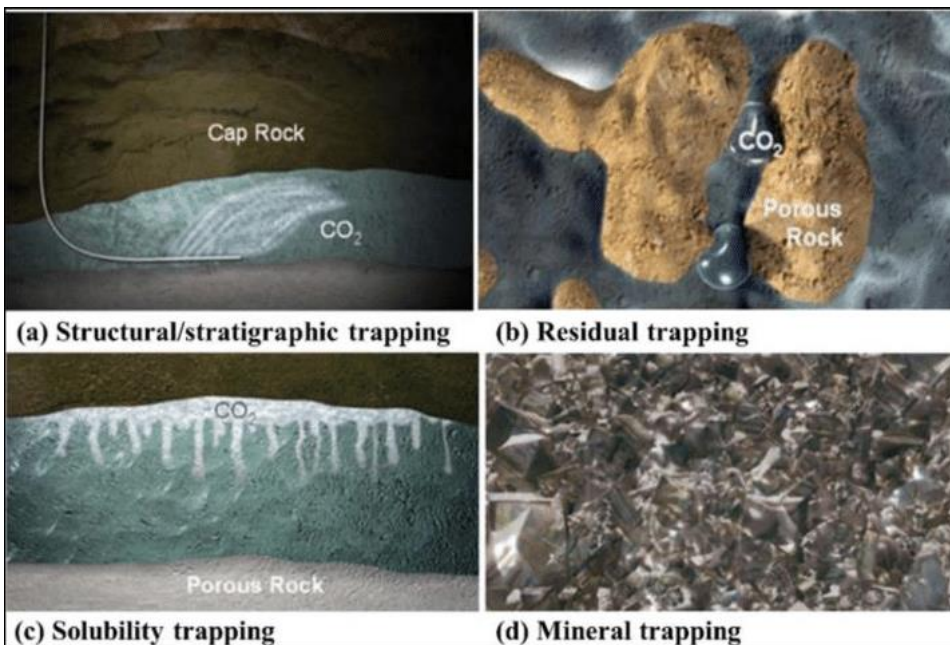


Figure 3 shows different trapping mechanisms for CO₂ in the subsurface (Aminu et al. 2017)

See Aminu et al. (2017) and Zhang & Song (2014) for more information on secondary trapping mechanisms.

Types of storage

We have several options to where we can geologically store the CO₂, with the most common being depleted oil and gas reservoirs, saline aquifers, active oil and gas fields (through Enhanced Oil Recovery (EOR)), and in basalt. Both onshore and offshore options exist, where offshore storage is generally more expensive. For more information on different storage options see Aminu et al. (2017). It should be noted that EOR based CO₂ storage is mostly done with the focus of enhanced oil production and is generally not considered a positive climate initiative.

Depleted Oil and Gas Reservoirs

When the oil and gas has been extracted from a reservoir, it can be filled up with the same volume of CO₂. Since the reservoir has trapped oil and gas there for millions of years it can hold CO₂ as well unless we created a leakage through, for example, a poorly constructed well. The benefits with depleted oil and gas fields are that they already have existing infrastructure, information, and experience from the reservoir, which can significantly lower costs, risks, and rate of deployment. The negatives are limited global storage capacity, it can be in conflict of interest with the petroleum industry, and older wells can pose some risk of leakage. An example of storage in a depleted reservoir is the Greensand project in Denmark, aiming at storing up to 1.5 Mt of CO₂ a year (see Project Greensand (2023)).

Saline Aquifers

Saline aquifers are large underground reservoirs containing brine as pore fluid. If there are good cap rocks above the reservoir, it can store CO₂ in the same way as with depleted O&G reservoirs. The benefits of saline aquifers are that they are much more abundant, greater in storage capacity, and therefore allow for more flexibility in choosing locations. The negatives are that there is often little information about the reservoir, no wells and little or no infrastructure which can significantly increase cost. There is also risk of increased cost due to the need to verify cap rock integrity, extra reservoir modelling, and in general operating with an unknown reservoir. Examples of storage in saline aquifers are the Sleipner and Snøhvit projects, which have the capacity to inject around 1.5 Mt of CO₂ per year (Eiken, et al., 2011).

Basalt

Basalt storage is based on pumping dissolved CO₂ in water into a young basalt reservoir, where it will mineralise to a solid (95% within two years) and considered permanently stored (Carbfix, 2023). This might offer storage sites for CO₂ in locations where more traditional storage options are not available or too expensive. The negatives are that large amounts of water are needed (27 times the CO₂) which again demands more storage space. More research and testing are needed to verify this method as a large-scale alternative, but an example of basalt storing is the Carbfix concept which has injected around 0.1 Mt of CO₂ since 2014 (Carbfix, 2023).

Enhanced Oil/Gas Recovery in operational oil and gas fields

Several CO₂-EOR fields are in commercial activity but may have limited capacity in the big picture and are generally not a positive climate initiative. These fields may also have different regulation than normal CCS, and calculating the actual amount CO₂ stored is not straight forward due to injected CO₂ eventually ending up in the production well. The climate impact of EOR and EGR also depends on the ratio of CO₂ stored and CO₂ emitted during the combustion of the fossil fuel

extracted in the enhanced recovery process, normally resulting in a significant addition of CO₂ to the atmosphere.

Risks of leakage

The concept of CO₂ storage in geological structures is already commercially active, there are several examples of successful storage, and there is a lot of competence transfer from the O&G industry. It is not, however, without risks and challenges.

Leakage to the surface

One of the primary concerns associated with CCS is the potential for stored CO₂ to escape back to the surface, and into the atmosphere. In reservoirs featuring a robust cap rock, risks are normally associated with factors like faults, induced fractures, and wells (see figure 4). However, it's worth noting that numerous projected storage sites have few or no old wells, have no faults, and are unlikely to experience fracturing during injection, resulting in a very low risk of leakage.

For reservoirs where some of these factors are present, it doesn't necessarily indicate an inadequate seal, but it does necessitate additional caution when evaluating risks, implementing monitoring activities, and formulating response plans. In certain instances, when the risk is deemed excessively high, the reservoir may need to be abandoned. Competent governmental oversight is crucial to ensure the quality of these assessments.

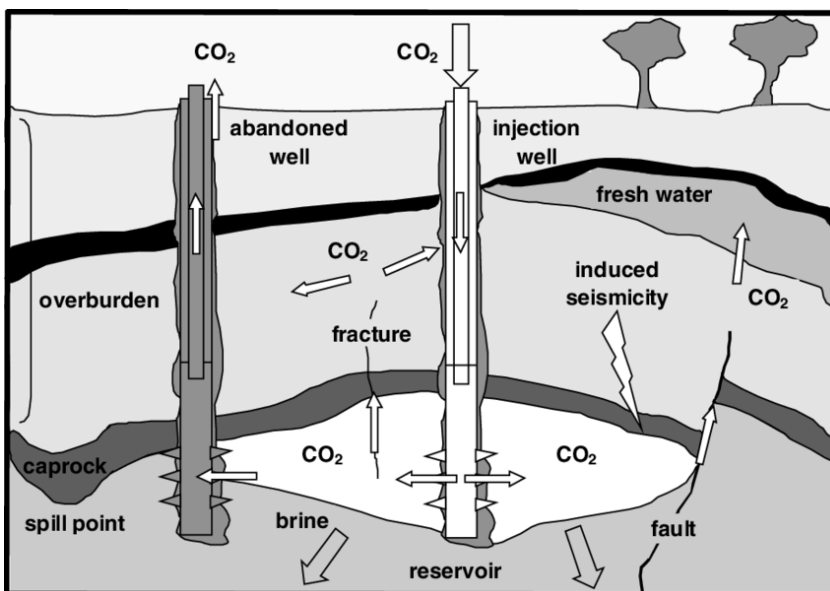


Figure 4 shows various risks that can be associated with CO₂ storage, where the white arrows show potential pathways for CO₂ flow. Figure courtesy of Damen, Faaji, & Turkenburg (2006).

Faults:

Faults represent larger fractures already existing in the subsurface and can either be fully sealed, acting as effective barriers, or allow for fluid flow, serving as pathways through the cap rock. Thus, it is of importance to thoroughly assess risks when faults go through the cap rock. This assessment should also contain appropriate monitoring strategies and response plans. Fault properties and sealing mechanisms have been extensively studied over the past 20-30 years, particularly in the oil and gas industry (Pei, Paton, Knipe, & Wu, 2015). However, it's important to acknowledge that faults introduce an elevated level of risk and may, in certain cases, render a reservoir unsuitable for CO₂ storage.

Fractures:

Injecting fluids into the subsurface alters reservoir pressure and can induce fractures. Induced fractures typically pose a concern only if they penetrate the cap rock, and in some instances, they are desired to facilitate improved CO₂ injection. A key consideration is conducting site-specific risk assessments with geomechanical analysis. Tests can be performed to determine fracture pressures, coupled with close monitoring of borehole pressures, enabling safe injection practices. Nonetheless, if injection pressures increase past safety margins and injectivity decreases, reservoir abandonment may become necessary. Microseismic monitoring can prove beneficial in reservoirs with an elevated risk of fracturing.

Wells:

Wells are designed to prevent undesirable fluid migration within and around them. However, poorly designed wells can inadvertently create leakage pathways. This is particularly critical to assess when multiple old wells exist in the reservoir, which is often the case in depleted oil and gas reservoirs. It is important to establish monitoring and response plans to effectively manage the heightened risk associated with the presence of old wells.

Earthquakes:

Earthquakes occur when energy stored in the Earth's crust is suddenly released as a fault slips. Energy accumulates in the crust over time due to tectonic forces and when the stress acting on the fault exceeds its strength, it slips. Most earthquakes take place at tectonic plate boundaries, but they can also happen within a plate's interior.

Although most earthquakes happen naturally, human activities like wastewater injection have been known to trigger significant earthquakes (Ellsworth, 2013). Notably, the majority of injection wells

worldwide don't induce earthquakes, but caution is crucial in areas with a history of seismic activity, especially if the reservoir is near active faults. Here, continuous monitoring of injection pressure, volumes, and seismic activity is essential.

Seismic activity thresholds, similar to those used in shale gas, wastewater, and geothermal systems, can also be applied to CO₂ storage to reduce injection when significant seismicity is experienced. Earthquake risks are mainly associated with potential damage to nearby infrastructure, but can potentially pose a risk for leakage if there are faults going through the cap rock (See Ellsworth (2013) for more information).

Leakage out of the licensed area

In a regulatory context, leakage may also include migration of CO₂ out of the licensed area (storage complex), even though it does not leak towards the surface. This type of leakage is of importance for several reasons including a conflict of interest with other operators and the new area might not be risk assessed. Risk assessments regarding the conformance of CO₂ within the licensed area should be conducted for each individual reservoir, with a detailed monitoring and response plan.

In case of leakage to the surface

If there is proven leakage from a CO₂ storage facility in Europe it could impact the environment and have a financial impact on the operator, and possibly the government. Costs related to leakage can include the cost of environmental restoration, reservoir intervention, cost of CO₂ tax or emission quotas, environmental fines and more. In addition, leakage can severely hurt public acceptance and the deployment of CCS in society. To avoid this, robust regulation, careful site characterisation, responsible operation, monitoring, and a clear financial liability is important.

Environmental impacts

Research, including natural CO₂ site observations, laboratory experiments, and modelling, indicates that most low-level fault or well-related leakage scenarios tend to have limited and temporary spatial impacts, with rapid recovery (Jones, et al., 2015). Factors like mixing, dispersion, and buffering reactions often mitigate effects, and harmful elements rarely exceed drinking water guidelines. While larger releases from open wells or major pipeline leaks could have higher impacts, they are less probable and should be more detectable and remediable (Jones, et al., 2015). Other impacts to consider include increased pressure on ecosystems due to increased human activity, such as an increased number of seismic surveys.

Financial impacts

In the case of leakage, Article 19 on Financial Security, of the EU CCS Directive, aims to ensure that CCS operators can cover the costs of monitoring, safety, environmental, and other obligations (European Parliament, 2009). Thus, preventing these expenses from becoming a financial risk for taxpayers. For more information on financial liability in the EU CCS Directive see Wifling (2020).

Measurement, Monitoring and Verification (MMV)

Once the CO₂ is stored safely in the ground, we need to verify that the CO₂ plume behaves as expected. This is normally done through a variation of monitoring techniques depending on the risks associated with the specific storage complex, data which again are used to create and update a numerical model of the reservoir. In the EU, this is regulated through the CO₂ storage directive (European Parliament, 2009). See the Northern Lights injection permit for a detailed example of how the CO₂ directive is interpreted for a specific case (MDIR, 2023)

In short, we need a detailed plan for monitoring activities which is based on the risks associated with the specific reservoir. Each of these monitoring activities must have a response plan based on what is observed. A numerical model is needed to model CO₂ behaviour and should be updated based on new monitoring data. This plan should again be verified, approved, and followed up on by a responsible governmental body. Monitoring data should of course be open access for the possibility of quality assurance in case of doubt, to facilitate industry knowledge-sharing, and to build public confidence in CCS technology. Below are brief descriptions of some of the more common monitoring activities, and of numerical models.

Numerical models

A numerical model serves as a digital representation of subsurface conditions for CO₂ storage. This allows for the testing and simulation of various injection scenarios and strategies without the need for real-world experimentation. For instance, the model can predict the time it takes for CO₂ injected at a well to reach the boundary of the licensed area. This is particularly valuable in subsurface environments, where accessing the reservoir is both challenging and costly. See figure 5 for an example of information that can be gathered from numerical simulations.

However, it's crucial to recognise the high uncertainties and limitations inherent in these models. They offer a simplified view of the complex real-world conditions and provide indications rather than precise predictions. Therefore, while they are valuable as learning

tools to enhance decision-making and understanding of subsurface processes, they should not be relied upon without scrutiny.

When used by skilled professionals and updated regularly with new monitoring data, numerical models can significantly improve decision-making and risk management. Numerical models are actively employed in Measurement, Monitoring and Verification activities for CO₂ storage in Europe. It is therefore essential for government bodies to possess comprehensive knowledge of both the benefits and limitations of these subsurface numerical models.

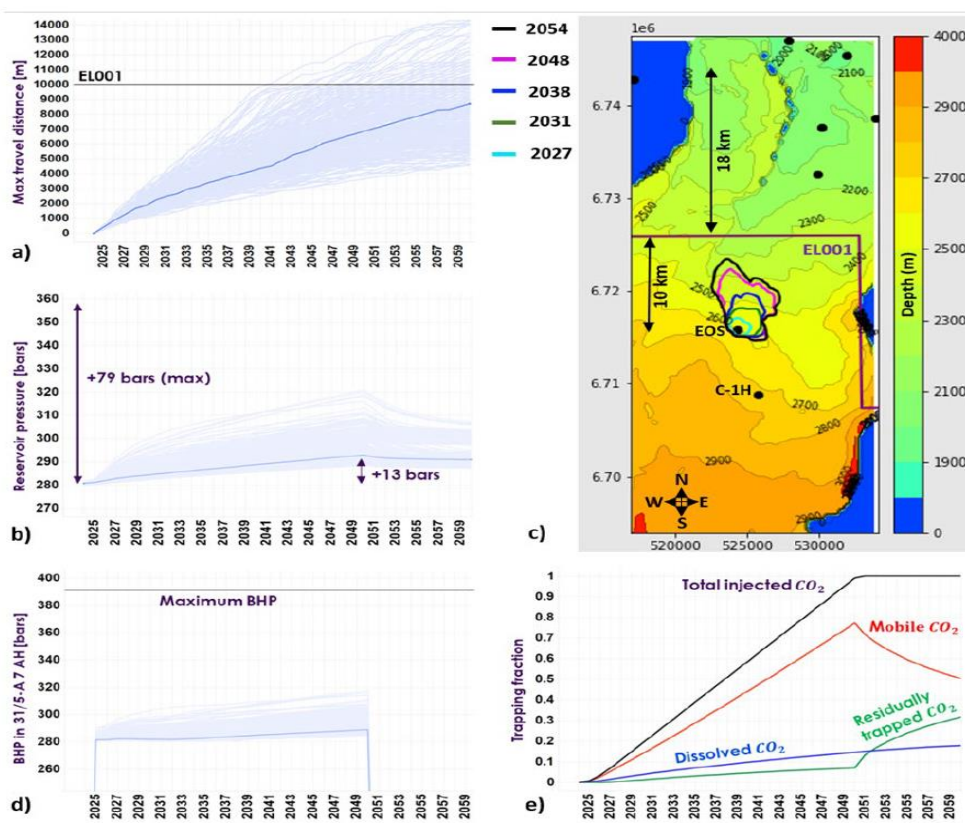


Figure 5 shows various results from numerical simulations of injection at Northern Lights. Four hundred simulations were run, and the dark blue line in the plots on the left column shows the average result. a) shows the migration distance, b) shows the reservoir pressure, c) shows the CO₂ plume expansion, d) shows the well pressure and e) shows the fraction of mobile, dissolved and residually trapped CO₂. Image courtesy of Northern Lights, and see (MDIR, 2023) for a more detailed explanation of the simulations.

3D and 4D Seismic surveys

3D seismic surveys gather information about the subsurface including rock layers and pore fluids (see figure 6a for an illustration of how the information can be gathered). 4D seismic is a time lapse of 3D seismic surveys, often at the time scale of years (figure 6b). This way we can observe changes in, for example pore fluids over time, and consequently the migration of CO₂ in the storage complex. This is a very valuable method to observe how the CO₂ behaves in the reservoir, update our numerical models, and in general learn more about how CO₂ behaves in the subsurface.

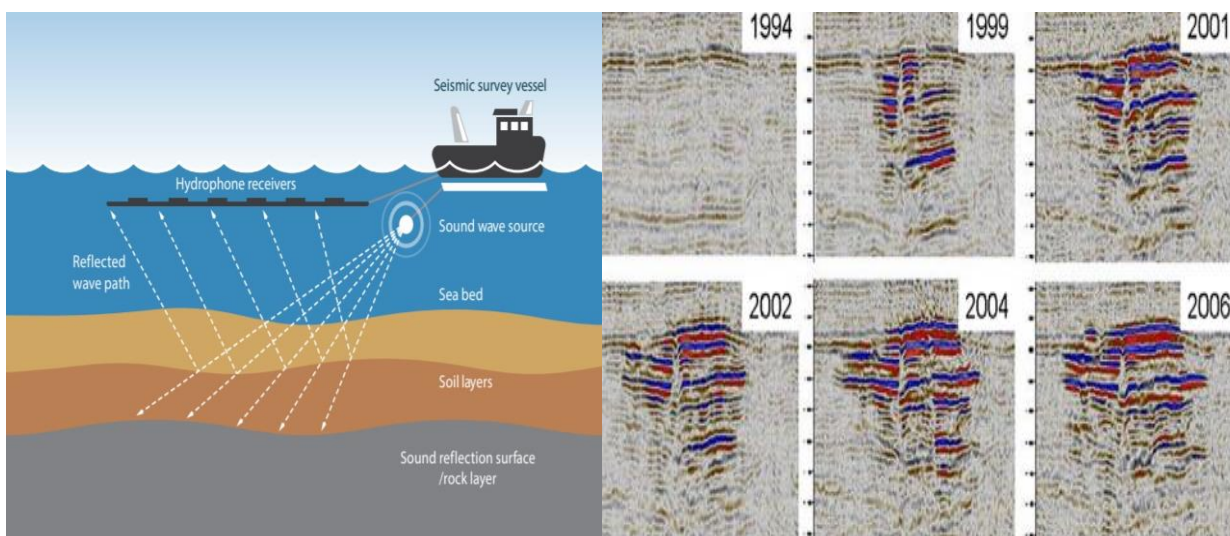


Figure 6: 6a: To the left an illustration of how seismic surveys can be done. Shooting soundwaves towards the seabed and based on the reflected wave properties one can analyse both rock type and pore fluid. 6b: To the right a time-lapse seismic data of the presence of CO₂ where the presence of CO₂ is illustrated by the blue and red colour (From Hermandrud et al. (2009)) As can be seen the CO₂ is trapped under cap rock but migrates slightly laterally.

Surface Deformation Monitoring

When we inject or extract large amounts of fluid from underground reservoirs, we can sometimes observe ground deformation on the surface as a result of the pressure changes. Onshore this can be monitored through, for example, time lapse satellite radar imaging. An example of this service is Interferometric Synthetic Aperture Radar (InSar), which can monitor millimetre changes in ground surface elevation. This is especially important when the reservoir is underlying infrastructure and/or housing. The In Salah project experienced a couple of centimetres of surface elevation during injection (Eiken, et al., 2011).

Overlying aquifer monitoring

If the reservoir is underlying a different aquifer, one can monitor the CO₂ levels in the aquifer to detect leakages of CO₂. Tracers could also be added to the injected CO₂ to be able to verify that the observed CO₂ is from the injection process. This can, for example, also be part of a response plan in the event where other monitoring activities have identified increased risk or unexpected behaviour.

Microseismic monitoring

Microseismic monitoring can detect small movements in the ground, like activation of faults and induced fractures. If several microseismic monitoring sensors, including sensors in the wells, are in place it is also possible to locate the fracture or fault with some accuracy. This is of greater importance if there are faults going through the cap rock, and if high injection pressures are expected/experienced. But it is important to note that fracturing within the reservoir rock does not necessarily compromise the cap rock and is sometimes positive as it can increase injectivity. As with many of the other monitoring applications, the value of this one is site specific.

Temperature and Pressure monitoring

Downhole pressure and temperature can be monitored to provide information that helps assess CO₂ migration, fracturing and allow for updated reservoir models and injection strategies.

Surface/Seabed monitoring

The surface or seabed can be monitored to detect the unlikely event of CO₂ leakage. This again can be part of a response plan if unexpected behaviour is experienced through other monitoring activities.

Examples of active storage projects

There are several active storage projects, but two of the most known and well researched sites are Sleipner located offshore Norway, and Quest located onshore Canada.

Sleipner

The Sleipner Project in the North Sea is an example of CO₂ storage in a saline aquifer. The project has been injecting approximately 1 Mt CO₂ per year into a nearby saline formation since September 1996. Evidence from 20+ years of experience of CO₂ storage shows no detected leakages (Eiken, et al., 2011).

Quest

The Quest CCS project in Alberta, Canada stores around 1 Mt CO₂ per year in a saline aquifer at a depth of about 2 km below ground. As of December 2021, Quest has successfully injected over 6.8 million tons of CO₂ since its project commencement in 2015, with reservoir performance evaluations suggesting sustained injectivity throughout the project's lifespan. Measurement, Monitoring, and Verification (MMV) data indicate that no CO₂ has migrated beyond the storage complex (Rock, 2017).

The storage situation in Europe: Do we have enough space?

The short answer is yes.

It's a common misunderstanding that CCS is limited by CO₂ storage capacity. The reality is, there are more underground storage resources than are needed to meet climate targets. It can, however, be argued that CCS is currently limited by available injection capacity as most reservoirs are not ready for injection yet. The 2014 Zero Emissions Platform (ZEP) report "CCS and the Electricity Market Modelling the lowest-cost route to decarbonizing European power" estimated that up to 27Gt of CO₂ would be needed to be captured and stored in Europe. The EU 2050 Energy Roadmap estimates that 3.5 to 12.8Gt of CO₂ will be stored in Europe by 2050. With a theoretical capacity in of around 80Gt in Norway alone, there is more than enough for the different scenarios (Halland, 2014).

Europe

The Norwegian Continental Shelf (NCS):

Norway is on the trajectory of having licenses capable of injecting approximately 40 Mt CO₂ /year by 2030, which can easily be injected in the already over 1100 Mt of matured capacity. With around 80000 Mt of estimated capacity which can be matured, the NCS also provides storage space for significant volumes from Europe (Halland et al., 2014).

Brief overview:

1.1 Gt of matured storage space in the Utsira/Skade formation and the Johansen/Cook formation

43 Gt of estimated storage capacity in Saline Aquifers

24 Gt of estimated storage capacity in Depleted Oil and Gas reservoirs

United Kingdom: Although no specific capacities are provided for 96 saline aquifers, 192 hydrocarbon fields offer a total storage capacity of 4 – 6 Gt.

Netherlands: The Netherlands has substantial storage capacity in hydrocarbon fields, estimated at 10 Gt, and moderate capacity in 18 saline aquifers, approximately 1.4 Gt.

Belgium: Belgium's total storage capacity includes approximately 242 Mt in saline aquifers (mean value) across six locations.

Denmark: A 2020 assessment estimated a storage capacity of 12 – 25 Gt in saline aquifers and hydrocarbon fields.

See Anthonsen & Christensen (2021) for more information on the storage capacity in Europe.

CO₂ purity specifications for storage

The purity specifications for the CO₂ delivered for storage vary but are typically above 99%. Purity is of importance for several reasons during both transport and storage, including corrosion, flow behaviour and environmental impact. Water content is reduced to avoid risk of corrosion, impurities reduced to have predictable flow behaviour, and toxic impurities are minimized as not to add a further toxicity issue in the event of leakage (both during transport and storage).

Minimising corrosion, having predictable fluid behaviour, and minimising environmental impact in case of leakage is crucial and needs to be addressed, but higher than necessary purity specifications add unnecessary costs. Therefore, a global industry standard should be defined to facilitate safe transport and storage at low costs.

Current Status of CCS

Currently, there are 30 operational CCS facilities, 11 under construction, and many in various stages of development, capturing around 40 million tons of CO₂ per year (as of 2022). The majority of these operational facilities are in the US and Canada, often linked to Enhanced Oil Recovery (EOR) operations, but some large-scale storage projects in saline aquifers are active, like Sleipner, Snøhvit, and Quest (See Global CCS Institute (2022) for more information on the global status of CCS). Most of these CCS projects are full-value chain projects, including capture, transport, and storage. However, more CCS networks are in deployment, where emitters share transport and/or storage resources. It should, however, be noted that most of these projects are related to oil and gas production, and great efforts are needed to accelerate CCS on hard to abate industrial emissions.

FAQ and/or common myths

“The technology is unproven”: Carbon capture and storage (CCS) technologies have been extensively tested and deployed successfully in various locations worldwide. Currently CCS projects capture and inject over 40 million tons of CO₂ per year, which have resulted in 100s of millions of tons stored permanently over the last decades (Bui, et al., 2018; Global CCS Institute, 2022). In addition, the technical feasibility of the concept builds on decades of experience from the oil and gas industry.

“There is not enough storage space”: There are ample suitable geological formations to accommodate vast amounts of captured CO₂, and in Norway alone there is enough capacity to meet the needs of Europe to reach 2050 goals for CO₂ storage (Halland, 2014). It is, however, important to differentiate between readily available storage space and not.

“There is insufficient regulation”: Robust regulations and standards exist to govern CCS operations and ensure safety in both Norway and the EU (European Parliament, 2009; Halland, 2014). It is, however, important to make sure we compare and improve regulation on a global scale to make sure we all operate under the same standard.

“We don't know the risks”: Extensive research and risk assessments have been conducted to understand and mitigate potential risks associated with CCS, but it is always important to properly assess the risks associated with each specific reservoir (Aminu, Nabavi, Rochelle, & Manovic, 2017). In addition, governmental oversight (as by the Petroleum Safety Authority and Environmental Agency in Norway) is important to ensure that risks are taken into account.

“There is a great chance of leakage”: Properly designed and managed CCS sites have very low risks of CO₂ leakage, and no leakages have been detected from current storage sites (Aminu, Nabavi, Rochelle, & Manovic, 2017). In addition, even in the case of leakage the impacts are expected to be limited (Jones, et al., 2015).

“Liability is not handled”: Legal frameworks and liability mechanisms are in place, in many locations around the world, to address potential issues related to CCS operations. It is, however, a young industry and it is important to focus on developing a strong regulatory framework for the entire CCS project lifecycle to ensure predictability for operators and investors (Global CCS Institute, 2019; Wifling, 2020).

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