WP SCCS 2020-01

SCCS

CO_2 GEOLOGICAL STORAGE: Commonly asked and critical questions

About this report

Created: December 2020
Last updated: February 2023

Author:
Richard Lindsay Stevenson

With input from:
Rebecca Bell
Professor R Stuart Haszeldine

Cite as:
Stevenson, R.L. (2020) CO_2 Geological Storage: Commonly asked and critical questions - https://sccs.org.uk/why-ccs/faqs

---

This report contains a list of commonly asked questions concerning the safety and levels of risk associated with offshore underground storage of carbon dioxide (CO_2). The list of questions and answers is framed in the context of the UK Continental Shelf (UKCS) and was compiled by:

- Reviewing questions and concerns appearing in the public perception and NGO literature; and
- Expert review of the compiled question list.

Answers are based on the evidence base gathered and cited here.

Table of Contents

1. *What is CO_2?* 4
2. *How do you store CO_2?* 5
3. *How can we be sure it's safe?* 6
4. *How do we know the CO_2 will stay there?* 7
5. *How will we know if the CO_2 leaks?* 8
6. *What will happen if the CO_2 leaks?* 9
7. *What will happen to the sea and marine life if the CO_2 leaks?* 10
8. *Will drinking water be affected if the CO_2 leaks?* 11
9. *What will happen if there's a seismic event?* 11
10. *Will storing CO_2 underground cause seismic events?* 12
11. *What is the difference between Enhanced Oil Recovery and CO_2 storage?* 13
12. *Is storing CO_2 the same as fracking?* 14

References 15

Commonly asked and critical questions about CO_2 Geological Storage

1. What is CO_2?

CO_2 is a naturally occurring substance that is not normally dangerous to human or environmental health. It is naturally present in human blood and the atmosphere – we breathe it out, and plants need it to grow. It also leaks naturally from volcanoes and geysers, can be found in natural underground reservoirs and dissolves in seawater as part of the natural carbon cycle. CO_2 is therefore a fundamental and essential part of nature. CO_2 does not burn and will not explode; it is only at high concentrations that CO_2 becomes dangerous. In human and animal health terms, CO_2 can be toxic and pose a threat to life through asphyxiation, but only when it displaces oxygen down to dangerously low levels. CO_2 is far more dangerous as a major greenhouse gas, the most significant environmental impact of which is to increase global temperatures, exacerbating climate change with damaging impacts on global human health and biodiversity. CO_2 captured from industrial processes may contain extremely low levels of impurities, though these are well understood and managed and are well within acceptable risk levels of current human activities.

References title:

Health and Safety Executive (2011). Assessment of the major hazard potential of carbon dioxide (CO_2). (Health and Safety Executive 2011)

Brown, A., et al. (2017). "IMPACTS: Framework for Risk Assessment of CO_2 Transport and Storage Infrastructure." Energy Procedia 114: 6501-6513. (Brown, Eickhoff et al. 2017)

2. How do you store CO_2?

Geological storage is the last of the three major steps in the CCS 'chain'. It can take place both onshore and offshore. In the UK, only offshore geological storage sites are being considered. CO_2 is stored at depths of around one kilometre (and at least 800 metres) in carefully selected sites with rock formations that are both porous and permeable.

At the storage site, a borehole is drilled (or an existing one used) into porous and permeable rock, into which large tonnages of liquid CO_2 are then injected. The CO_2 displaces the salty water which normally occupies the millimetre-sized voids (pores) in the rock. The storage site is overlain by a layer of impermeable rock (caprock), which, together with other geochemical processes, acts to stop any flow of CO_2 back to the surface. These processes are the same geological forces that kept the original fluids contained and they work together to increase the storage security of injected CO_2 over time. Depending on the characteristics of the site and any monitoring requirements, as few as one or two boreholes are required to operate a CO_2 storage site, which will be offshore, deep beneath the North Sea seabed.

Reference title:

GCCSI (2020). "Understanding CCS." from https://www.globalccsinstitute.com/why-ccs/what-is-ccs/. (GCCSI 2020)

Kumar, S., et al. (2020). "A comprehensive review of value-added CO_2 sequestration in subsurface saline aquifers." Journal of Natural Gas Science and Engineering 81: 103437. (Kumar, Foroozesh et al. 2020)

Miocic, J. M., et al. (2019). "420,000 year assessment of fault leakage rates shows geological carbon storage is secure." Scientific reports 9(1): 1-9. (Miocic, Gilfillan et al. 2019)

Busch, A. and N. Kampman (2018). "Migration and leakage of CO_2 from deep geological storage sites." Geological Carbon Storage: Subsurface Seals and Caprock Integrity: 283-303. (Busch and Kampman 2018)

3. How can we be sure it's safe?

Research and real-world experience tell us that CO_2 geological storage is safe and secure. Leakage is very unlikely to occur (see Q3), but if it did, it would be localised and temporary, and would be very unlikely to cause any significant harm to ecosystems or communities. The knowledge and understanding that we have of natural CO_2 reservoirs and real-world experience from industrial CO_2 storage projects, coupled with an extensive and ongoing research base, provide very high confidence in the safety and security of CO_2 geological storage. Hundreds of millions of tonnes of anthropogenic CO_2 have been safely transported, injected and stored in geological formations for over four decades.

Reference title:

Ringrose, P. S. (2018). "The CCS hub in Norway: some insights from 22 years of saline aquifer storage." Energy Procedia 146: 166-172. (Ringrose 2018)

SCCS (2015). "Open letter to Christiana Figueres, Executive Secretary of the United Nations Framework Convention on Climate Change." from https://sccs.org.uk/cop21-open-letter?highlight=WyJjb3AyMSJd. (SCCS 2015)

GCCSI (2020). "Understanding CCS." from https://www.globalccsinstitute.com/why-ccs/what-is-ccs/. (GCCSI 2020)

4. How do we know the CO_2 will stay there?

The long-term consequences of storing CO_2 underground are very well understood because naturally occurring reservoirs have been shown to securely contain CO_2 for tens of millions of years. The most suitable storage sites for CO_2 are at least 800 metres beneath the seabed and occur in the same geological formations as oil and gas reservoirs. The same geological structures and mechanisms that kept oil and gas securely contained for millions of years will equally ensure that the CO_2 is securely locked away and unable to return to the surface.

Reference title:

Anderson, J. S., et al. (2018). "Assessment of shallow subsea hydrocarbons as a proxy for leakage at offshore geologic CO_2 storage sites." International Journal of Greenhouse Gas Control 74: 19-27. (Anderson, Romanak et al. 2018)

Karstens, J., et al. (2017). "Focused fluid flow and the sub-seabed storage of CO_2: Evaluating the leakage potential of seismic chimney structures for the Sleipner CO_2 storage operation." Marine and Petroleum Geology 88: 81-93. (Karstens, Ahmed et al. 2017)

Chadwick, R. A., et al. (2017). "CO_2 Storage: Setting a Simple Bound on Potential Leakage through the Overburden in the North Sea Basin." Energy Procedia 114: 4411-4423. (Chadwick, Williams et al. 2017)

Kumar, S., et al. (2020). "A comprehensive review of value-added CO_2 sequestration in subsurface saline aquifers." Journal of Natural Gas Science and Engineering 81: 103437. (Kumar, Foroozesh et al. 2020)

Lu, J., et al. (2009). "Long-term performance of a mudrock seal in natural CO_2 storage." Geology 37(1): 35-38. (Lu, Wilkinson et al. 2009)

Gilfillan, S. M. V., et al. (2008). "The noble gas geochemistry of natural CO_2 gas reservoirs from the Colorado Plateau and Rocky Mountain provinces, USA." Geochimica et Cosmochimica Acta 72(4): 1174-1198. (Gilfillan, Ballentine et al. 2008)

Alcalde, J., et al. (2018). "Estimating geological CO_2 storage security to deliver on climate mitigation." Nature communications 9(1): 1-13. (Alcalde, Flude et al. 2018)

Ringrose, P. S. (2018). "The CCS hub in Norway: some insights from 22 years of saline aquifer storage." Energy Procedia 146: 166-172. (Ringrose 2018)

Miocic, J. M., et al. (2019). "420,000 year assessment of fault leakage rates shows geological carbon storage is secure." Scientific reports 9(1): 1-9. (Miocic, Gilfillan et al. 2019)

Sathaye, K. J., et al. (2014). "Constraints on the magnitude and rate of CO_2 dissolution at Bravo Dome natural gas field." Proceedings of the National Academy of Sciences 111(43): 15332-15337. (Sathaye, Hesse et al. 2014)

Busch, A. and N. Kampman (2018). "Migration and leakage of CO_2 from deep geological storage sites." Geological Carbon Storage: Subsurface Seals and Caprock Integrity: 283-303. (Busch and Kampman 2018)

Bond, C. E., et al. (2017). "The physical characteristics of a CO_2 seeping fault: The implications of fracture permeability for carbon capture and storage integrity." International Journal of Greenhouse Gas Control 61: 49-60. (Bond, Kremer et al. 2017)

Molari, M., et al. (2019). "CO_2 leakage can cause loss of benthic biodiversity in submarine sands." Marine Environmental Research 144: 213-229. (Molari, Guilini et al. 2019)

5. How will we know if the CO_2 leaks?

CO_2 storage sites are carefully selected according to specific criteria designed to ensure that the CO_2 does not leak. However, comprehensive risk management strategies are a regulatory requirement of any proposed project, which means that safeguards are in place to ensure the safety and security of CO_2 transport and storage. Measuring, monitoring and verification (MMV) will be in place which means that, in the unlikely event of CO_2 starting to move towards the surface, this would be detected, and the operator would intervene to control, minimise and prevent leakage. MMV techniques and technologies that have been used in the oil and gas industry for decades are broadly transferable to CO_2 transport and storage, and a range of CO_2-specific techniques has also been developed and used successfully. Bespoke MMV strategies will be tailored to the characteristics of individual storage sites.

Reference title:

Pawar, R. J., et al. (2015). "Recent advances in risk assessment and risk management of geologic CO_2 storage." International Journal of Greenhouse Gas Control 40: 292-311. (Pawar, Bromhal et al. 2015)

Jenkins, C. (2020). "The State of the Art in Monitoring and Verification: an update five years on." International Journal of Greenhouse Gas Control 100: 103118. (Jenkins 2020)

Jenkins, C., et al. (2015). "The state of the art in monitoring and verification—ten years on." International Journal of Greenhouse Gas Control 40: 312-349. (Jenkins, Chadwick et al. 2015)

Yonkofski, C., et al. (2019). "Risk-based monitoring designs for detecting CO_2 leakage through abandoned wellbores: An application of NRAP's WLAT and DREAM tools." International Journal of Greenhouse Gas Control 91: 102807. (Yonkofski, Tartakovsky et al. 2019)

Hannis, S., et al. (2017). "Review of offshore CO_2 storage monitoring: operational and research experiences of meeting regulatory and technical requirements." Energy Procedia 114: 5967-5980. (Hannis, Chadwick et al. 2017)

Harbert, W., et al. (2016). "Progress in monitoring strategies for risk reduction in geologic CO_2 storage." International Journal of Greenhouse Gas Control 51: 260-275. (Harbert, Daley et al. 2016)

Hannis, S., et al. (2015). "Review of offshore monitoring for CCS Projects, 2015/02, July, 2015." (Hannis, Chadwick et al. 2015)

Dean, M., et al. (2020). "Insights and guidance for offshore CO_2 storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects." International Journal of Greenhouse Gas Control 100: 103120. (Dean, Blackford et al. 2020)

Anderson, J. S., et al. (2017). "Gas source attribution techniques for assessing leakage at geologic CO_2 storage sites: Evaluating a CO_2 and CH_4 soil gas anomaly at the Cranfield CO_2-EOR site." Chemical Geology 454: 93-104. (Anderson, Romanak et al. 2017)

Dean, M. and O. Tucker (2017). "A risk-based framework for Measurement, Monitoring and Verification (MMV) of the Goldeneye storage complex for the Peterhead CCS project, UK." International Journal of Greenhouse Gas Control 61: 1-15. (Dean and Tucker 2017)

Tucker, O., et al. (2013). "Development of an Offshore Monitoring Plan for a Commercial CO_2 Storage Pilot." Energy Procedia 37: 4317-4335. (Tucker, Garnham et al. 2013)

6. What will happen if the CO_2 leaks?

In the unlikely event that CO_2 were to leak from a carefully selected storage site, the leak would be fixed, and any environmental damage remediated to restore the site to a safe and secure state. This would be achieved by applying measures that have been successfully applied in the hydrocarbon industry for over 50 years, as well as new techniques developed specifically for CO_2 geological storage. Measures include management of the injection process to reduce the pressure in the store that is driving the movement of CO_2, and a range of methods to plug leaks, including the use of sealants (e.g. cements, gels, foams, nanoparticles) and hydraulic, gas and chemical barriers, some of which react with the CO_2 to turn it into a stable mineral form. To date, such measures have not been required as, despite intensive monitoring, there have been no confirmed leaks from existing CO_2 geological storage projects. Corrective measures covering potential leakage pathways, which can be broadly categorised as either manmade (e.g. related to the well and injection operations) or natural (e.g. caprock failure, faults or fractures), are a key part of storage risk management. Implications of leakage for adjacent environmental uses such as fishing, aquaculture and offshore renewables are likely minimal, though this requires further study.

Responsibility for corrective measures would lie with different parties at different stages over a site's lifetime: the operator would likely be responsible during the operational phase and the post-closure period up until the point at which the operating licence expires; at this point, responsibility would likely transfer to the competent authority, i.e. Scottish or UK Government, depending on the location of the storage site. More work is required to establish this issue of transfer of liability more clearly, particularly given the regulatory transition associated with the UK's exit from the EU.

Reference title:

Neele, F., et al. (2014). "MiReCOL: Developing Corrective Measures for CO_2 Storage." Energy Procedia 63: 4658-4665. (Neele, Grimstad et al. 2014)

Wilkinson, M., et al. (2017). "MiReCOL: Remediation of Shallow Leakage from a CO_2 Storage Site." Energy Procedia 114: 4227-4236. (Wilkinson, Edlmann et al. 2017)

Castaneda-Herrera, C. A., et al. (2018). "Review of CO_2 leakage mitigation and remediation technologies." Geological Carbon Storage: Subsurface Seals and Caprock Integrity 238: 327. (Castaneda-Herrera, Stevens et al. 2018)

Govindan, R., et al. (2018). A methodology for CO_2 storage leakage remediation techniques performance assessment and portfolio optimisation. 14th Greenhouse Gas Control Technologies Conference Melbourne. (Govindan, Nie et al. 2018)

Manceau, J. C., et al. (2014). "Mitigation and remediation technologies and practices in case of undesired migration of CO_2 from a geological storage unit—Current status." International Journal of Greenhouse Gas Control 22: 272-290. (Manceau, Hatzignatiou et al. 2014)

Peng, S. (2017). "Overview of CO_2 leakage problems and sealants for CO_2 leakage remediation." (Peng 2017)

2009, E. DIRECTIVE 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL 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, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006. 2009; Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0031. (2009 2009)

7. What will happen to the sea and marine life if the CO_2 leaks?

Impacts of CO_2 leakage on the sea and marine life are likely to be small compared to the impacts of ongoing processes such as bottom trawler fishing and ocean acidification. Should CO_2 leak from the seabed, any impacts will be highly localised (radius of tens of metres) and the risk of significant harm being caused to the sea or marine life is very low. There would be impacts on the immediate ecosystem, but the recovery from these is expected to be rapid - within one growing cycle or season – although the impacts on specific plants or animals will depend on their stage of development.

Reference title:

Jones, D. G., et al. (2015). "Developments since 2005 in understanding potential environmental impacts of CO_2 leakage from geological storage." International Journal of Greenhouse Gas Control 40: 350-377. (Jones, Beaubien et al. 2015)

Dean, M., et al. (2020). "Insights and guidance for offshore CO_2 storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects." International Journal of Greenhouse Gas Control 100: 103120. (Dean, Blackford et al. 2020)

Rodríguez-Romero, A., et al. (2014). "Simulation of CO_2 leakages during injection and storage in sub-seabed geological formations: Metal mobilization and biota effects." Environment International 68: 105-117. (Rodríguez-Romero, Basallote et al. 2014)

Molari, M., et al. (2019). "CO_2 leakage can cause loss of benthic biodiversity in submarine sands." Marine Environmental Research 144: 213-229. (Molari, Guilini et al. 2019)

Wallmann, K., et al. (2015). "Best practice guidance for environmental risk assessment for offshore CO_2 geological storage." (Wallmann, Haeckel et al. 2015)

Totland, C., et al. (2020). "The correlation between pO_2 and pCO_2 as a chemical marker for detection of offshore CO_2 leakage." International Journal of Greenhouse Gas Control 99: 103085. (Totland, Eek et al. 2020)

Pearce, J., et al. (2014). "A Guide for Assessing the Potential Impacts on Ecosystems of Leakage from CO_2 Storage Sites." Energy Procedia **63**: 3242-3252. (Pearce, Jones et al. 2014)

8. Will drinking water be affected if the CO_2 leaks?

The risks to drinking water from a CO_2 leak from an offshore storage site are very low. CO_2 can mobilise trace elements already in the subsurface, which can have an adverse effect on drinking water, though the risk of this happening is very low with levels falling within the normal range for existing oil and gas activities.

Reference title:

Lions, J., et al. (2014). "Potential impacts of leakage from CO_2 geological storage on geochemical processes controlling fresh groundwater quality: A review." International Journal of Greenhouse Gas Control 22: 165-175. (Lions, Devau et al. 2014)

Montes-Hernandez, G., et al. (2013). "Experimental assessment of CO_2-mineral-toxic ion interactions in a simplified freshwater aquifer: Implications for CO_2 leakage from deep geological storage." Environmental science & technology 47(12): 6247-6253. (Montes-Hernandez, Renard et al. 2013)

Cahill, A. G. and R. Jakobsen (2013). "Hydro-geochemical impact of CO_2 leakage from geological storage on shallow potable aquifers: A field scale pilot experiment." International Journal of Greenhouse Gas Control 19: 678-688. (Cahill and Jakobsen 2013)

Dai, Z., et al. (2019). Chapter 5 - Reactive Transport Modeling of Geological Carbon Storage Associated With CO_2 and Brine Leakage. Science of Carbon Storage in Deep Saline Formations. P. Newell and A. G. Ilgen, Elsevier: 89-116. (Dai, Viswanathan et al. 2019)

Carruthers, K., et al. (2016). Potential environmental impacts of offshore UK geological CO_2 storage: EPSC2016-15678. (Carruthers, Wilkinson et al. 2016)

Hillebrand, M., et al. (2016). "Toxicological risk assessment in CO_2 capture and storage technology." International Journal of Greenhouse Gas Control 55: 118-143. (Hillebrand, Pflugmacher et al. 2016)

9. What will happen if there's a seismic event?

CO_2 storage sites are normally situated away from earthquake zones or high-risk areas. The North Sea basin is a tectonically stable area and, while seismic events do occasionally occur, there has been no significant impact on oil and gas operations to date, providing confidence in the low likelihood and degree of potential impacts on CO_2 geological storage operations. Evidence from two demonstration projects in Japan (the Nagaoka pilot project in 2004 and the Tomakomai CCS demonstration project in 2018) - one of the most seismically active regions in the world - confirmed that no leaks were detected following large earthquakes, with CO_2 injection continuing safely once investigations had concluded.

Reference title:

Japan CCS Co. Ltd (2018). Research Report on Impacts of Hokkaido Eastern Iburi Earthquake on CO_2 Reservoir. (Japan CCS Co. Ltd 2018)

RITE (Research Institute of Innovative Technology for the Earth) (2007). "Demonstration Test and Monitoring at the Iwanohara Test Site." from http://www.rite.or.jp/English/lab/geological/demonstration.html. (RITE (Research Institute of Innovative Technology for the Earth) 2007)

10. Will storing CO_2 underground cause seismic events?

It is possible, but unlikely: the injection of CO_2 into the porous rock causes an increase in pressure in the reservoir, which could cause a small seismic event (induced seismicity). This is likely only during the active injection phase and near aftermath. The risks and consequences of induced seismicity, however, are very well understood and managed, because other human activities, such as mining and oil and gas operations, can also cause seismic events if not properly managed. Experience gained from these industries, along with careful site selection; mandatory comprehensive risk management and monitoring strategies; the suite of existing seismic monitoring technologies; and measures to control the injection rate and reservoir pressure, will help to reduce any risk of induced seismicity from storing CO_2 underground.

References title:

Vilarrasa, V. and J. Carrera (2015). "Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO_2 could leak." Proceedings of the National Academy of Sciences 112(19): 5938-5943. (Vilarrasa and Carrera 2015)

Oldenburg, C.M., *The risk of induced seismicity: is cap-rock integrity on shaky ground?* Greenhouse Gases: Science and Technology, 2012. 2(4): p. 217-218. (Oldenburg 2012)

White, J. A. and W. Foxall (2016). "Assessing induced seismicity risk at CO_2 storage projects: Recent progress and remaining challenges." International Journal of Greenhouse Gas Control 49: 413-424. (White and Foxall 2016)

Nicol, A., et al. (2013). "Induced Seismicity; Observations, Risks and Mitigation Measures at CO_2 Storage Sites." Energy Procedia 37: 4749-4756. (Nicol, Gerstenberger et al. 2013)

Verdon, J. P. (2014). "Significance for secure CO_2 storage of earthquakes induced by fluid injection." Environmental Research Letters 9(6): 064022. (Verdon 2014)

Sawada, Y., et al. (2018). "Tomakomai CCS Demonstration Project of Japan, CO_2 Injection in Progress." Energy Procedia 154: 3-8. (Sawada, Tanaka et al. 2018)

11. What is the difference between Enhanced Oil Recovery and CO_2 storage?

Enhanced Oil Recovery (EOR) is the term for a range of techniques that oil producers can use to improve the recovery rate of oil wells. These can involve thermal, gas injection or chemical injection approaches. The injection of CO_2 is one approach that has been used to improve oil production. CO_2 EOR has been used in a number of studies as an analogue for CO_2 injection in dedicated storage sites. However, the nature of CO_2 injection in each of these cases may differ for several reasons, limiting the usefulness of this analogy. There are no known current project proposals in Scotland to combine EOR activity with CO_2 storage.

References title:

Anderson, J. S., K. D. Romanak, C. Yang, J. Lu, S. D. Hovorka and M. H. Young (2017). "Gas source attribution techniques for assessing leakage at geologic CO_2 storage sites: Evaluating a CO_2 and CH_4 soil gas anomaly at the Cranfield CO_2-EOR site." Chemical Geology 454: 93-104. (Anderson, Romanak et al. 2017)

He, H., Y. Zhao, X. Yang, Y. Gao and X. Wu (2015). "Study and application of safety risk evaluation model for CO_2 geological storage based on uncertainty measure theory." Mathematical Problems in Engineering 2015. (He, Zhao et al. 2015)

Jenkins, C., A. Chadwick and S. D. Hovorka (2015). "The state of the art in monitoring and verification—Ten years on." International Journal of Greenhouse Gas Control 40: 312-349. (Jenkins, Chadwick et al. 2015)

Koornneef, J., A. Ramírez, W. Turkenburg and A. Faaij (2012). "The environmental impact and risk assessment of CO_2 capture, transport and storage – An evaluation of the knowledge base." Progress in Energy and Combustion Science 38(1): 62-86. (Koornneef, Ramírez et al. 2012)

12. Is storing CO_2 the same as fracking?

No. These two activities do share some similarities in approach, but their applications and end results are quite different. Fracking is for carbon extraction; CCS is for carbon storage.

Fracking involves drilling a borehole into organic rich mudrock (shale) and injecting large volumes of water, sand and chemicals at high pressure. The process is designed to form thousands of cracks (fractures) in the shale, which contains gas and oil, to allow these hydrocarbons to escape from the rock and flow up a borehole to the surface. Fracturing the rock in this way causes small earthquakes (induced seismicity). Many tens of boreholes are typically needed to undertake a fracking development on land.

CO_2 geological storage involves drilling a borehole (or using an existing one) into porous and permeable rock and injecting large tonnages of liquid CO_2. The injected CO_2 displaces the salty water which normally occupies the millimetre-sized voids (pores) in the rock. The storage site is overlain by a layer of non-permeable rock (caprock), which, together with other geochemical processes, acts to stop any flow of CO_2 back to the surface. Depending on the characteristics of the site and any monitoring requirements, as few as one or two boreholes are required to operate a CO_2 storage site, which will be offshore, deep beneath the North Sea seabed.

References title:

BGS (2021). "BGS shale gas research." From https://www.bgs.ac.uk/geology-projects/shale-gas/shale-gas-extraction/

Smythe, D. K. (2020). "Inadequate Regulation of the Geological Aspects of Shale Exploitation in the UK." International Journal of Environmental Research and Public Health 17(19): 6946. [99]

GCCSI (2020). "Understanding CCS." from https://www.globalccsinstitute.com/why-ccs/what-is-ccs/. [55]

Kumar, S., et al. (2020). "A comprehensive review of value-added CO2 sequestration in subsurface saline aquifers." Journal of Natural Gas Science and Engineering 81: 103437. [56]

Miocic, J. M., et al. (2019). "420,000 year assessment of fault leakage rates shows geological carbon storage is secure." Scientific reports 9(1): 1-9. [57]

Busch, A. and N. Kampman (2018). "Migration and leakage of CO2 from deep geological storage sites." Geological Carbon Storage: Subsurface Seals and Caprock Integrity: 283-303. [58]

References

2009, E. (2009). "DIRECTIVE 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL 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, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006." from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0031.

Alcalde, J., S. Flude, M. Wilkinson, G. Johnson, K. Edlmann, C. E. Bond, V. Scott, S. M. V. Gilfillan, X. Ogaya and R. S. Haszeldine (2018). "Estimating geological CO2 storage security to deliver on climate mitigation." Nature Communications 9(1): 2201.

Anderson, J. S., K. D. Romanak and T. A. Meckel (2018). "Assessment of shallow subsea hydrocarbons as a proxy for leakage at offshore geologic CO2 storage sites." International Journal of Greenhouse Gas Control 74: 19-27.

Anderson, J. S., K. D. Romanak, C. Yang, J. Lu, S. D. Hovorka and M. H. Young (2017). "Gas source attribution techniques for assessing leakage at geologic CO2 storage sites: Evaluating a CO2 and CH4 soil gas anomaly at the Cranfield CO2-EOR site." Chemical Geology 454: 93-104.

Bond, C. E., Y. Kremer, G. Johnson, N. Hicks, R. Lister, D. G. Jones, R. S. Haszeldine, I. Saunders, S. M. V. Gilfillan, Z. K. Shipton and J. Pearce (2017). "The physical characteristics of a CO2 seeping fault: The implications of fracture permeability for carbon capture and storage integrity." International Journal of Greenhouse Gas Control 61: 49-60.

Brown, A., C. Eickhoff, J. E. A. Reinders, I. Raben, M. Spruijt and F. Neele (2017). "IMPACTS: Framework for Risk Assessment of CO2 Transport and Storage Infrastructure." Energy Procedia 114: 6501-6513.

Busch, A. and N. Kampman (2018). "Migration and leakage of CO2 from deep geological storage sites." Geological Carbon Storage: Subsurface Seals and Caprock Integrity: 283-303.

Cahill, A. G. and R. Jakobsen (2013). "Hydro-geochemical impact of CO2 leakage from geological storage on shallow potable aquifers: A field scale pilot experiment." International Journal of Greenhouse Gas Control 19: 678-688.

Carruthers, K., M. Wilkinson and I. B. Butler (2016). Potential environmental impacts of offshore UK geological CO2 storage: EPSC2016-15678.

Castaneda-Herrera, C. A., G. W. Stevens and R. R. Haese (2018). "Review of CO2 leakage mitigation and remediation technologies." Geological Carbon Storage: Subsurface Seals and Caprock Integrity 238: 327.

Chadwick, R. A., G. A. Williams and D. J. Noy (2017). "CO2 Storage: Setting a Simple Bound on Potential Leakage through the Overburden in the North Sea Basin." Energy Procedia 114: 4411-4423.

Dai, Z., H. Viswanathan, T. Xiao, A. Hakala, C. Lopano, G. Guthrie and B. McPherson (2019). Chapter 5 - Reactive Transport Modeling of Geological Carbon Storage Associated With CO2 and Brine Leakage. Science of Carbon Storage in Deep Saline Formations. P. Newell and A. G. Ilgen, Elsevier: 89-116.

Dean, M., J. Blackford, D. Connelly and R. Hines (2020). "Insights and guidance for offshore CO2 storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects." International Journal of Greenhouse Gas Control 100: 103120.

Dean, M. and O. Tucker (2017). "A risk-based framework for Measurement, Monitoring and Verification (MMV) of the Goldeneye storage complex for the Peterhead CCS project, UK." International Journal of Greenhouse Gas Control 61: 1-15.

GCCSI. (2020). "Understanding CCS." from https://www.globalccsinstitute.com/why-ccs/what-is-ccs/.

Gilfillan, S. M. V., C. J. Ballentine, G. Holland, D. Blagburn, B. S. Lollar, S. Stevens, M. Schoell and M. Cassidy (2008). "The noble gas geochemistry of natural CO2 gas reservoirs from the Colorado Plateau and Rocky Mountain provinces, USA." Geochimica et Cosmochimica Acta 72(4): 1174-1198.

Govindan, R., Z. Nie, A. Korre, S. Durucan, J.-Q. Shi, M. Hadi Mosleh, F. Neele, M. Wilkinson and N. Heinemann (2018). A methodology for CO2 storage leakage remediation techniques performance assessment and portfolio optimisation. 14th Greenhouse Gas Control Technologies Conference Melbourne.

Hannis, S., A. Chadwick, D. Connelly, J. Blackford, T. Leighton, D. Jones, J. White, P. White, I. Wright and S. Widdicomb (2017). "Review of offshore CO2 storage monitoring: operational and research experiences of meeting regulatory and technical requirements." Energy Procedia 114: 5967-5980.

Hannis, S., A. Chadwick, J. Pearce, D. Jones, J. White, I. Wright, D. Connelly, S. Widdicombe, J. Blackford and P. White (2015). "Review of offshore monitoring for CCS Projects, 2015/02, July, 2015."

Harbert, W., T. M. Daley, G. Bromhal, C. Sullivan and L. Huang (2016). "Progress in monitoring strategies for risk reduction in geologic CO2 storage." International Journal of Greenhouse Gas Control 51: 260-275.

He, H., Y. Zhao, X. Yang, Y. Gao and X. Wu (2015). "Study and application of safety risk evaluation model for CO2 geological storage based on uncertainty measure theory." Mathematical Problems in Engineering 2015.

Health and Safety Executive (2011). Assesment of the major hazard potential of carbon dioxide (CO2).

Hillebrand, M., S. Pflugmacher and A. Hahn (2016). "Toxicological risk assessment in CO2 capture and storage technology." International Journal of Greenhouse Gas Control 55: 118-143.

Japan CCS Co. Ltd (2018). Research Report on Impacts of Hokkaido Eastern Iburi Earthquake on CO2 Reservoir.

Jenkins, C. (2020). "The State of the Art in Monitoring and Verification: an update five years on." International Journal of Greenhouse Gas Control 100: 103118.

Jenkins, C., A. Chadwick and S. D. Hovorka (2015). "The state of the art in monitoring and verification—ten years on." International Journal of Greenhouse Gas Control 40: 312-349.

Jones, D., S. Beaubien, J. Blackford, E. Foekema, J. Lions, C. De Vittor, J. West, S. Widdicombe, C. Hauton and A. Queirós (2015). "Developments since 2005 in understanding potential environmental impacts of CO2 leakage from geological storage." International Journal of Greenhouse Gas Control 40: 350-377.

Karstens, J., W. Ahmed, C. Berndt and H. Class (2017). "Focused fluid flow and the sub-seabed storage of CO2: Evaluating the leakage potential of seismic chimney structures for the Sleipner CO2 storage operation." Marine and Petroleum Geology 88: 81-93.

Koornneef, J., A. Ramírez, W. Turkenburg and A. Faaij (2012). "The environmental impact and risk assessment of CO2 capture, transport and storage – An evaluation of the knowledge base." Progress in Energy and Combustion Science 38(1): 62-86.

Kumar, S., J. Foroozesh, K. Edlmann, M. G. Rezk and C. Y. Lim (2020). "A comprehensive review of value-added CO2 sequestration in subsurface saline aquifers." Journal of Natural Gas Science and Engineering 81: 103437.

Lions, J., N. Devau, L. de Lary, S. Dupraz, M. Parmentier, P. Gombert and M.-C. Dictor (2014). "Potential impacts of leakage from CO2 geological storage on geochemical processes controlling fresh groundwater quality: A review." International Journal of Greenhouse Gas Control 22: 165-175.

Lu, J., M. Wilkinson, R. S. Haszeldine and A. E. Fallick (2009). "Long-term performance of a mudrock seal in natural CO2 storage." Geology 37(1): 35-38.

Manceau, J. C., D. G. Hatzignatiou, L. de Lary, N. B. Jensen and A. Réveillère (2014). "Mitigation and remediation technologies and practices in case of undesired migration of CO2 from a geological storage unit—Current status." International Journal of Greenhouse Gas Control 22: 272-290.

Miocic, J. M., S. M. Gilfillan, N. Frank, A. Schroeder-Ritzrau, N. M. Burnside and R. S. Haszeldine (2019). "420,000 year assessment of fault leakage rates shows geological carbon storage is secure." Scientific reports 9(1): 1-9.

Molari, M., K. Guilini, L. Lins, A. Ramette and A. Vanreusel (2019). "CO2 leakage can cause loss of benthic biodiversity in submarine sands." Marine Environmental Research 144: 213-229.

Montes-Hernandez, G., F. Renard and R. Lafay (2013). "Experimental assessment of CO2-mineral-toxic ion interactions in a simplified freshwater aquifer: Implications for CO2 leakage from deep geological storage." Environmental science & technology 47(12): 6247-6253.

Neele, F., A.-A. Grimstad, M. Fleury, A. Liebscher, A. Korre and M. Wilkinson (2014). "MiReCOL: Developing Corrective Measures for CO2 Storage." Energy Procedia 63: 4658-4665.

Nicol, A., M. Gerstenberger, C. Bromley, R. Carne, L. Chardot, S. Ellis, C. Jenkins, T. Siggins and P. Viskovic (2013). "Induced Seismicity; Observations, Risks and Mitigation Measures at CO2 Storage Sites." Energy Procedia 37: 4749-4756.

Oldenburg, C. M. (2012). "The risk of induced seismicity: is cap-rock integrity on shaky ground?".

Pawar, R. J., G. S. Bromhal, J. W. Carey, W. Foxall, A. Korre, P. S. Ringrose, O. Tucker, M. N. Watson and J. A. White (2015). "Recent advances in risk assessment and risk management of geologic CO2 storage." International Journal of Greenhouse Gas Control 40: 292-311.

Pearce, J., D. Jones, J. Blackford, S. Beaubien, E. Foekema, V. Gemeni, K. Kirk, J. Lions, R. Metcalfe, C. Moni, K. Smith, M. Stevens, J. West and F. Ziogou (2014). "A Guide for Assessing the Potential Impacts on Ecosystems of Leakage from CO2 Storage Sites." Energy Procedia 63: 3242-3252.

Peng, S. (2017). "Overview of CO_2 leakage problems and sealants for CO_2 leakage remediation."

Ringrose, P. S. (2018). "The CCS hub in Norway: some insights from 22 years of saline aquifer storage." Energy Procedia 146: 166-172.

RITE (Research Institute of Innovative Technology for the Earth). (2007). "Demonstration Test and Monitoring at the Iwanohara Test Site." from http://www.rite.or.jp/English/lab/geological/demonstration.html.

Rodríguez-Romero, A., M. D. Basallote, M. R. De Orte, T. Á. DelValls, I. Riba and J. Blasco (2014). "Simulation of CO2 leakages during injection and storage in sub-seabed geological formations: Metal mobilization and biota effects." Environment International 68: 105-117.

Sathaye, K. J., M. A. Hesse, M. Cassidy and D. F. Stockli (2014). "Constraints on the magnitude and rate of CO2 dissolution at Bravo Dome natural gas field." Proceedings of the National Academy of Sciences 111(43): 15332-15337.

Sawada, Y., J. Tanaka, C. Suzuki, D. Tanase and Y. Tanaka (2018). "Tomakomai CCS Demonstration Project of Japan, CO2 Injection in Progress." Energy Procedia 154: 3-8.

SCCS. (2015). "Open letter to Christiana Figueres, Executive Secretary of the United Nations Framework Convention on Climate Change." from https://sccs.org.uk/cop21-open-letter?highlight=WyJjb3AyMSJd.

Totland, C., E. Eek, A. E. A. Blomberg, I.-K. Waarum, P. Fietzek and A. Walta (2020). "The correlation between pO2 and pCO2 as a chemical marker for detection of offshore CO2 leakage." International Journal of Greenhouse Gas Control 99: 103085.

Tucker, O., P. Garnham, P. Wood, W. Berlang and I. Susanto (2013). "Development of an Offshore Monitoring Plan for a Commercial CO2 Storage Pilot." Energy Procedia 37: 4317-4335.

Verdon, J. P. (2014). "Significance for secure CO2 storage of earthquakes induced by fluid injection." Environmental Research Letters 9(6): 064022.

Vilarrasa, V. and J. Carrera (2015). "Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO2 could leak." Proceedings of the National Academy of Sciences 112(19): 5938-5943.

Wallmann, K., M. Haeckel, P. Linke, L. Haffert, M. Schmidt, S. Buenz, R. James, C. Hauton, M. Tsimplis and S. Widdicombe (2015). "Best practice guidance for environmental risk assessment for offshore CO2 geological storage."

White, J. A. and W. Foxall (2016). "Assessing induced seismicity risk at CO2 storage projects: Recent progress and remaining challenges." International Journal of Greenhouse Gas Control 49: 413-424.

Wilkinson, M., K. Edlmann, I. Demic and A. Korre (2017). "MiReCOL: Remediation of Shallow Leakage from a CO2 Storage Site." Energy Procedia 114: 4227-4236.

Yonkofski, C., G. Tartakovsky, N. Huerta and A. Wentworth (2019). "Risk-based monitoring designs for detecting CO2 leakage through abandoned wellbores: An application of NRAP's WLAT and DREAM tools." International Journal of Greenhouse Gas Control 91: 102807.