Geological methods

Carbon dioxide storage in geological formations below the German North Sea

Carbon dioxide storage in the deep subsurface of the North Sea is technically feasible and has been practised for decades beneath Norwegian waters. Under the German North Sea, there are rock formations in which large quantities of carbon dioxide could presumably be stored, too. Nevertheless, important questions remain unanswered, which are to be addressed and answered in the CDRmare research mission – with the aim of enabling carbon dioxide storage in the geological subsurface of the German North Sea in compliance with the precautionary principle.

Permanent storage of carbon dioxide beneath the seafloor

There is a consensus in scientific climate research that humanity will only mitigate climate change and its growing impacts and risks, if it reduces the amount of its annual carbon dioxide emissions into the atmosphere to net zero. Germany, for example, aims to balance its greenhouse gas emissions (including methane and nitrous oxide) and removal efforts by 2045.

Human-induced carbon dioxide emissions originate from burning of fossil fuels such as oil, natural gas and coal; and from changes in land use, such as slashing and burning forests, conversion of grassland to cropland, or draining of wetlands. So far, nobody knows how we can completely avoid these emissions in the future in an ecological and socially acceptable way. In fact, experts assume that Germany will still be emitting residual carbon dioxide and other greenhouse gases in the middle of the 21st century. In optimistic scenarios, their level is estimated at 10 to 20 per cent of current emissions. This corresponds to annual emissions of about 60 to 130 million tonnes of greenhouse gases, most of which are methane and nitrous oxide.

To offset these emissions, we will have to remove the same amount of carbon dioxide from the atmosphere. The gas will then have to be stored safely. Yet some of the residual emissions can also be avoided by preventing their release into the atmosphere in the first place. This is done by capturing the carbon dioxide at its source and then storing it permanently underground. Experts refer to this technological option for avoiding CO_2 emissions as carbon capture and storage (CCS).

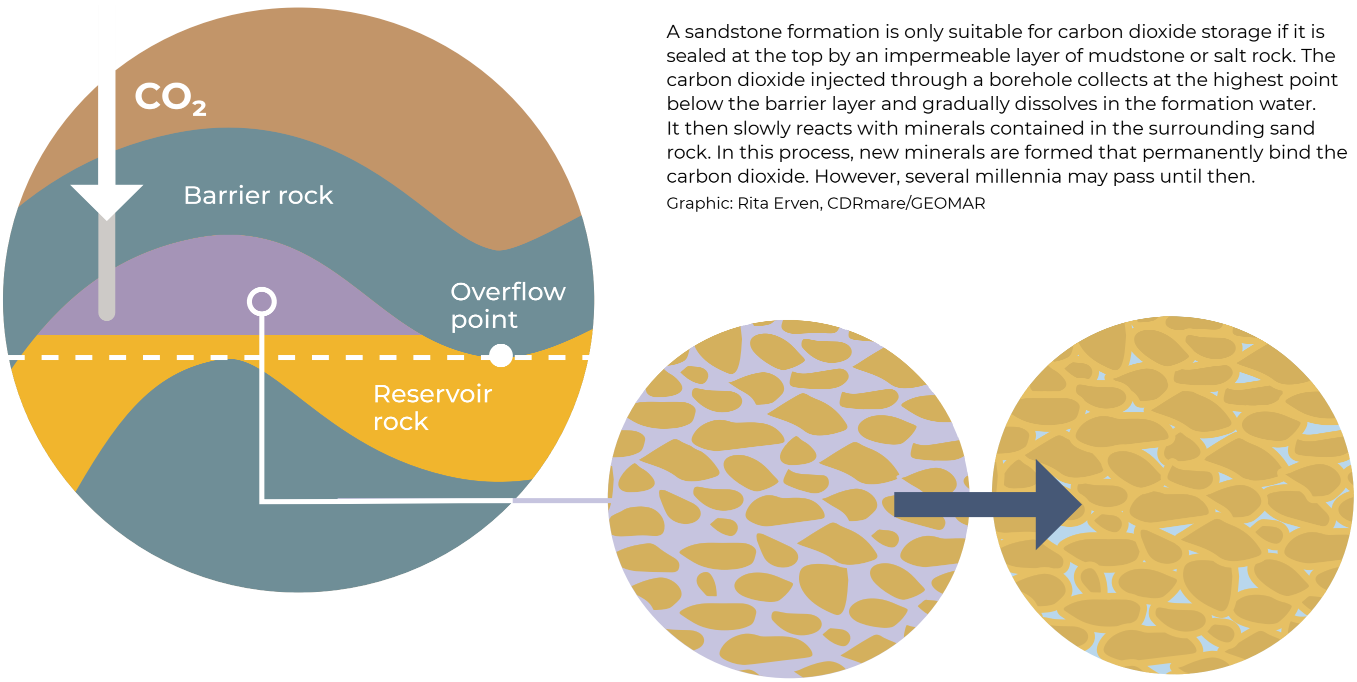
Germany's only offshore island, Helgoland, consists of the same sandstone formations that can be found at great depths beneath the seabed of the North Sea and that geologists propose to use as a reservoir for captured carbon dioxide.
Photo: Frederic Diercks, Pixabay

It is intended to prevent future carbon dioxide emissions from industry that cannot be avoided even if renewable energies are used. The underground storage of captured carbon dioxide is also a central component of important carbon dioxide removal methods such as direct air capture and bioenergy generation with carbon dioxide capture and storage (BECCS).

Sandstone formations, which are found both on land and in the deep subsurface of shelf seas (800 meters and deeper), are particularly suitable as geological carbon dioxide reservoirs. These rock layers have pores between the individual sand grains in which the injected carbon dioxide can spread. A prerequisite for permanent storage is that the reservoir rocks are overlain by a suitable barrier layer, e.g. of mudstone or salt rock. Such a layer seals the reservoir rock and prevents the injected carbon dioxide from rising and possibly escaping.

If a storage site meets these and other geological requirements, the captured carbon dioxide can be compressed and injected into the storage formations via one or more boreholes. There, the carbon dioxide spreads out in the rock pores filled with highly saline water and gradually dissolves in it. Experts refer to this saline pore water as »formation water«. Since the injected carbon dioxide is lighter than the formation water, it rises in the reservoir rock, collects at the highest point under the barrier layer and is thereby trapped in the reservoir rock.

Over time, the carbon dioxide dissolves in the formation water. The resulting solution is heavier than water, so the carbon dioxide no longer rises to the surface. Subsequently, the carbon dioxide dissolved in the water reacts with minerals contained in the sandstone and is converted into dissolved bicarbonate. In this form, the introduced carbon no longer has a harmful effect on the climate, even if the dissolved bicarbonate were to escape into the sea. How quickly the conversion of carbon dioxide into bicarbonate takes place depends on how many reactive minerals are present in the reservoir rock. The bicarbonate eventually forms solids in which the introduced carbon is permanently bound. However, it can take several millennia for these processes to be completed.



A sandstone formation is only suitable for carbon dioxide storage if it is sealed at the top by an impermeable layer of mudstone or salt rock. The carbon dioxide injected through a borehole collects at the highest point below the barrier layer and gradually dissolves in the formation water. It then slowly reacts with minerals contained in the surrounding sand rock. In this process, new minerals are formed that permanently bind the carbon dioxide. However, several millennia may pass until then.
Graphic: Rita Erven, CDRmare/GEOMAR

Carbon dioxide storage projects in the North Sea

The North Sea features many areas that could be suitable for deep underground carbon dioxide storage. According to calculations, around 150 billion tons of CO_2 could be stored in its sub-seafloor sandstone formations. As a shelf sea, the North Sea is also not particularly deep. Its maximum water depth in German waters is just 60 meters, which makes the construction or installation of injection facilities on platforms and on the seabed comparatively easy.

Most states located around the North Sea are already injecting carbon dioxide deep into the seabed or are about to set up CCS projects. The Norwegian oil company Equinor (formerly Statoil) made the first step in 1996: After the Norwegian government introduced a nationwide carbon dioxide tax, the carbon dioxide contained in natural gas was no longer released into the atmosphere, but was captured on site at the offshore production platform and injected into a sandstone formation deep beneath the platform. Other companies and countries are now following suit, as rising prices for carbon dioxide emission certificates mean that storing the greenhouse gas deep underground is gradually becoming a lucrative business. It is estimated that it costs between 80 and 200 euros to capture one ton of CO_2, transport it by pipeline to the ocean, and inject it underground. Certificates to emit the same amount of carbon dioxide into the atmosphere cost about 80 euros at the beginning of 2022. Several new carbon dioxide storage projects are currently being planned and implemented below the North Sea – for example off the coast of Rotterdam (Netherlands), beneath the Danish and British North Seas, and beneath Norwegian waters.

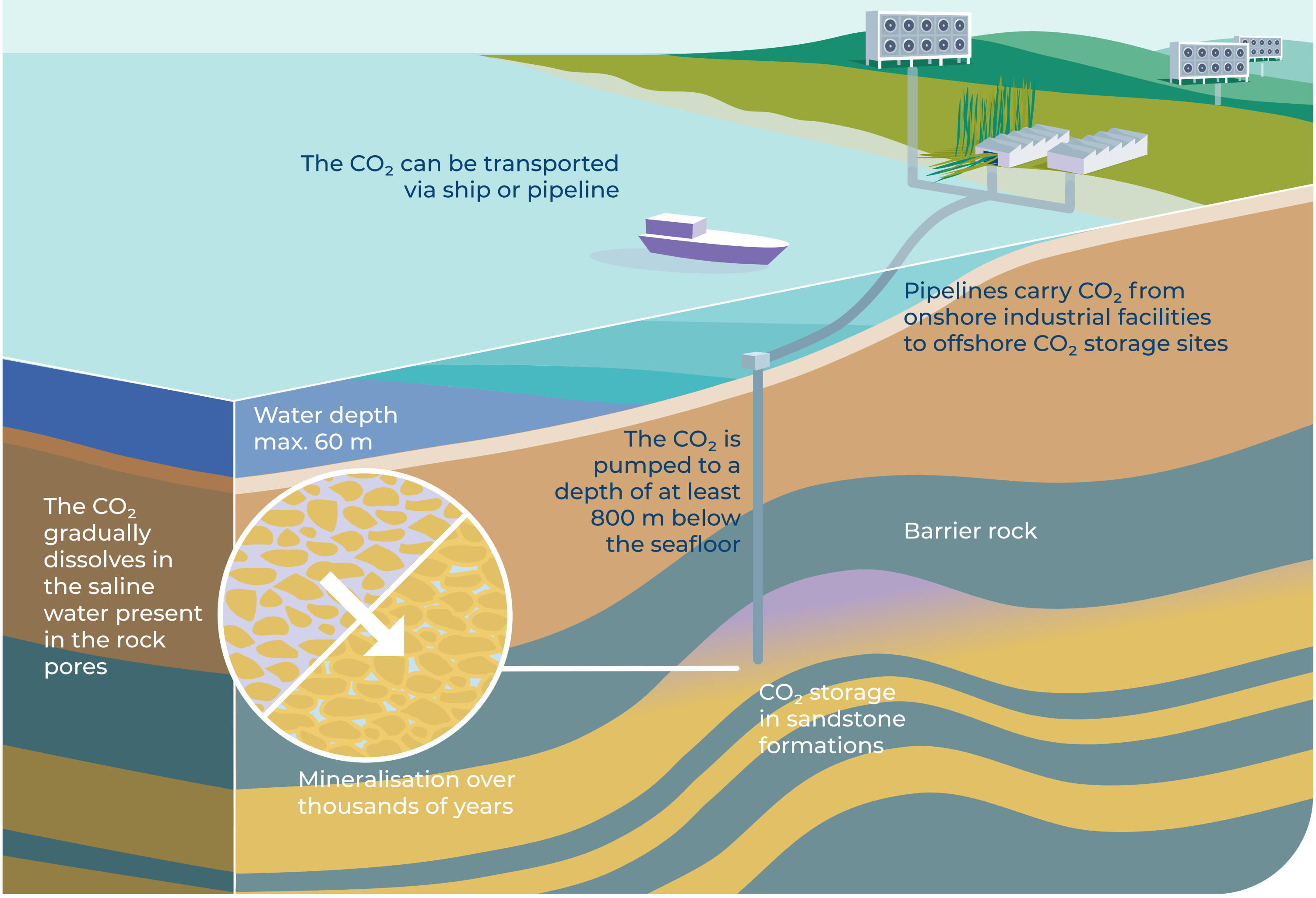
CO_2 storage in sandstone formations of the German North Sea

Costs associated with capture, liquefaction, transport, storage, monitoring: **approximately 150 to 250 euros per ton of carbon dioxide**

Duration of storage:
permanently possible, monitoring required

Scalability:
CO_2 storage at industrial scale is possible

Technical level of development:
The method is **feasible** and is already **being used successfully** outside Germany.



For storage in the ocean's subsurface, liquid carbon dioxide is transported by pipeline or by ship to the relevant ocean site and injected through one or more boreholes into deep porous sandstone formations.
Graphic: Rita Erven, CDRmare/GEOMAR

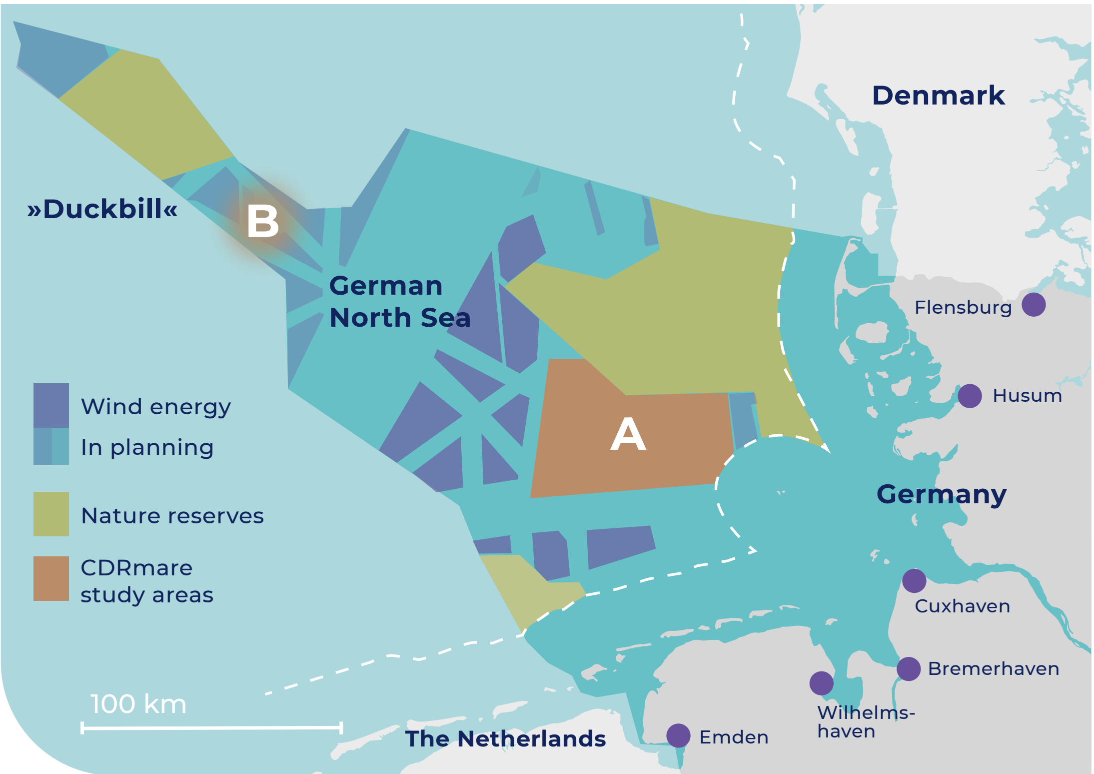
A feasible approach with open questions

The safe capture and storage of carbon dioxide in the deep subsurface of the North Sea has been technically feasible for decades. However, before a demonstration project can be considered under the German North Sea, there are a lot of open questions to be answered

How much carbon dioxide could be stored in the bedrock underneath the German North Sea?

So far, only rough estimates exist on how much carbon dioxide could be stored in the sandstone formations of the German North Sea. These estimates range from 3.6 to 10.4 billion tons of carbon dioxide. A storage capacity of this magnitude would theoretically be sufficient to inject the carbon dioxide emissions of German industries over several decades into the sea bed, which have so far been difficult to avoid. It is unclear, however, how much carbon dioxide the various rock formations in the subsurface of the German North Sea can actually hold and which sites are best suited as future storage sites based on the storage and barrier properties of the rock layers at depth.

In CDRmare, researchers examine the characteristics and storage capacities of sandstone formations in the German North Sea and remap potential storage sites. For two selected areas, they create three-dimensional high-resolution numerical reservoir models in which they can realistically simulate the storage of 10 million tons of carbon dioxide per year.



In the research mission CDRmare, researchers create computer-based reservoir models of the deep subsurface of two German North Sea areas, referred to as Areas A and B in this map. Using these models, they simulate the injection and storage of 10 million tons of carbon dioxide per year. Among other things, they investigates whether carbon dioxide storage in the deep subsurface would affect the operation of planned and existing offshore wind power plants.

Graphic: Rita Erven, CDRmare/GEOMAR, Rita Erven/CDRmare, illustration based on maps of Federal Maritime and Hydrographic Agency of Germany

How should the captured carbon dioxide be transported offshore and how much will it cost to store it below the seabed?

The two ongoing carbon dioxide storage projects under Norwegian waters have so far only used carbon dioxide that is captured from natural gas and then stored deep underground. In the North Sea Sleipner Project, the carbon dioxide is separated from natural gas, captured and injected at sea while in the Snøhvit project located in the Norwegian Barents Sea, carbon dioxide is separated on land and transported back to the offshore storage formation via pipelines on the seafloor. Transport via pipelines and ships is also planned for carbon dioxide storage in the Norwegian Northern Lights project located in the North Sea and for other projects off the coast of the Netherlands, Denmark and the UK.

Cost estimates for various CCS projects at ocean sites vary, as there are many project-specific factors that make general statements difficult. According to a recent international analysis, the costs for carbon dioxide capture, transport, injection into the subsurface and subsequent monitoring of the CO_2 storage facility are around 80 to 200 euros per ton of carbon dioxide. However, neither technical concepts for the transport and storage of carbon dioxide at an industrial scale nor realistic cost estimates exist for a project under the German North Sea, yet.

In CDRmare, researchers develope technical concepts for the transport and storage of carbon dioxide at an industrial scale for the two storage sites studied under the German North Sea. They also carry out cost estimates for the construction and operation of the necessary facilities.

What are the risks for people and the environment associated with carbon dioxide storage in the subsurface of the German North Sea?

Based on experience from ongoing carbon dioxide storage projects and extensive research over the past two decades, this question can be answered rather easily. Where carbon dioxide is stored in the seabed, there are theoretical risks:

> Some of the carbon dioxide injected into the subsurface rises through so-called faults or along boreholes and escapes at the seafloor (leakage);

> Very saline formation water, as well as heavy metals and other substances that may be contained in it and are harmful to the environment, leak from the seabed and affect local ecosystems;

> Pressure changes in the reservoir rock reactivate existing geological faults and trigger earthquakes that could threaten the stability and functionality of seabed-anchored infrastructure;

> Marine mammals may be disturbed or potentially harmed by noise generated during the exploration of suitable storage sites, construction of the facilities, and monitoring of the storage site.

Which of these risks actually occur and to what extent depends on local conditions and must be thoroughly investigated in advance of any carbon dioxide storage project.

What if carbon dioxide escapes from the seabed?

The seabed of the North Sea is not a tightly sealed area. On the contrary: natural gas escapes from the seabed in many places. About 1 to 70 tons of natural gas are released per year at each of these sites. Its origin is not always clear. It is either formed by microorganisms in the seafloor or can rise from the deep subsurface through faults and other permeable structures cutting through impermeable cap rocks. In addition, natural gas escapes around many abandoned wells at an annual rate of 1 to 19 tons per well.

Researchers in CDRmare investigate whether such pathways for natural gas release could also be used by CO_2 that is stored in sub-seabed geological formations and compromise the safety of storage sites.

To date, carbon dioxide leaks at modern wells constructed specifically for the purpose of CO_2 storage have not been reported. Norwegian storage projects, which have been in operation for many years, have also not experienced carbon dioxide leaks from the seafloor. Nevertheless, when selecting storage sites, attention must be paid to the existence of faults and other permeable sedimentary structures in the subsurface through which carbon dioxide and, under certain circumstances, formation water could rise to the seafloor. At the same time, it must be verified whether old wells are present and, if so, whether they are tightly sealed.

In preparation for a subsea CO_2 storage project, the formation water in the selected storage formations must also be chemically analysed. Based on the results, it is possible to assess what environmental risks could occur should the formation water and any heavy metals or other environmentally harmful substances contained therein escape from the seafloor.

Release experiments on the seafloor of the North Sea show that escaping carbon dioxide dissolves immediately in the near-bottom seawater, changing its chemical properties. The seawater around the point of release acidifies, affecting the living conditions particularly of mussels and other calcifying animals. The area affected by acidification is comparatively small (approx. 10 - 50 square metres), when about the same amount of carbon dioxide escapes as natural gas at the North Sea outlets described above.

Similar observations have been made by scientists on land. If CO_2 escapes from the subsurface above natural carbon dioxide deposits there, the area affected by the gas tends to be only a few tens of square meters.

For carefully explored and selected CO_2 storage sites in the marine area, only a very small amount of CO_2 can escape from the storage site if it is used according to plan. Accordingly, the resulting environmental damage to the seafloor would affect only small areas and more than 99 % of the stored CO_2 would remain permanently in the storage formation.

Nevertheless, leakage must be largely avoided. Suitable early warning and monitoring systems are needed to detect deviations from the expected storage behavior at an early stage, to take appropriate countermeasures quickly.

In the research mission CDRmare, scientists investigate the seabed and all known wells in two selected areas for possible natural gas leaks and develop methods to contain potential CO_2 leaks.

What if carbon dioxide injection triggers movement in the subsurface.

When carbon dioxide is injected into a reservoir rock, the pressure in the rock formation increases. As a result, existing faults within this rock formation may be activated. In other words, cracks in the rock could widen at certain points or rock layers could shift against each other. These movements in the subsurface can possibly create pathways through which the stored carbon dioxide and formation water can rise and later escape from the seafloor.

In marine areas where earthquakes already occur naturally, existing faults could be activated as a result of the pressure changes in the reservoir rock. This could trigger earthquakes that would endanger the stability of wind turbines or pipelines. In comparison, a CO_2 pilot storage facility in Nagaoka, Japan, survived a magnitude 7 earthquake unscathed. However, conclusions about other storage sites are only possible to a limited extent because site-specific conditions have to be taken into account.

Whether on land or at sea, potential sites for deep underground carbon dioxide storage must be extensively explored. Their geological characteristics, possible leakage paths and the locally prevailing pressure and temperature conditions must be investigated before a decision can be made on their suitability as CO_2 storage sites. In other words, if geological CO_2 storage is to be used in Germany in the future, geological investigations of suitable reservoirs must be intensified and expanded.

In CDRmare, researchers simulate and evaluate the geotechnical risks of carbon dioxide storage in the subsurface of the two selected marine areas for neighboring or overlying wind farms and other structural infrastructure such as pipelines.

Noise pollution impacts on marine mammals

In the search for possible carbon dioxide storage sites in the ocean floor, the same geophysical methods are used as in the search for oil and gas deposits. These include active seismic methods where, for example, so-called air guns are lowered into the water from a ship. With each blast, sound waves are generated that penetrate deep into the subsurface and are reflected by the rock layers. Based on the propagation and reflection of the sound waves, scientists can map the shape and structure of the subsurface. The disadvantage of air guns is that their sound waves cause underwater noise. Very little is known about their effects on marine life and especially on noise-sensitive North Sea inhabitants such as harbour porpoises. Because harbour porpoises rely on acoustic signals for orientation, communication, and foraging, underwater noise affects their behaviour and can drive them out of their native habitat in the long term. Very high sound levels of certain frequencies can also injure and sometimes permanently harm the animals.

In CDRmare, researchers study the effects of active seismic surveys, particularly the use of air guns, on harbour porpoises. Their goal is to better assess the risks of seismic measurements and other noise-intensive work for marine mammals and to develop appropriate protective measures.

Harbour porpoises (*Phocoena phocoena*) produce high-frequency short echolocation clicks to orient themselves underwater, identify prey, or communicate with each other. Consequently, they depend on well-functioning hearing. The use of active seismic sensing methods generates shock waves underwater that can drive the animals away and possibly injure them

Photo: Sytske Dijksen, Ecomare, Wiki Commons

How can carbon dioxide storage sites be monitored and risks mitigated in the long term?

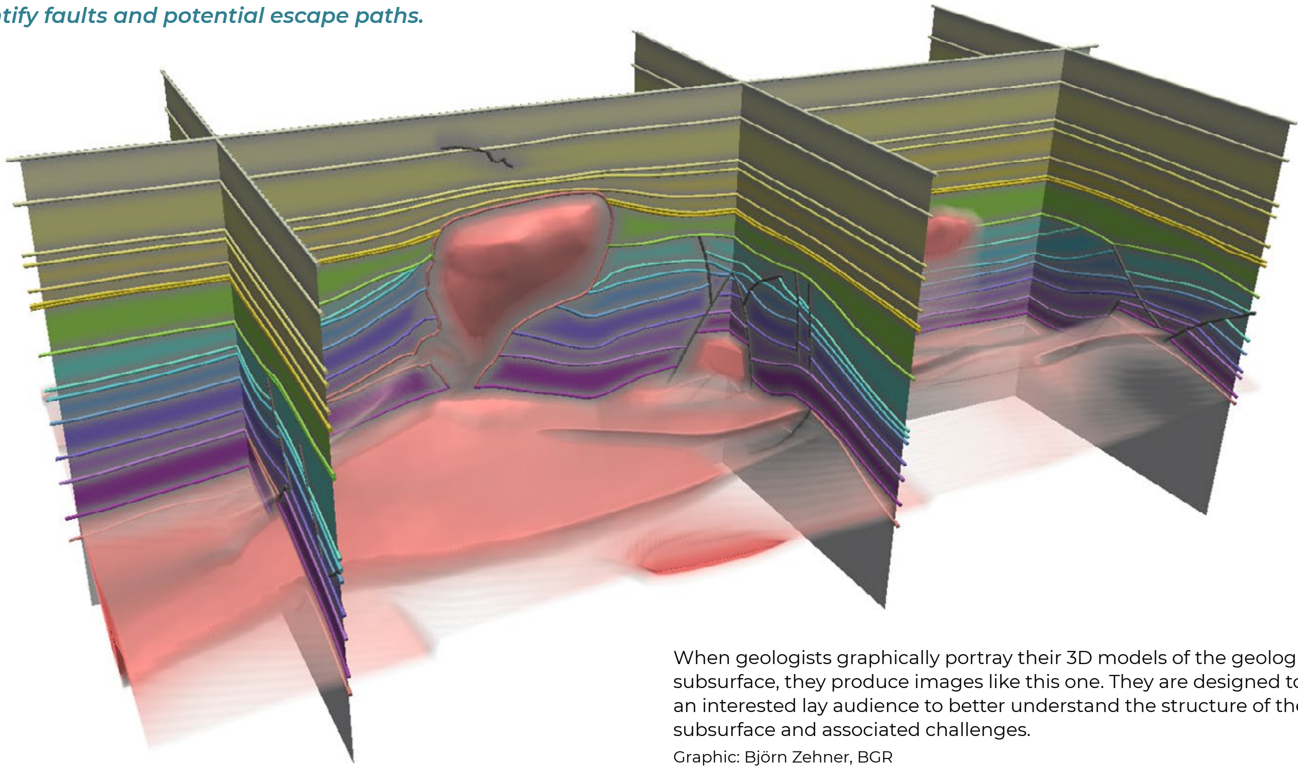
The injection and storage of carbon dioxide in the seabed must be monitored extensively and also over a long period of time for several reasons – these include checking whether the carbon dioxide is spreading in the reservoir rock as expected and detecting possible CO_2 leaks in a timely manner, even after CO_2 injection has already been completed. Active seismic measurements play an important role in this context. However, to minimise their impact on marine life, such measurements should be kept to a minimum.

A supplementary monitoring approach could be so-called passive seismic methods, which have so far only been tested in the deep ocean. For this purpose, highly sensitive measuring devices are placed on the seafloor, which then record both naturally occurring seismic events and those caused by CO_2 injection – all without making any noise.

In CDRmare, scientists investigates whether they can use passively collected data to draw conclusions about CO_2 dispersion and pressure conditions in the subsurface and identify faults and potential escape paths.

Another argument in favour of using passive seismic methods is that they allow for continuous monitoring. However, where passive seismic instruments are located on the seafloor, they must be protected from destruction. This means that fishing and the anchoring of ships and boats may have to be restricted. Before implementing a CO_2 storage project under the German North Sea, it is therefore essential to coordinate the many different claims for use near the seafloor and, if necessary, to set priorities for different areas.

In CDRmare, researchers develope a passive seismic and thus noise-free monitoring system for future carbon dioxide storage in the deep subsurface of the North Sea. This system is intended to be spatially scalable and able to cover all phases of carbon dioxide storage – that is, both the time before and during the injection of the carbon dioxide into the subsurface and the time afterwards.



When geologists graphically portray their 3D models of the geological subsurface, they produce images like this one. They are designed to help an interested lay audience to better understand the structure of the subsurface and associated challenges.
Graphic: Björn Zehner, BGR

Does carbon dioxide storage in the seabed affect other forms of marine activity?

Shipping, wind farms, fishing, pipelines, natural gas production: The German North Sea is already an intensely used marine area. At the same time, it is also an important habitat for many different marine species, which should be protected and preserved by establishing marine protected areas. To avoid conflicts with marine conservation and other uses, potential CO_2 storage sites would need to be integrated into marine spatial planning.

So far, however, marine spatial plans for German waters only take into account the use of the seabed, the water column, and the airspace above it. More extensive use of the seabed at various depths is not mentioned even in the new specifications that came into force in 2021.

In CDRmare, scientists analyse the status quo of marine spatial planning in the German North Sea and develope options for how carbon dioxide storage projects could be taken into account in future planning and how potential conflicts of use could be dealt with.

Which legal framework conditions exist?

Due to the existing legal regulations in Germany, projects for CO_2 storage in the subsurface of the German North Sea are currently not possible. However, at the international level important legal groundwork was established as early as 2006: Both the Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter (London Convention) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), which applies to the North Sea, now permit the underground storage of carbon dioxide in the continental shelf of a coastal state and in other areas of the seabed. Germany is a party to both treaties.

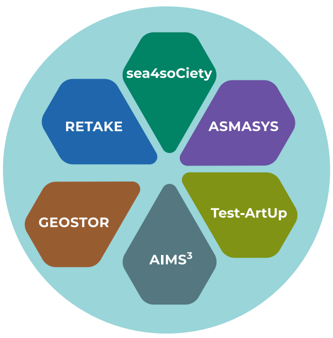
The EU Directive on the storage of carbon dioxide also applies to the member states of the European Union, which the German government implemented nationally in August 2012, including the Carbon Capture and Storage Act (KSpG).

In particular, two passages in the KSpG are currently preventing the implementation of storage projects in the German North Sea: Firstly, the law contains a clause according to which applications for approval of carbon dioxide storage facilities should have been submitted by the end of 2016 (other conditions apply to so-called research storage sites). Secondly, the German federal law grants each federal state the right to exclude certain areas from possible carbon dioxide storage. Mecklenburg-Western Pomerania, Lower Saxony and Schleswig-Holstein have used this right to exclude all marine areas under their responsibility from underground carbon dioxide storage. By doing so, they have virtually imposed a ban on underground carbon dioxide storage in the near-coastal area of the German North Sea.

Since the wording of the KSpG limits the power of the federal states to prohibit testing and demonstration of permanent storage to »specific areas«, the general exclusion of the seabed was already met with legal concerns immediately after the KSpG came into force. Politically, however, this step was not discussed further due to the high level of public approval. It is currently unclear, for example, whether carbon dioxide storage projects beyond the 12-nautical-mile territorial sea could be realised if the application deadline were extended, or whether these could also be subject to the federal-state ban.

Overall, the current legal situation for carbon dioxide storage projects in the subsurface of the German North Sea requires considerable clarification. However, given the increasing urgency to effectively halt climate change, the barriers in the National Carbon Capture and Storage Act are likely to be subject to increasing scrutiny. The KSpG's mandated re-evaluation of the law's application and lessons learned internationally provides an appropriate occasion to discuss ways in which these obstacles can be removed

In CDRmare, legal experts and geoscientists investigates the conditions under which a future demonstration project for carbon dioxide storage in the subsurface of the German North Sea could be compatible with legal and regulatory requirements if the application deadline were extended, and the extent to which application and approval procedures need to be made more specific in order to reconcile marine protection and use.



All research activities described here are carried out within the CDRmare consortium »GEOSTOR – Submarine Carbon Dioxide Storage in Geological Formations of the German North Sea«.

In the German Alliance for Marine Research (DAM) research mission CDRmare, various marine CO_2 removal and storage methods (alkalinity enhancement, blue carbon, artificial buoyancy, CCS) are investigated with regard to their potential, risks and trade-offs, and consolidated using a transdisciplinary assessment framework.

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