GEOSTOR

GEOSTOR – Submarine Carbon Dioxide Storage in Geological Formations of the German North Sea

CO_2 storage deep below the German North Sea: The seven most important outcomes of GEOSTOR research

CDRmare INSIGHTS

For the past three years, experts from the CDRmare research consortium GEOSTOR have been investigating where and how captured carbon dioxide (CO_2) could be safely and permanently stored in the deep seabed under the German North Sea, and which corresponding prerequisites would have to be met. In the following, we summarise seven of their most relevant findings.

1. Geological formations deep below the German North Sea have the potential to store 0.9 to 5.5 billion metric tons of carbon dioxide.

2. If Germany plans to take advantage of this CO_2 storage potential below the German North Sea, foreseeable conflicts with other forms of ocean use and marine conservation will need to be avoided or resolved.

3. A potential storage structure investigated in detail by GEOSTOR could accommodate more than 300 million metric tons of CO_2. Up to 10 million metric tons of CO_2 could be injected and stored there per year.

4. Some old wells in the North Sea seabed leak natural gas that has formed and accumulated in the upper 1000 metres of the seabed. Whether or not these boreholes pose a risk for future, deeper-lying CO_2 storage sites must be assessed on a case-by-case basis.

5. According to the concept and feasibility study prepared by GEOSTOR, developing a CO_2 storage facility at the coast, transporting CO_2 through the North Sea, and storing it below seabed would cost between € 14 and € 57 per metric ton of CO_2. Transporting CO_2 through a pipeline would be cheaper in the long term than transporting it by ship.

6. GEOSTOR experts have developed a monitoring system which would notify CO_2 storage site operators of any naturally occurring or operations-related seismic events in the seabed in near real-time.

7. The legislative changes announced by Germany's federal government will enable CO_2 storage below the German North Sea. The GEOSTOR project has shown for the first time that large quantities of CO_2 could be stored there, providing a scientific basis for the planned legal initiatives.

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Key message 1

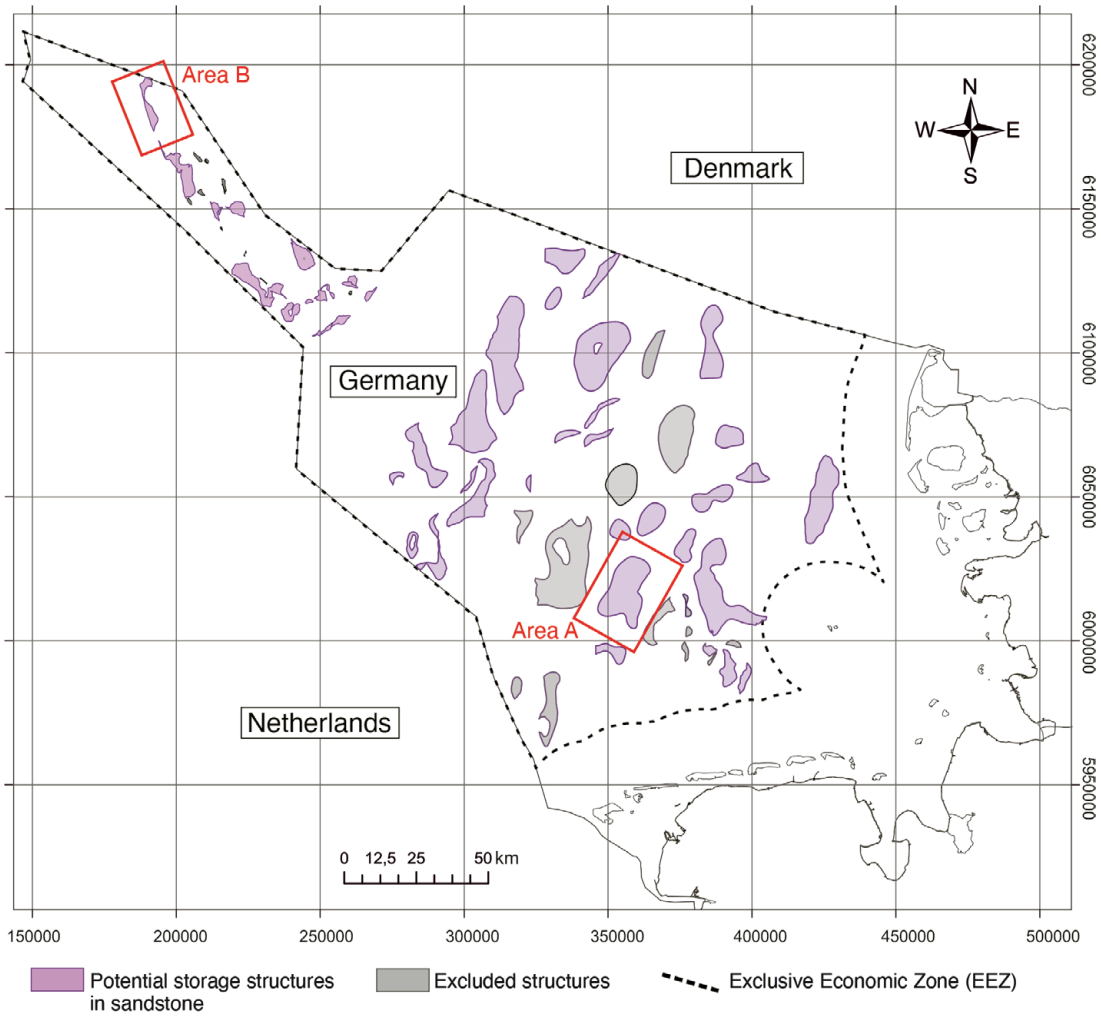
Geological formations deep below the German North Sea have the potential to store 0.9 to 5.5 billion metric tons of carbon dioxide.

In theory, this storage potential would be enough to permanently store a large proportion of the CO_2 captured in Germany deep under the German North Sea. Estimates suggest that between 30 and 60 million tonnes of CO_2 would need to be stored each year. How much CO_2 can actually be stored in this region depends on a number of other factors. The estimated storage potential represents a theoretical maximum, which will be reduced in subsequent analysis and selection processes.

The conclusions regarding the geological CO_2 storage potential in the German North Sea are the result of the first comprehensive analysis and reanalysis of the relevant geological data, both conducted by the experts of the CDRmare research consortium GEOSTOR. The analyses only apply to Buntsandstein formations that are located below the seafloor of Germany's Exclusive Economic Zone (EEZ) in the North Sea – in other words at a distance between 12 and 200 nautical miles (approx. 22 to 370 kilometres) from the coast.

The reservoir rocks identified are mainly sandstone formations (Buntsandstein) that occur at a depth of approximately 1 to 4 kilometres below the seabed. The focus of the analysis has been on so-called trap structures within these sandstone formations, which are covered by at least 20-metre-thick, impermeable layers of clay or halite, which seal the reservoir rock and help to retain the stored carbon dioxide.

It has yet to be determined which of the potential storage structures investigated should actually be used for CO_2 storage. To make this decision, each potential structure must first be further explored und subjected to a range of geotechnical tests.



This map shows the potential sandstone storage structures. The grey structures have already been ruled out due to their limited capacity, major faults in the barrier rock, insufficient barrier rock thickness or insufficient structural depth.

Graphic: Fuhrmann et al. 2024

Key message 2

If Germany plans to take advantage of this CO_2 storage potential below the German North Sea, foreseeable conflicts with other forms of ocean use and marine conservation will need to be avoided or resolved.

Many parts of the German North Sea are currently in use, have been designated for specific future uses, or have been set aside for marine conservation. Consequently, there are very few regions where CO_2 could be injected and stored in the deep seafloor without creating conflicts with commercial shipping, wind energy production, nature conservation, fishing or the military.

Accordingly, Germany has to find ways to avoid or resolve conflicts between CO_2 storage beneath the North Sea and other forms of use. This includes considering whether a given marine region could be made available for multiple forms of use simultaneously – e.g. at different depths. In terms of resolving these conflicts, examining the respective activities in each conflict is indispensable.

Potential conflicts of use must be identified and addressed in a timely manner. This includes conducting seismic surveys of the seabed and exploratory drilling in areas where offshore wind farms are to be built in the near future. Once construction work has begun, the extensive geophysical investigations of the subsurface can no longer be carried out using conventional methods – making site exploration for future CO_2 storage projects far more complex and expensive, or even impossible.

For offshore wind farms, CO_2 storage beneath them could pose a risk if the injection process were to trigger significant seismic events or cause substantial seabed uplift, potentially compromising the stability and operational integrity of the wind turbines. Research conducted by GEOSTOR experts indicates that this risk can largely be ruled out by selecting suitable pressure threshold values for injection and storage. However, they will only be able to make definitive statements regarding the potential risks and damage prevention in the course of the project's second phase, after all geotechnical modelling has been completed and the seabed has been investigated in more detail.

Key message 3

A potential storage structure investigated in detail by GEOSTOR could accommodate more than 300 million metric tons of CO_2. Up to 10 million metric tons of CO_2 could be injected and stored there per year.

The storage structure under consideration lies in GEOSTOR Region A (see the map on p. 2), in the southeast section of the German EEZ. This area is home to a large trap structure with a thick layer of sandstone as the reservoir horizon, which is covered by impermeable layers of clay or salt. GEOSTOR experts have created a high-resolution 3D reservoir model for the area and run computer simulations of how the CO_2 would be injected into the seafloor and its long-term behaviour there.

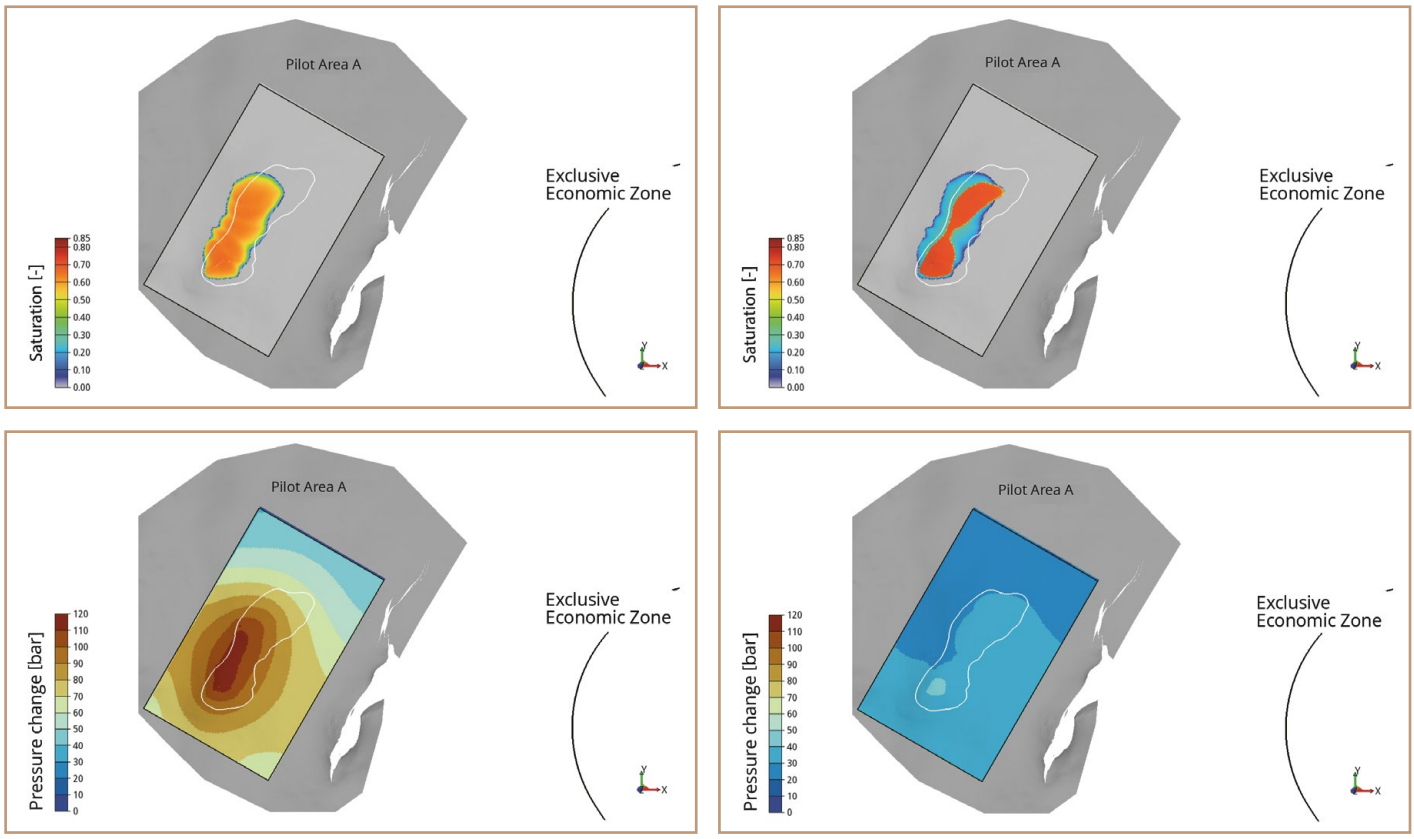
For the initial simulations, the experts focused on the ambitious goal of injecting roughly 10 million metric tons of CO_2 per year over a 30-year period. For comparison, this rate is more than ten times higher than that used in the two Norwegian CO_2 storage projects »Sleipner« and »Snøvhit«.

The simulations revealed that multiple boreholes would be needed to store such large quantities of CO_2 in the seabed. Although seafloor pressures rise during injection, they can be kept at or below a maximum pressure limit derived from high-resolution GEOSTOR geomechanical simulations to avoid damage to the storage rock or clay layers.

In addition, GEOSTOR experts determined that selecting the appropriate well type and positioning can not only minimize reservoir pressure but also control the spatial distribution of CO_2, enabling optimal utilization of the storage site while adhering to pressure limits. The workflow developed for this purpose is generally transferable to other storage sites.

The pressure increase created by injection can be problematic, since the cover layers include an old borehole and certain disturbances in the rock that could potentially become weak points and leakage pathways. With increasing pressures, the likelihood of CO_2 rising to these weak points and ultimately being released into the environment also rises. Moreover, the existing disturbances could be activated and (micro-)earthquakes could be triggered, which in the case of larger quakes could negatively impact infrastructures, e.g. wind turbines, located above or in the vicinity of the storage site.

The GEOSTOR experts are currently working to assess the actual scope of these risks. To do so, they have to estimate the stresses at work in the overlying rock formations and simulate key processes in the subsurface using high-resolution models. Once these steps are complete, they will propose a pressure threshold for the area modelled, one that has to be adhered to during injection so as to minimise the risk of leaks and triggering earthquakes. Given that the pressure increase also depends on the injection rate, this threshold will also define how much CO_2 per year could actually be stored under the selected assumptions regarding the distribution of the injection boreholes at the site.



The figures show the hypothetical spatial distribution of CO_2 saturation/reservoir pressure after 30 years of consistent CO_2 injection (left) and 100 years after the last injection (right). The rectangular modelling area is 22 kilometres wide and 36 kilometres long.

Graphic: Firdovsi Gasanzade & Sebastian Bauer, CAU

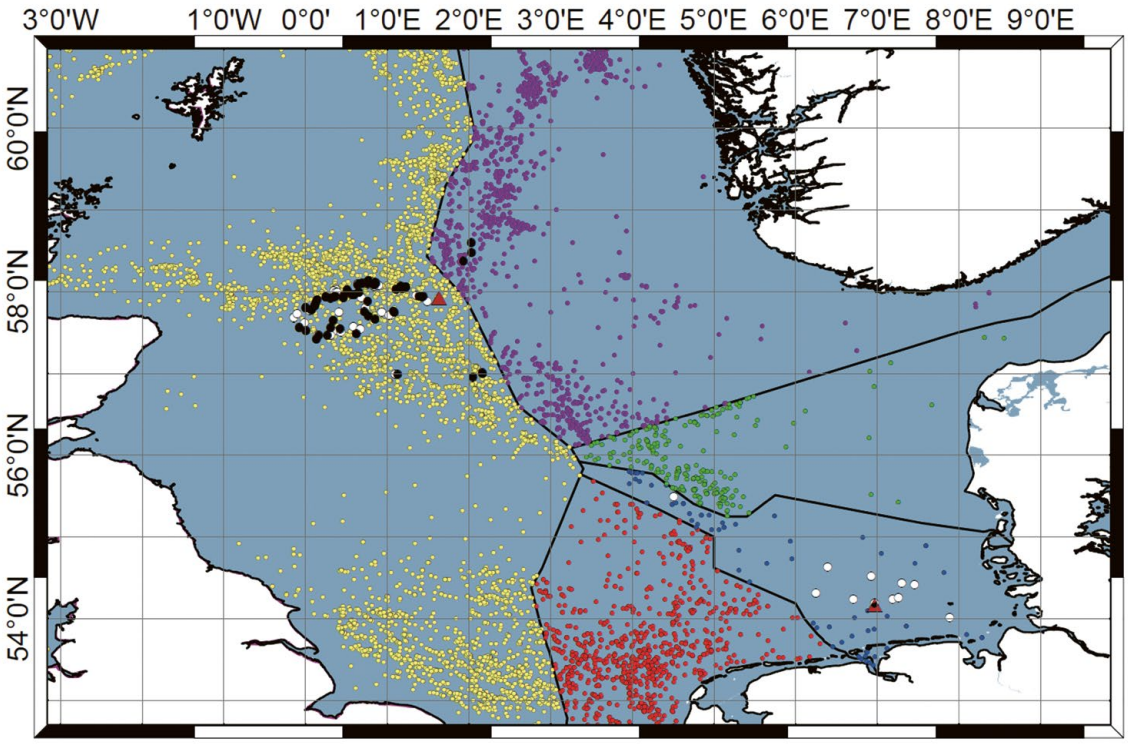
Key message 4

Some old wells in the North Sea seabed leak natural gas that has formed and accumulated in the upper 1000 metres of the seabed. Whether or not these boreholes pose a risk for future, deeper-lying CO_2 storage sites must be assessed on a case-by-case basis.

The seabed of the North Sea is riddled with boreholes. Experts are aware of ca. 17,000 abandoned boreholes, that extend several kilometres below the seafloor. 91 boreholes are located in Germany's Exclusive Economic Zone. For the majority of them, it remains unclear whether or not they can be sufficiently well sealed to withstand contact with CO_2 or pressure increases.

Over the past few years, experts from the GEOSTOR research consortium have investigated 121 abandoned boreholes in the Norwegian, British and German sectors of the North Sea. According to their findings, between 0.8 and 5.2 metric tons of methane per year were released from the seafloor at 59 of the boreholes assessed. The methane stems from natural accumulations that form in the topmost 1,000 metres below the seafloor, and which were either directly drilled into in the past, or from which gas eventually found its way to a borehole. In the North Sea, there are also numerous sites where methane is naturally released by the seafloor.

With one exception, no leaks were found in any of the abandoned boreholes assessed in the German North Sea: gas was only leaking from Figge Maar, a blowout crater created during the first German drilling (B1) in 1964.



Map of abandoned boreholes in the North Sea. The colours of the dots mark the locations of the abandoned boreholes in the North Sea sectors of the border states. Black dots: leaks detected. White dots: no leaks detected. Red triangles: blowout craters in the German and British sectors of the North Sea.

Graphic: Matthias Haeckel, GEOMAR

To what extent the abandoned boreholes pose a leakage risk for CO_2 storage sites located at more than 1,000 m depth must be evaluated on a case-by-case basis. If a given borehole extends down to the geological formation used for storage, the risk is substantially higher than if the borehole ends far above the storage rock and the overlying cap rock.

The GEOSTOR research findings underscore the importance of considering old boreholes when looking for suitable CO_2 storage sites. If such holes are present, their integrity must be investigated, assessed, and potentially ensured or restored by additional means.

Abandoned boreholes aren't just problematic in connection with CO_2 injection deep beneath the sea: according to estimates, there are more than 20,000 of these boreholes on the German mainland. Seen in this light, the 91 boreholes in the seabed of the German North Sea constitute a manageable risk for the CO_2 storage formations.

Key message 5

According to the concept and feasibility study prepared by GEOSTOR, developing a CO_2 storage facility at the coast, transporting CO_2 through the North Sea, and storing it below seabed would cost between € 14 and € 57 per metric ton of CO_2. Transporting CO_2 through a pipeline would be cheaper in the long term than transporting it by ship.

In the CDRmare research consortium GEOSTOR, experts have for the first time analysed in detail which facilities and infrastructures would be needed to inject large quantities of captured carbon dioxide under the German North Sea and how much the transport and injection would cost per metric ton of CO_2.

The point of departure for the project scenario was the assumption that the carbon dioxide would need to be transported from a not-yet-created »CO_2 hub« in Wilhelmshaven to a storage site deep below the German North Sea. For this purpose, two areas located roughly 130 and 300 kilometres from Wilhelmshaven respectively were considered (Areas A and B in the map above). For each potential site, the experts prepared calculations for both phases of the project: first, initiating CO_2 injection with the aid of ship-based transport from the mainland to the injection site; second, the construction of a pipeline through which compressed, liquid carbon dioxide could then be pumped from Wilhelmshaven to the injection site.

The calculations show that the investment costs for creating a CO_2 storage site deep below the German North Sea would amount to more than 2.1 billion Euros. In this regard, the highest cost points would be the construction of the CO_2 hub and marine storage site with corresponding injection drilling, and the construction of the pipeline.

For the first project phase, using ship-based transport, circa 3 million metric tons of CO_2 per year were calculated; for the second phase, using pipeline-based transport, the number was 10 million. This difference in capacities also affects the price: for a storage project involving ship-based transport to Area A, the GEOSTOR experts calculate a price range of 27 to 58 Euros per metric ton of CO_2. In contrast, due to the lower operating costs and higher CO_2 transport capacity, the price for the pipeline solution is estimated at only 14 to 29 Euros per metric ton of injected CO_2. These cost estimates include operating costs and the investments for the construction of a CO_2 hub at the coast, a pipeline and an offshore storage facility. However, they do not include the cost of CO_2 capture and overland transport to the CO_2 hub in Wilhelmshaven.

Further, it should be kept in mind that, in their project scenario, the experts designed the pipeline to lead through existing corridors already being used for shipping, other pipelines, and/or power cables. Whether such an approach would be permissible and feasible – and if so, how – would still need to be assessed from both a legal and geotechnical standpoint.

Key message 6

GEOSTOR experts have developed a monitoring system which would notify CO_2 storage site operators of any naturally occurring or operations-related seismic events in the seabed in near real-time.

The monitoring of CO_2 storage sites must serve multiple purposes and meet a range of legal requirements. As part of the GEOSTOR project, geotechnical challenges and the options for exploring and monitoring marine CO_2 storage sites were identified and discussed. Comprehensive monitoring would require the use of several different technologies; passive seismic monitoring is one of the potential technologies considered in the system design prepared by GEOSTOR.

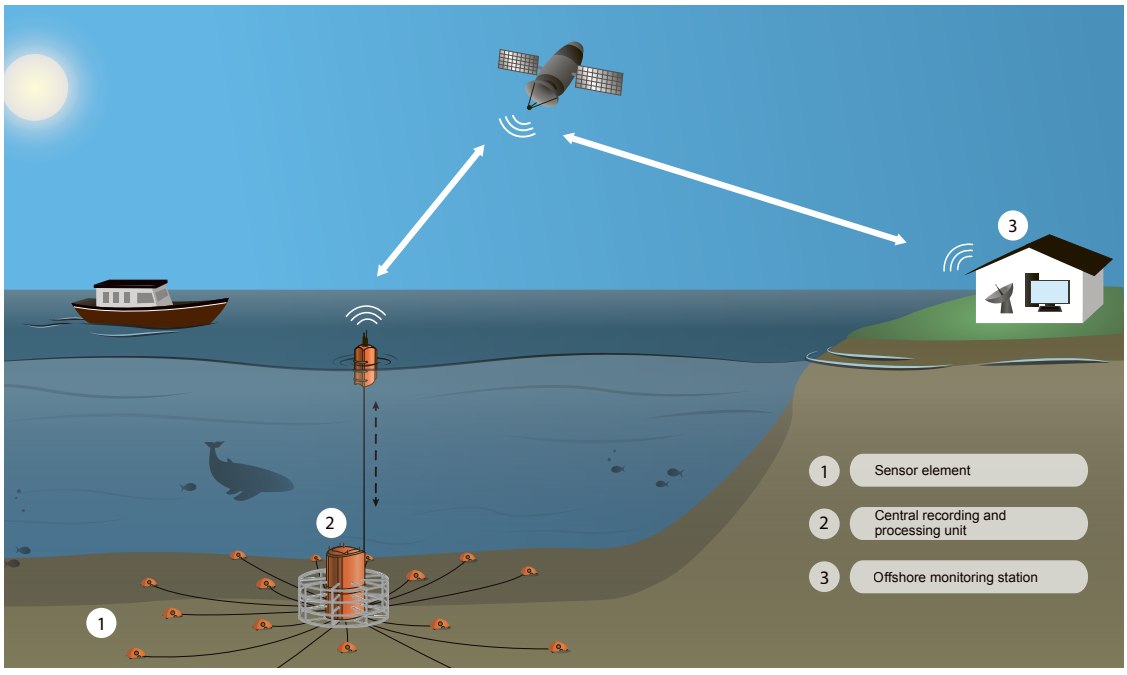
The newly developed monitoring system will consist of multiple seismological sensors, which would be installed above and adjacent to the storage site and be capable of detecting even the smallest disturbances in the subsurface. In the proposed design, all sensors are connected to a central data-recording unit, which in turn transmits its data to the water's surface via a cable, where a radio buoy transmits the monitoring data to land via satellite.

A computer programme with artificial intelligence scans all incoming monitoring data for certain predefined parameters. The programme is trained to recognise signals triggered by CO_2 injection and distinguish them from the background noise at the surface. This noise can be produced by e. g. wind and wave action, or by shipping traffic.

As such, the monitoring system is capable of identifying even the smallest underground disturbances that can be induced by the injection and the resulting pressure increase. Any microquakes, which can be caused by injection, can be detected and located early on, making it possible to take corresponding countermeasures before a more substantial earthquake occurs.

The sensors and their central data unit were designed for permanent use on the seafloor once installed. In addition, the sensors' design allows trawling nets to smoothly slide over them.

In the second phase of the GEOSTOR project, researchers aim to test whether this monitoring system works effectively and proves reliable by conducting initial measurements in Area A. As part of this effort, they also intend to record natural subsurface seismic activity prior to the start of CO_2 storage, in order to distinguish it from potential earthquakes that may occur as a result of CO_2 injection.



Concept for the seismological monitoring of CO_2 storage sites

Graphic: Florian Schmid, K.U.M.

Key message 7

The legislative changes announced by Germany's federal government will enable CO_2 storage below the German North Sea. The GEOSTOR project has shown for the first time that large quantities of CO_2 could be stored there, providing a scientific basis for the planned legal initiatives.

In the spring of 2024, Germany's Federal Ministry for Economic Affairs and Climate Action released a draft Carbon Management Strategy for industry, together with a draft law on the storage and transport of CO_2. In late May 2024, both drafts were approved by the Federal Cabinet. They are to be reviewed and potentially ratified by the Bundestag and Bundesrat, which would pave the way for CO_2 storage in Germany's Exclusive Economic Zone (EEZ) in the North Sea and set the legal and planning-related framework conditions for industrial CCS projects in Germany. In addition, the federal government plans to permit CO_2 export. To do so, Germany will ratify the corresponding amendments to the London Protocol and make the necessary changes to the High Seas Dumping Act.

The GEOSTOR research consortium has shown for the first time that large amounts of CO_2 could be stored in Germany's EEZ if foreseeable conflicts of use were successfully resolved. Moreover, GEOSTOR experts were actively involved in the consultation process for the Carbon Management Strategy. They provided extensive analyses of which legal framework conditions would need to be changed, and of how the current requirements could be met in order to realise carbon dioxide storage projects in the subsurface of the German North Sea.

In this way, the GEOSTOR research consortium has provided an essential scientific basis for the federal government's planned legislative changes.

IMPRINT

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