8 Injecting carbon dioxide deep beneath the sea

> When carbon dioxide is captured during industrial activities or is removed directly from the atmosphere, the question of appropriate storage arises. Because underground land-based storage sites harbour risks and provoke protests from local communities, the search for storage options in rocks deep beneath the sea is intensifying. The technology for this already exists and has been employed for decades in various pilot projects.

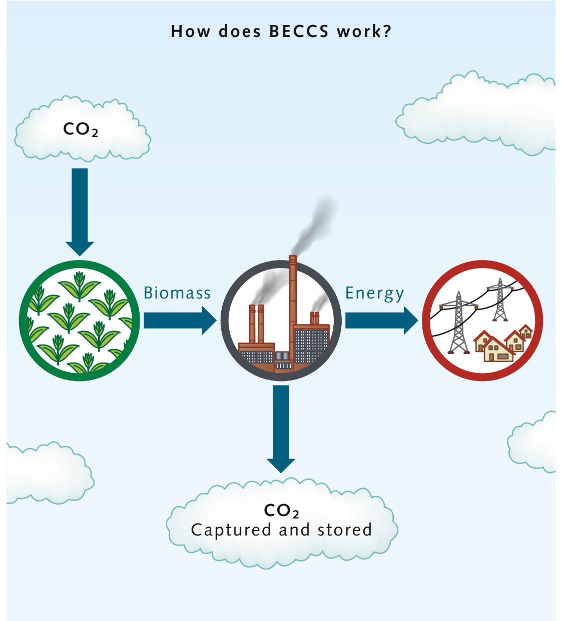
Gas storage in sandstone layers and basalt rocks

> Rock layers at depths of 1000 to 4000 metres underneath the seabed are potential storage sites for carbon dioxide. These can be depleted oil or natural gas fields, or rocks whose pore spaces are presently filled with saltwater. Two approaches are currently being investigated. In one, carbon dioxide is injected into deep-lying sandstone formations, a method already used in the North Sea. In the second approach, the gas is injected into the reactive and porous upper basalt layer of the ocean crust in the hope that it will mineralize there relatively quickly.

Carbon dioxide capture – a technology with a disposal problem

Theoretically, unavoidable residual emissions can be offset by direct removal from the atmosphere of the same amounts of the greenhouse gas carbon dioxide that were originally released. The technology used for this removal is collectively referred to as Direct Air Capture (DAC). However, all the methods for doing this are bound by the requirement that the extracted carbon dioxide be further processed or safely stored. This applies to all carbon dioxide released, including that captured on-site from steel and concrete plants, waste incinerators, or other large emission sources (often referred to as point sources), to avoid its escape into the atmosphere. This technological option for preventing carbon dioxide emissions is termed Carbon Capture and Storage (CCS).

Process emissions
"Process emissions" refers to the release of greenhouse gases that are not a result of the use of fossil fuels and raw materials for producing energy, but are generated by the process-related use of carbonaceous source materials in making certain products. In Germany, process emissions are produced primarily in the glass, lime and cement industries. These make up one-fourth of the industrial emissions.



8.1 > In BECCS, plant biomass is used to generate electricity or heat. CO_2 released in the process is separated and stored or permanently reprocessed.

CCS is not limited to reducing heavy-industry greenhouse emissions from fossil sources. The technology is also a key component of energy and heat production in biomass-fired cogeneration plants with subsequent carbon capture and storage (Bioenergy with Carbon Capture and Storage, BECCS), one of the most important land-based carbon dioxide removal methods to date. Without CCS this process would be just as inconceivable as direct removal of carbon dioxide from the air or water (Direct Air Carbon Capture and Storage, DACCS) would be.

In early 2023 there were 35 plants in operation worldwide for the capture or removal of carbon dioxide. Their combined removal capacity was 45 million tonnes of carbon dioxide per year. This is almost exactly the amount of carbon dioxide that companies in Germany emitted in the course of their industrial processes in the year 2021. Additional removal plants are presently planned or being built. According to the International Energy Agency (IEA), more than 200 new plants have been announced to begin capture or removal operations by the year 2030. Their additional removal capacity adds up to more than 220 million tonnes of carbon dioxide per year.

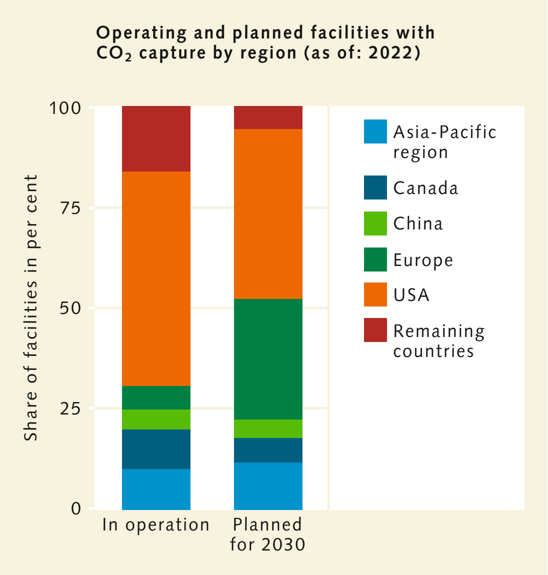
There are now a number of technical methods that can be employed to capture carbon dioxide from gas streams. The most thoroughly tested and widely used capture methods are chemical absorption and physical capture. In chemical absorption, the carbon dioxide reacts with a binding chemical, from which it must then be separated at a great expense of energy. In physical separation, on the other hand, the carbon dioxide either accumulates on a hard surface (for example, on activated carbon) or it is dissolved in a liquid solvent.

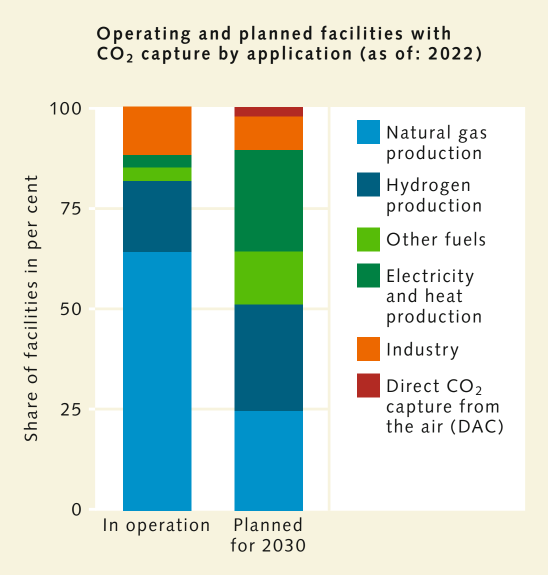
Both chemical and physical capture processes are employed in the course of natural gas production, which currently accounts for around two-thirds of the carbon dioxide captured worldwide. In many places, the natural gas extracted from underground contains not only methane fuel but also carbon dioxide, in proportions ranging from less than three per cent to as much as 80 per cent – the latter, however, only in rare cases. This carbon dioxide must be separated out before the natural gas can be pumped into pipelines as almost pure methane. When the gas is eventually burned carbon dioxide emissions are again produced.

Capture systems are also used in other emission-intensive industrial processes, such as energy and heat generation from fossil fuels and biomass, fertilizer and steel production, refineries, and waste incineration. Furthermore, carbon dioxide capture will be necessary over the long term in the production of blue hydrogen and bioethanol fuel. In the future, greater amounts of carbon dioxide will arise due to the increasing use of direct air capture methods. The world's first DAC plant will begin operations in 2024, and should remove more than a million tonnes of carbon dioxide per year.

CCS will also play a key role in the decarbonization of the cement and lime industries. The production of one tonne of cement clinker (calcium oxide), the main component of cement, generates around 0.8 tonnes of carbon dioxide as a process emission, regardless of the fuel used. If the huge emissions from the cement and lime industry are to be avoided – globally, they amount to over two billion tonnes of carbon dioxide each year – it is important that demand for cement clinker be drastically reduced. But it is also essential to capture those emissions that cannot be prevented, and then to permanently store the gas or use it productively.

The Norwegian cement producer Norcem is presently installing the world's first cement CCS system at its factory in Brevik. It should begin operations in 2024, and will be able to capture 400,000 tonnes of carbon dioxide annually. The gas obtained will then be liquified and transported by ship to a carbon dioxide terminal operated by the *Northern Lights Project* on the western coast of Norway. From there, the liquified gas will be pumped 100 kilometres through a pipeline in the North Sea and ultimately injected into a sandstone formation 2600





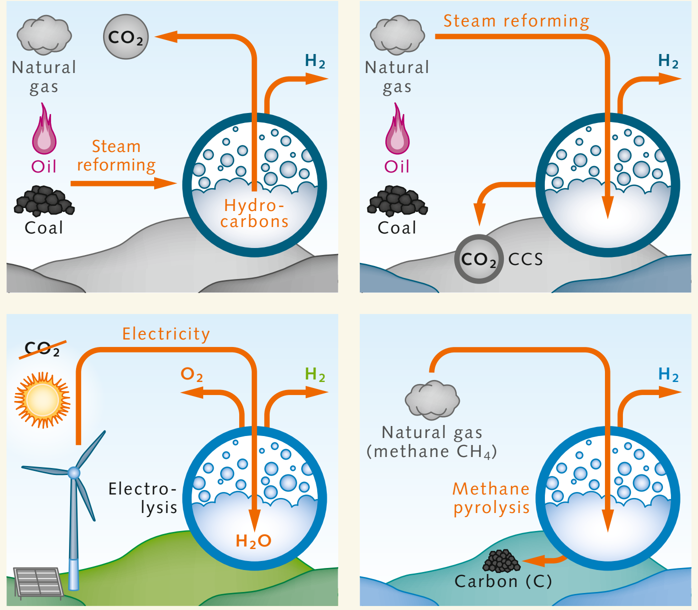
8.2 and 8.3 > Carbon dioxide capture facilities currently operate mainly in the USA, and are mostly associated with the production of natural gas.

The colours of hydrogen

Hydrogen can be produced in different ways. The most common method currently used is steam reforming, by which methane is broken down to produce carbon dioxide and hydrogen. If the carbon dioxide is ultimately released into the atmosphere as a greenhouse gas emission, the hydrogen is termed "grey". But if the carbon dioxide is stored or reprocessed, the hydrogen can be referred to as "blue". Grey and blue hydrogen are both used in industrial processes and for power production.

Blue hydrogen should be replaced by "green" hydrogen over the long term. This is produced by the process of electrolysis, which means that an electrical current is used to split water into its molecular components, hydrogen and oxygen. If the electricity used comes from renewable energy sources, the process is climate-neutral and the hydrogen produced is termed "green".

Another option for making climate-neutral hydrogen is methane pyrolysis using energy from renewable sources. In this method, methane is split into hydrogen and solid carbon. Solid carbon is a granulate that can be safely stored in old mine shafts, for example, and used again later. The climate-neutral hydrogen produced by methane pyrolysis is called "turquoise" hydrogen.



8.4 > The four methods for producing hydrogen are distinguished by their source material, the energy source, the necessary production steps, and ultimately by the balance of emissions.

metres below the sea floor. Large-scale CCS projects are also being planned by cement producers in the USA and Great Britain.

In view of the ambitious plans for facilities to implement carbon dioxide capture and removal, new underground storage capacities will need to be developed worldwide. Hundreds of these development projects are presently planned. The International Energy Agency (IEA) projects that, by 2030, it will be possible to store more than 420 million tonnes of captured carbon dioxide deep underground annually. This storage capacity corresponds roughly to the amount of carbon dioxide that, according to current estimates, can be captured in 2030 and subsequently needs to be safely stored.

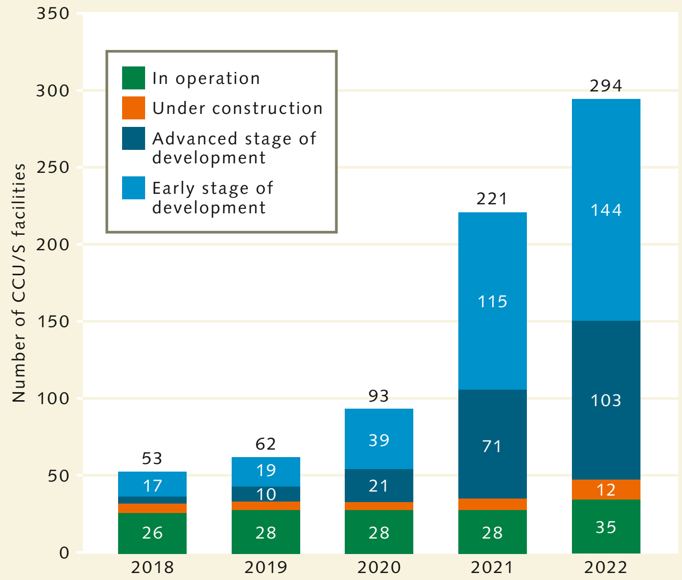
Underground carbon dioxide storage

The pore spaces in rock layers at depths of 1000 to 4000 metres are particularly suitable for carbon dioxide storage. These are found either in depleted oil and natural gas fields or in rocks whose pore spaces are filled with saltwater. In order to be useful for storage, however, the rock layers must be overlain by an impermeable cover or barrier layer. This generally consists of fine clay or salt rock and prevents the escape of stored carbon dioxide from the reservoir rocks.

Whether the barrier is effective or not depends on the local geological conditions. The necessary conditions were not present in Algeria in 2004, when the oil companies BP and Statoil began to inject carbon dioxide from natural gas production into rocks at a depth of 1.9 kilometres. Seven years after beginning the *In Salah CCS Project*, after the operators had injected 3.8 million tonnes of carbon dioxide, the work was discontinued. Geophysical and geochemical control measurements had reinforced the suspicion that injected carbon dioxide might be able to escape from the reservoir rock into the 300-metre-thick barrier layer through pressure-induced cracks and faults in the subsurface. The risk of leakage was too great.

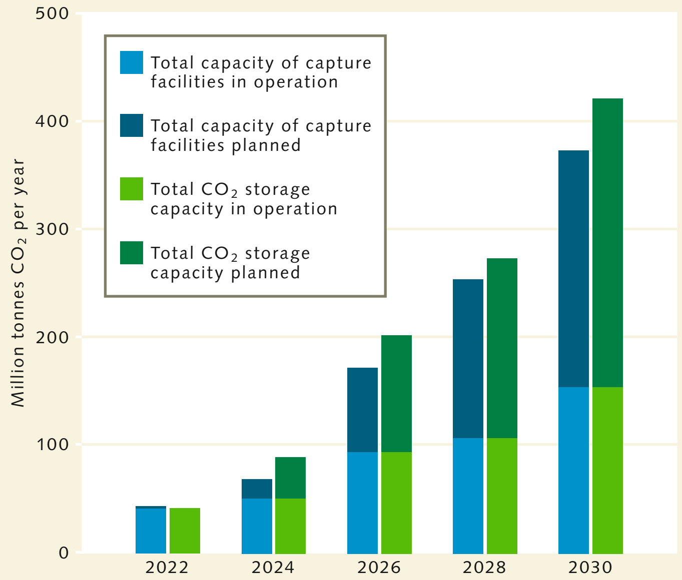
Specialists have learned from the debacle, however, and have incorporated some of the measurement methods

8.5 > High-purity carbon powder is formed during pyrolysis when methane (natural gas) is heated to over 1000 degrees Celsius and split into its elemental components, carbon and hydrogen. The powder is used in the production of many products, from modern building and construction materials to high-tech applications such as energy storage.



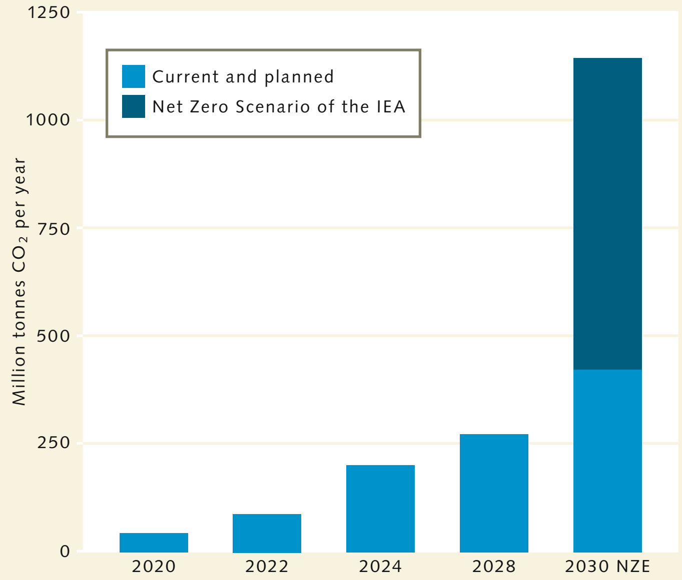
Trends in the number of projects for CO_2 capture from 2018 to 2022

8.6 > Worldwide, the number of facilities planned, under construction or in operation for capturing carbon dioxide rose continuously during the period from 2018 to 2022.



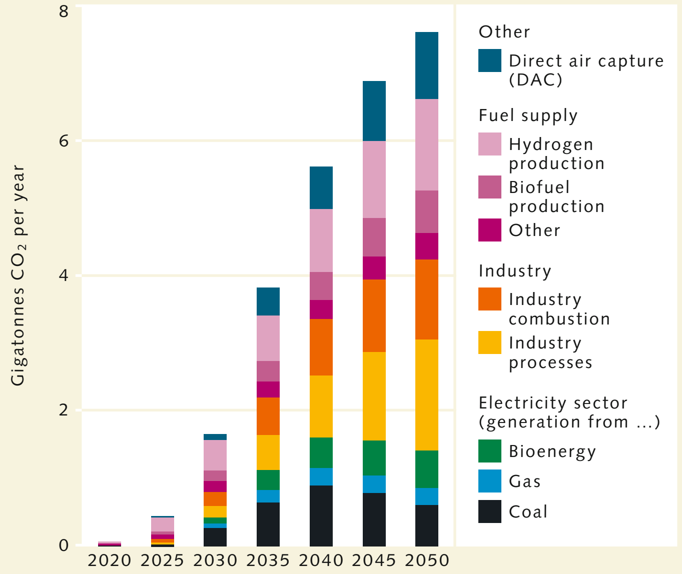
Comparison of current and planned CO_2 capture capacity vs. storage capacity for the years 2022 to 2030 (as of: September 2023)

8.7 > The number of planned development projects for geological reservoirs has also increased significantly. Projections indicate that sufficient storage capacities will be available for captured CO_2 in 2030.



Current and planned CO_2 storage capacity for the years 2020 to 2030 compared to the Net Zero Scenario (NZE) of the International Energy Agency (IEA) (as of: September 2023)

8.8 > There is a large discrepancy, however, between the planned and operational CO_2 storage capacities vs. those that would be necessary for a Net Zero Scenario in the year 2030, according to calculations by the IEA.



Global CO_2 capture 2020 to 2030 in the Net Zero Scenario (NZE) of the International Energy Agency (IEA)

8.9 > According to calculations by the IEA, an estimated 7.6 billion tonnes of CO_2 will have to be captured in the year 2050, of which some 40 per cent are energy and process-related emissions by the industrial sector.

8.10 > This facility captures carbon dioxide from the ambient air and produces fuel from it. It was developed by the Canadian company Carbon Engineering, which is also involved in building the first large DAC plant in the USA.

employed at that time into their manual of relevant preliminary exploration and monitoring methods for geological carbon dioxide reservoirs. When all pressure thresholds are strictly observed in carbon dioxide injection today, at least 99 per cent of the injected carbon dioxide remains in the appropriate rock formations. It is also known, however, that certain geotechnical risks increase during the process of carbon dioxide injection. Pressure changes in the subsurface can trigger earthquakes or cause the land surface to rise. It is also conceivable that, as a result of carbon dioxide injection, pore waters from the deep subsurface could rise up and salinate or otherwise pollute groundwater layers.

For these reasons, plans to inject captured carbon dioxide on land, particularly in densely populated regions, are commonly met with rejection and protests from the local populations. In addition to the lack of public acceptance, however, the high costs and significant energy expenditure for carbon dioxide capture have also contributed to the fact that such processes have only been applied on a large scale in relatively few industrial projects.

A controversial method gaining momentum

Recently, however, attitudes have changed in politics and business. Under increasing pressure to effectively reduce their own emissions, more and more countries and companies are planning to implement CCS. The government of the USA, for example, in its infrastructure law of November 2021, has included more than 12 billion US dollars to be spent for CCS projects and related activities. Of that total, 2.5 billion US dollars are earmarked for search and validation of storage sites, eight billion US dollars for hydrogen production plants – including those for blue hydrogen – and the Department of Energy wants to invest

Carbon dioxide utilization – new ideas with the long-term goal of a circular economy

Captured carbon dioxide can be used either directly or it may undergo various biological or chemical processes prior to being used as a raw material or ingredient in the manufacture of various products (Carbon Capture and Utilization, CCU). Currently, according to the International Energy Agency (IEA), about 230 million tonnes of carbon dioxide are directly utilized worldwide every year. Almost 130 million tonnes are used to make synthetic urea for fertilizers. Oil companies inject an estimated 80 million tonnes into the subsurface in order to extract oil reserves more quickly and as completely as possible (Enhanced Oil Recovery, EOR). The remaining carbon dioxide is utilized in the food and beverage industries or is pumped into greenhouses to enhance plant growth. Carbon dioxide can also be used as an extinguishing agent or refrigerant.

There are some relatively new proposals to use captured carbon dioxide as a carbon source in the production of synthetic fuels for ships and aircraft, for carbon-based feedstocks in chemical industry, or for plastics and construction materials. If these prove to be feasible on a large scale, products containing carbon from captured carbon dioxide could replace materials formerly made from fossil-sourced carbon. The ultimate goal of these ideas would be to establish an added-value chain and circular economy for carbon, in which carbon from coal, oil or natural gas is no longer needed.

For the production of chemicals and fuels from carbon dioxide, the gas must be synthesized with hydrogen. In this way, methanol and other hydrocarbons can be produced that will ultimately be useful in chemical industry or as synthetic fuels. A pilot project for this purpose is being planned at a refinery in Schleswig-Holstein, for example. If chemical industry implements the CCU projects it has already announced, the sector could see an estimated five million tonnes of captured carbon dioxide being used worldwide for fuel production in 2030. However, almost half of the proposed projects are still in the early development stage, and in many locations the pipelines and other infrastructures for transporting hydrogen and carbon dioxide are not yet in place.

Emissions balance – the devil is in the details

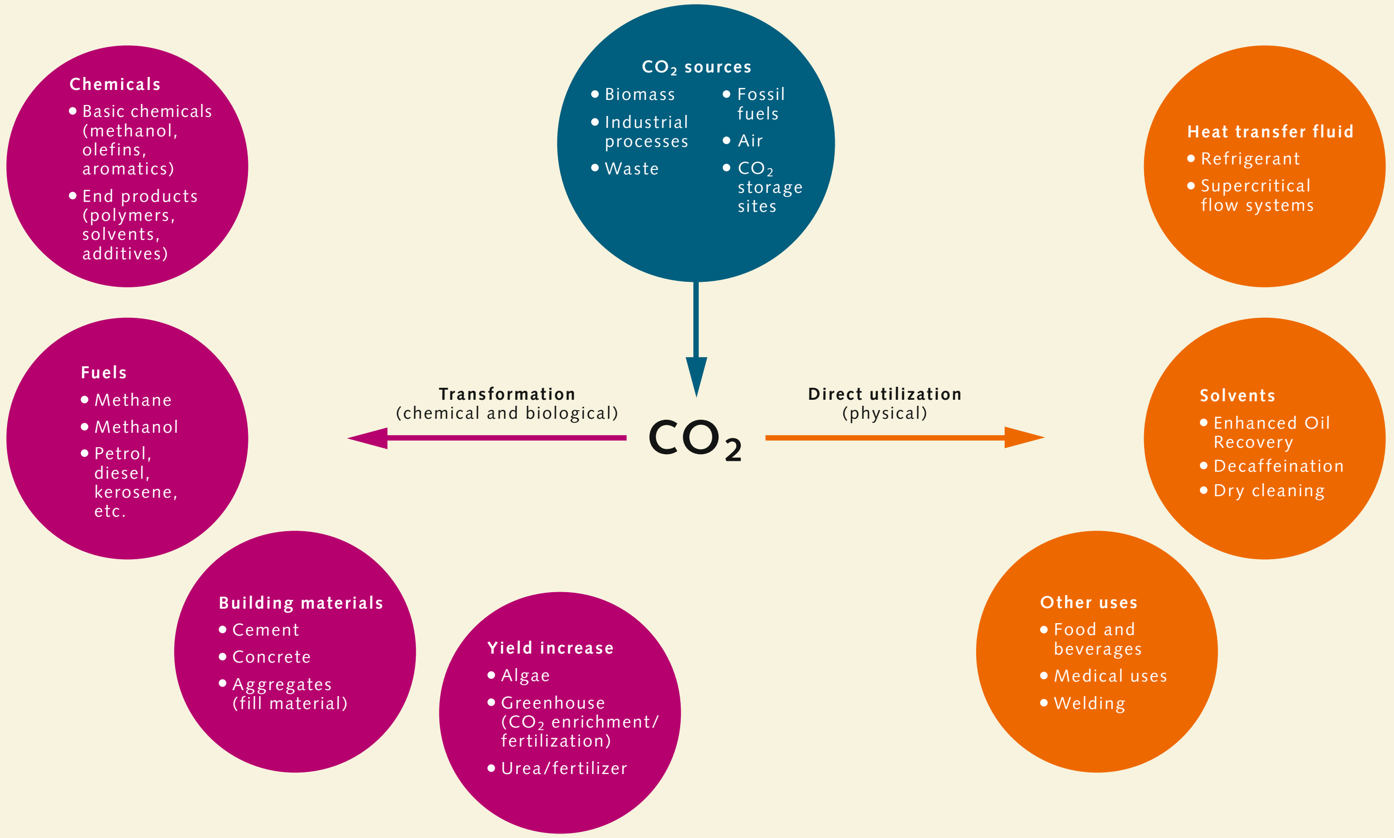
The emissions balances for the various carbon dioxide processing methods are highly complex. The products that are made can only be considered climate neutral if the carbon dioxide used originates from the atmosphere, if green hydrogen is used, and all of the production processes are powered by energy from renewable sources. But even under these conditions, the reprocessing of carbon dioxide can only be designated as permanent removal in a few exceptional cases.

This status requires that the manufactured products be used or recycled over a climate-relevant time period (longer than 100 years), and they must also retain the carbon they contain for that long. However, these two conditions are very rarely met.

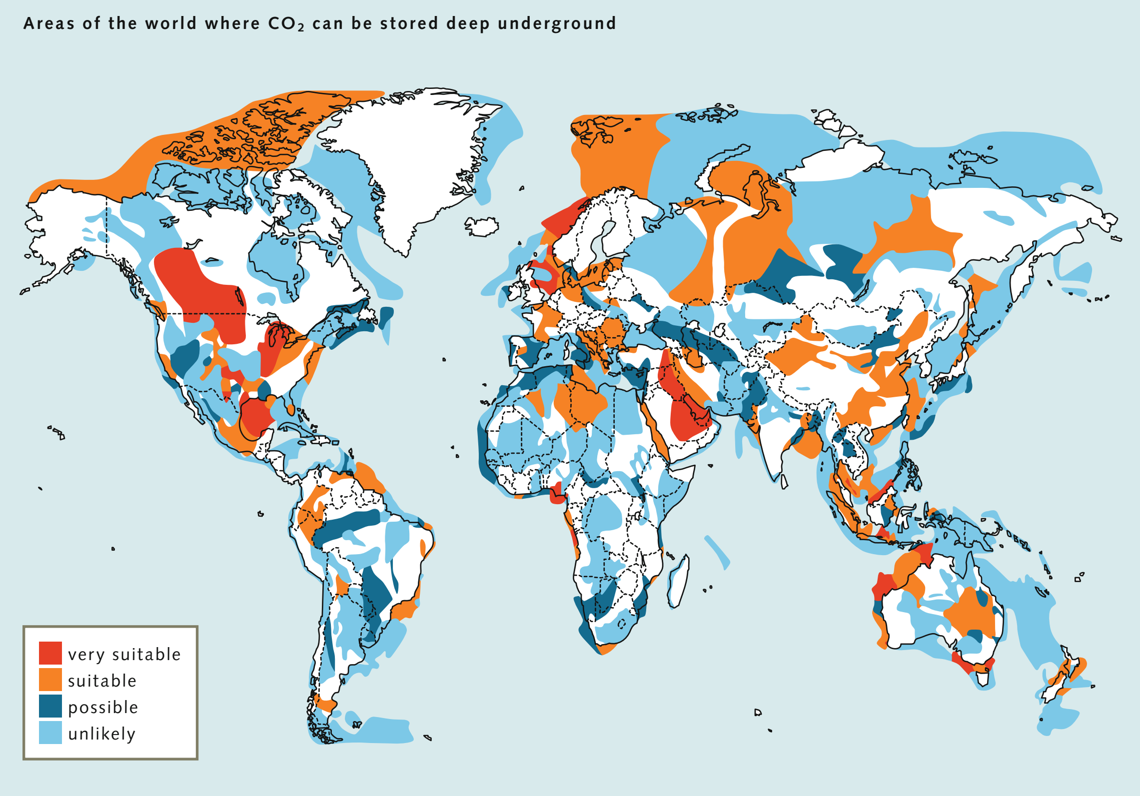
As a rule, CCU products only last for a few weeks or months, and during their use or disposal the carbon they contain is released again in the form of carbon dioxide. This is the case, for example, when the synthetic fuel product is burned in ship motors or airplane turbines. The climate balance of the fuel is only neutral if an equivalent amount of carbon dioxide was removed from the atmosphere to make the fuel as was emitted during its production and combustion.

If the carbon dioxide used in CCU products originates from oil, natural gas or coal, there will even be new emissions created in the long run. This means that only a few of the yet known and applied CCU technologies actually do result in the removal of carbon dioxide. In its development scenario for achieving carbon dioxide neutrality by 2050, the IEA assumes that only about five per cent of the captured carbon dioxide will actually be reprocessed in 2030. The greatest share of the greenhouse gas must therefore be stored underground.

Possible uses of CO_2 excluding the production of fossil fuels (figure after IEA 2019)



8.11 > Captured carbon dioxide, and particularly the carbon it contains, can be used in a large variety of applications. However, to achieve a positive climate effect, the gas or carbon must be processed in such a way that it can no longer escape into the atmosphere.



8.12 > Rock formations with large pore volumes overlain by impermeable barrier layers are especially well suited for the underground storage of carbon dioxide. These conditions are only present in some regions of the world.

more than 200 million US dollars in the development of new storage technology. Canada has introduced tax incentives for CCS projects, Denmark has committed to CCS subsidies of five million Euros, and Norway has pledged investments equivalent to 100 million US dollars. That money will be spent for the construction of three large hydrogen production plants. The European Union is already funding four CCS projects with money from its Energy and Innovation Fund, including a BECCS project in Stockholm, Sweden, a cement factory in France, a facility for producing hydrogen in Finland, and a factory for producing hydrogen, ammonia and ethylene in Belgium. Seven additional CCS projects have reached the second round in this funding competition.

According to new government plans, Great Britain aims to capture around 20 to 30 million tonnes of carbon dioxide in its industrial sector starting in the year 2030, and to inject the bulk of the gas underground in at least two storage projects (*East Coast* and *HyNet*). The governments of Japan, China, Malaysia, Indonesia and Australia are also supporting the search for and development of geological carbon dioxide storage and the associated infrastructures. In Australia the oil companies Chevron Australia and Exxon have already been operating the *Gorgon CCS Project* since 2019. This involves natural gas retrieved from offshore reservoirs and transported to land through a pipeline. The carbon dioxide it contains is then separated out and injected beneath Barrow Island off the northwest coast of Western Australia.

The oil-producing countries of North Africa and the Middle East are also pursuing CCS expansion plans. Three facilities for carbon dioxide capture are already operating in the region – one each in the United Arab Emirates, Saudi Arabia and Qatar. New storage projects are in the planning stage. The future outlook for CCS has never been better than it is now, according to the annual report for 2022 by the Global CCS Institute. Overall, however, the think tank draws a sobering conclusion: Global efforts to reduce greenhouse gas emissions, including investments in CCS, are still woefully inadequate.

Environmental and climate activists sharply criticize government support for CCS, especially for projects promoted by oil- and gas-producing companies to capture and store carbon dioxide from the burning or processing of fossil resources. The critics argue that such projects are examples of “greenwashing” and serve only to unnecessarily delay the phaseout of fossil-fuel use. The CCS opponents say that if all the green energy needed to capture carbon dioxide from fossil sources in a climate-neutral way were fed directly into the power grid, it would probably be sufficient to end the generation of electricity from coal, oil and natural gas. Other experts point out that CCS is indispensable if carbon dioxide removal methods such as BECCS and DACCS are to be employed at industrial levels. They assert that efforts in the search for storage sites, along with infrastructure and technological development, would thus have to continue.

According to the German Energy Agency (dena) around 34 to 73 million tonnes of carbon dioxide would have to be captured and stored in deep rock layers annually in the Federal Republic of Germany for the country to achieve its goal of greenhouse-gas neutrality by 2045. Because political obstacles make the technical storage of carbon dioxide on land practically impossible in many places, experts are now increasingly considering storage in the geological subsurface beneath the seas.

This could be feasible with the help of two approaches. In the first, compressed or liquified carbon dioxide would be injected into deep-lying sandstone formations, a procedure that is possible in all marine regions where these very common formations are found. By the second method, liquified carbon dioxide or carbon dioxide dis-

8.13 > At this liquefied natural gas plant on Barrow Island, Australia, carbon dioxide is captured during natural gas processing and injected underground some distance away at a depth of two kilometres.

8.14 > Since 1996, in the ***Sleipner Project*** of the Norwegian oil company Equinor, around 0.9 million tonnes of carbon dioxide have been captured annually during natural gas processing and subsequently stored deep beneath the North Sea.

Mechanisms for storing carbon dioxide in the deep subsurface

Structural trapping

An impermeable cap rock prevents the carbon dioxide from escaping upward from the reservoir rock.

Capillary/residual trapping

A large part of the CO_2 is trapped in the pore spaces between sand grains.

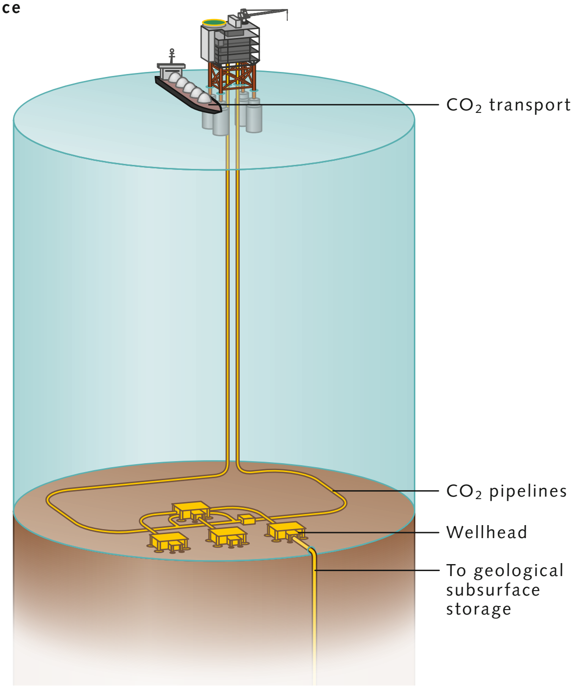
CO_2 dissolution

Over time, the injected CO_2 dissolves in the salty pore waters of the reservoir rock. The CO_2-rich water becomes heavier and sinks downwards.

Mineralization

The carbon dioxide dissolved in water reacts with minerals contained in the reservoir rocks, is transformed to dissolved bicarbonate, and is finally precipitated in the form of carbonate minerals. The former carbon dioxide is then firmly bound within these.

The stored CO_2 must be monitored using a variety of technologies during and after injection.



8.15 > Four mechanisms contribute to the feasibility of carbon dioxide being stored in deep-seated rock formations. The gas is not truly safely stored, however, until it dissolves in the pore waters and is ultimately mineralized.

solved in seawater would be injected into the highly reactive, porous upper basalt layer of the ocean crust or into rocks called flood basalts. The former are found primarily at the mid-ocean ridges. The latter can also occur near the coasts.

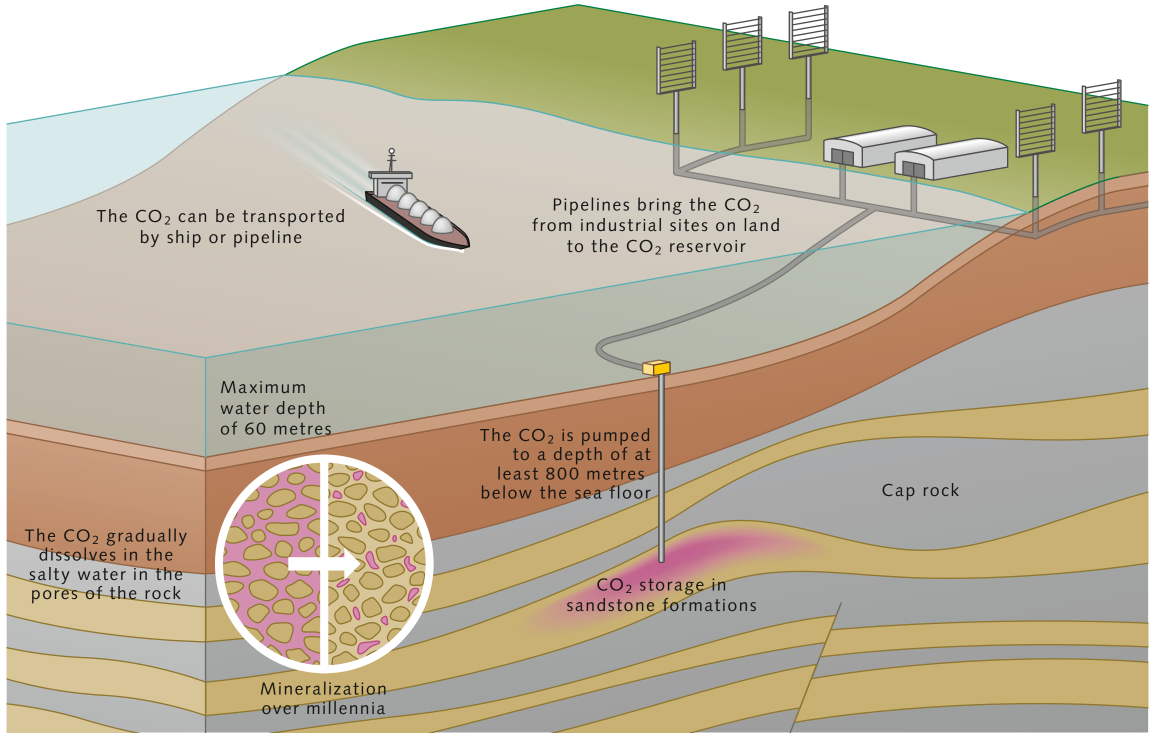
Carbon dioxide storage in sandstone formations

Sandstone formations that can be considered feasible to use as geological carbon dioxide reservoirs are found both on land and in the deep subsurface below the ocean floors (800 metres and deeper). Compared to other rocks, these sedimentary rock layers are more permeable and contain pores between the individual sand grains through which the injected carbon dioxide can disperse. A prerequisite for permanent storage in this case is also that the reservoir rock is capped by a suitable trapping layer composed, for example, of clay or salt. This kind of layer seals the reservoir rock and prevents the injected carbon dioxide from escaping upwards.

If a storage site fills these and some other geological requirements, the captured carbon dioxide can be compressed, liquified if appropriate, and injected through one or more boreholes into the storage formation. There, the carbon dioxide disperses into the rock pores that are filled with saline water. Geologists refer to this salty pore water as formation water. Because the injected carbon dioxide is lighter than the formation water, it tends to rise in the reservoir rocks. It collects at the highest point below the sealing cap rock and remains there as long as the cap rock is truly impermeable.

Over time, the carbon dioxide dissolves in the formation water. The resulting solution is heavier than water, and the carbon dioxide no longer rises towards the surface. Finally, the carbon dioxide dissolved in the water reacts with minerals contained in the sandstone and is converted to dissolved bicarbonate. In this form, the introduced carbon no longer has any harmful climate impact, even if the dissolved bicarbonate should escape into the sea. How fast the carbon dioxide is converted into bicarbonate depends upon how many reactive minerals are present in the reservoir rock. The bicarbonate eventually precipitates to form solids in which the introduced carbon is permanently bound. However, it can take

8.16 > Captured and compressed carbon dioxide can be transported to the injection site via pipeline or ship.



many thousands of years for this process to be completed.

Carbon dioxide storage projects in the North Sea

The North Sea has many areas that could be considered suitable for the storage of carbon dioxide in the deep subsurface. Calculations indicate that around 150 to 190 billion tonnes of carbon dioxide could be stored in underground sandstone formations if the Norwegian and Barents Seas are included. As a shelf sea, the waters of the North Sea are not especially deep. Its maximum depth in German waters is just 60 metres, which would make the construction or installation of injection facilities on platforms and the seabed comparatively easy.

Some North Sea countries are already injecting carbon dioxide deep into the sea floor or will soon begin to do so. It began with the Norwegian oil company Equinor (formerly Statoil) in 1996. After the Norwegian government introduced a national carbon dioxide tax in 1991, the company stopped releasing the carbon dioxide contained in the natural gas into the atmosphere, and began separating it on-site on the offshore production platforms and injecting it into sandstone formations deep below the platforms. Since 1996, in what is known as the *Sleipner Project*, around 0.9 million tonnes of carbon dioxide have been pumped into the subsurface every year.

Furthermore, in the *Snøhvit Project* in the Barents Sea, the company has been discharging around 0.7 million tonnes of carbon dioxide deep below the sea since 2009. This shows that the storage of carbon dioxide in the deep subsurface of the North Sea has been technically possible for decades. Furthermore, specialists have gained a high level of experience and knowledge in carrying out these kinds of storage projects in deep-lying sandstone formations.

Other companies and countries have begun to follow Equinor's example because increasing prices for carbon dioxide emission allowances are gradually making a profitable business out of its storage deep underground in the ocean. Capturing one tonne of carbon dioxide, transporting it by pipeline to the marine area, and pumping it into the subsurface costs an estimated 80 to 200 Euros, depending on the location of the site. In the year 2022, the allowance for emitting the same amount of carbon dioxide into the atmosphere cost around 80 Euros. Numerous new projects for storing carbon dioxide in the subsurface of the North Sea are presently being planned and implemented, for example off the coast of Rotterdam (The Netherlands), in the Danish and British zones of the North Sea, and below Norwegian waters. In each case, sandstone formations are investigated that are either saturated with saltwater (for example, *Sleipner* and *Snøhvit*) or from which natural gas and oil have previously been extracted.

Because industrial emission sources like cement plants or waste incineration plants are not usually located at the same place as possible utilizers of the captured carbon dioxide or near storage sites, this carbon dioxide must be transported. In the *Sleipner Project* in the Norwegian North Sea, the carbon dioxide is captured and injected directly on-location at the natural gas production site at sea, while in the *Snøhvit Project* in the Barents Sea the carbon dioxide is transported from a processing plant on land to the injection wells through pipelines on the sea floor. Transport by pipelines or ships is also planned for the storage of carbon dioxide in the Norwegian *Northern Lights Project* in the North Sea, and in further projects off the coasts of The Netherlands, Denmark and Great Britain.

CCS today is planned and implemented cooperatively

Although CCS projects in the past were primarily planned and implemented for an individual facility for the capture of carbon dioxide with its own downstream transport and storage system, in recent years, regional alliances of companies have been forming to develop and use joint transport and storage infrastructures (such as pipelines, port facilities, intermediate storage facilities, storage sites). A prominent example is the CCS project of the Port of Rotterdam, in which many of the companies that operate there are taking part. A similar association has formed in Houston, Texas. There, 14 companies are currently working on the construction of a large CCS infrastructure, mostly oil-producing companies and the chemical giant Dow. They want to capture carbon dioxide in their refineries and plants in the Port of Houston, feed it by pipeline into the Gulf of Mexico and inject it deep into the subsurface there.

Other companies are planning cross-border carbon dioxide transportation networks, on land and in the sea, in order to transport the greenhouse gas from the capture plants at point sources to the final storage sites. In the future, the oil company Santos, for example, wants to transport captured carbon dioxide from the northern Australian city of Darwin for injection into the maritime territory of the neighbouring island state, the Democratic Republic of Timor-Leste, through a pipeline previously used for natural gas.

8.17 > Outside the port of Rotterdam, captured carbon dioxide will be injected into a depleted gas field under the North Sea beginning in 2026. This, however, will be mostly to store carbon dioxide from fossil sources, which only prevents additional emissions. There is no actual removal of CO_2 from the atmosphere.

In Europe, the companies Wintershall Dea and Equinor want to build a carbon dioxide pipeline extending from Wilhelmshaven on the German North Sea coast into the Norwegian North Sea. Parallel to this, specialists in other projects are investigating whether it would be feasible to deploy tankers with load capacities of 30,000 to 70,000 cubic metres to transport captured carbon dioxide cost-effectively from more distant sources to storage facilities off the coasts of Norway and other shelf-sea states.

The risks of storing carbon dioxide in sandstone formations beneath the sea

Based on the experience gained from ongoing carbon dioxide storage projects and on research from the past two decades, scientists know very well the risks associated with the injection of carbon dioxide into sandstone formations beneath the seas. These include four main hazard issues, as follows:

- a portion of the carbon dioxide injected into the subsurface rises along faults or through the boreholes and escapes at the sea floor (leakage);
- very salty formation water, as well as heavy metals or other materials that it may contain and are harmful to the environment, escape at the sea floor and impact local ecosystems;
- pressure changes within the reservoir rocks reactivate existing geological faults and trigger earthquakes, which could endanger the stability and functionality of infrastructures located on the sea floor;
- marine mammals are disturbed or possibly harmed by noise that is made during the search for suitable storage formations, in construction of the facilities, or in subsequent monitoring of the storage site.

Which of these risks actually develops into a problem and to what degree depends on the local conditions, which must be thoroughly investigated in advance of any carbon dioxide storage project.

When carbon dioxide or formation water escapes from the seabed

As a rule, the sea floor of the shelf sea is not a tightly sealed surface. On the contrary, natural gas seeps out of the seabed in some places. In the North Sea, around one and up to a maximum of 70 tonnes of natural gas is released per year per seepage site. The origin of this gas is not always evident. It can either be formed by microorganisms living within the sea floor or it may rise along natural faults from gas reservoirs deep in the subsurface. In addition to this, in the North Sea natural gas escapes through old wells at a rate of one to 19 tonnes per leakage site per year.

As yet, there are no known carbon dioxide leaks at modern wells that were specially drilled for the purpose of carbon dioxide storage. Likewise, in the Norwegian storage projects, which have been operating for many years, no carbon dioxide has yet been released at the sea floor. However, in choosing storage sites, the possible existence of faults and other sediment structures in the subsurface through which the carbon dioxide and possibly formation water could rise to the surface has to be investigated. At the same time, it must be determined whether old wells are present and, if so, whether they are properly sealed.

In the preliminary stages of a carbon dioxide storage project beneath the sea, it is also crucial to chemically analyse the formation water in the selected reservoir formations. Based on the results, it will be possible to assess the environmental risks that could arise if the formation water should escape from the sea floor, along with the heavy metals or other environmentally harmful substances it might contain.

CO_2 release experiments on the sea floor of the North Sea show that escaping carbon dioxide is immediately dissolved in the near-bottom seawater, thus changing the chemical properties of the water. The seawater in the vicinity of the discharge site becomes acidified, which affects the living conditions, especially for mussels and other carbonate-forming creatures. The area affected by the acidification is comparatively small (approxmately ten to 50 square metres), if roughly an equal amount of carbon dioxide is released as the natural gas seeping from the North Sea leakage sites mentioned above.

When carbon dioxide storage sites in the marine realm are rigorously surveyed and selected, it is expected that only a very small amount of carbon dioxide would be able to escape from the storage facility when it is properly operated. It is presumed that more than 99 per cent of the stored carbon dioxide would remain underground over the long term.

Nevertheless, leakage must be prevented to the greatest extent possible. Effective early-warning and monitoring systems are necessary to detect deviations from the expected storage performance in a timely manner so that appropriate countermeasures can be taken. In recent years, great progress has been made in the research, testing and commercial application of monitoring technology. Monitoring technologies for the offshore sector in particular have been tested and further developed. In experiments by the specialists carrying out the testing, carbon dioxide was released on or in the sea floor to determine the effectiveness of a particular technology or method in detecting the escaping carbon dioxide. In one experiment in the British North Sea, sensors were able to detect carbon dioxide released at the very low rate of six kilograms per day in the sediment and in the water column.

On the whole, according to experts, a wide range of monitoring technologies is now available that can be used on a large scale for carbon dioxide storage. However, advances in technology are still possible and desirable, for example in the areas of sensor technology, data management and intelligent autonomous systems, including autonomous underwater vehicles. To date, these have limited autonomous decision-making capabilities, and can only travel along preprogrammed routes. What is needed, however, are fully autonomous underwater vehicles capable of acting intelligently in real time in response to sensor readings. Work is already underway to develop the required technology. If this could be implemented in the near future, the costs of monitoring storage sites would be reduced.

Engineers are also placing great hopes in fibre-optic-based monitoring systems. These would use fibre-optic cables with multiple sensors attached. The cables can be laid on the land surface, placed in the ground along pipelines or on the sea floor, and run directly into deep boreholes, so that both the injection and the storage of carbon dioxide can be closely monitored. Depending on the sensors selected, various parameters can be recorded in close temporal succession. Free carbon dioxide or carbon dioxide dissolved in water can thus be directly identified. The fibre-optic cables will also be used to determine the pressure, temperature and gas saturation in the pore spaces as well as seismicity and deformation in the subsurface. If the optical fibre is used as a geophone, seismic measurements can also be obtained. All that is currently lacking is informative long-term experience in the application of such monitoring cables, especially regarding the durability of the fibres and sensors in a harsh environment. For this reason, the application of these methods and others is being tested and further developed in a joint European research project. According to experts, their use in combination with conventional monitoring methods is already practical today. Over the long term, the cables could even completely replace conventional monitoring technology. The costs for the construction and use of such fibre-optic cables are comparatively low.

When carbon dioxide injection triggers motion in the subsurface

When carbon dioxide is injected into reservoir rocks, the pressure in the rock formation is increased. This can activate existing faults in the formation. This means that at some locations, cracks in the rock can expand or rock layers can be displaced relative to each other. As a result of such movements in the subsurface, paths could be created through which the stored carbon dioxide and the formation water rise and eventually escape at the sea floor.

In marine regions where earthquakes already occur naturally, pressure changes in the reservoir rocks could cause changes in the subsurface tension. This could then trigger earthquakes, which would endanger the stability of wind turbines or pipelines. A carbon dioxide pilot reservoir at Nagaoka, in the province Niigata, Japan, withstood

8.18 > For the exploration and monitoring of carbon dioxide reservoirs beneath the sea, airguns must be employed. The noise they produce likely poses a great danger and causes stress for harbour porpoises and other marine organisms.

a strong earthquake with an intensity of 7 with no damage. However, drawing conclusions about other storage sites is only possible to a limited extent, because the individual site-specific conditions need to be considered.

Whether on land or at sea, potential sites for storing carbon dioxide deep underground must be thoroughly examined. 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 feasibility for carbon dioxide storage.

Noise pollution for whales, fish and other animals

In the search and exploration for suitable carbon dioxide storage sites in the marine subsurface, the same geophysical methods are used as those employed in the search for oil and natural gas reserves. These include, among others, active seismic methods in which, for example, airguns are towed through the water by ships. These send out a series of sound waves that penetrate deep into the substrata and are differentially reflected by the rock layers. Through the transmission and reflection of the sound waves, scientists are able to map the form and structure of the subsurface.

The drawback to airguns is that their sound waves have an impact on marine life that is not yet well understood, especially on noise-sensitive North Sea inhabitants such as harbour porpoises. Because harbour porpoises depend on acoustic signals for orientation, as well as for communication and in searching for food, underwater noise influences their behaviour and, over the long term, could drive them out of their native habitat. Very high sound levels at certain frequencies can also injure and possibly even permanently harm the animals. The same is true in other shelf seas for the native marine mammals and other animals.

Based on this knowledge, and considering the already generally increasing noise levels in the coastal seas, it is essential to recognize the risks of high-intensity noise for marine organisms and to develop appropriate protection measures. The risks of increased noise produced during the search for storage sites must be considered, as well as sounds caused by injection and monitoring. In the same vein, noise levels must be taken into account in marine spatial planning – for example, in determining whether or not otherwise suitable rock strata underlying marine protected areas should be permitted for carbon dioxide storage.

Low-noise monitoring methods that are available include, for one, passive seismic techniques. These involve the placement of highly sensitive devices on the seabed that silently record both naturally occurring seismic events and those caused by carbon dioxide injection. A consideration here, however, is that where passive seismic measuring devices are placed on the seabed they need to be protected from destructive activities. Fishing and the anchoring of ships and boats may have to be prohibited in these areas.

Mounting claims upon the North Sea

With shipping, wind parks, fisheries, pipelines, and natural gas production, the German North Sea and many other marine regions are already being intensively utilized by human societies. But most of the areas are also important habitats for diverse marine species that must be protected and preserved through the designation of marine protected areas. To avoid conflicts with marine conservation and other uses, potential carbon dioxide storage sites need to be integrated into marine spatial planning.

To date, however, marine spatial planning for German waters only takes into account the use of the seabed, the water column, and the air space above it. Furthermore, an expanded use of the marine subsurface at different depths is not mentioned in the revised specifications that came into force in 2021. But the debate is under way among experts on how carbon dioxide storage can be integrated into Germany's marine spatial planning.

Carbon dioxide storage in reactive basalt rocks in the upper ocean crust

In addition to the Earth's sandstone formations, iron- and magnesium-rich rock layers are also viewed as possible carbon dioxide storage sites. Scientists refer to these as "mafic" or "ultramafic" rocks, terms derived from the element symbols "Ma" for magnesium and "Fe" for iron.

Magmatic rocks are particularly rich in iron and magnesium. This is especially true for basaltic volcanic rocks, either solid or unconsolidated. They are widely distributed, occurring on land (e.g. in India, Australia, Canada, and South Africa) as well as in the sea floor. The Earth's upper oceanic crust, for example, is composed of basaltic rocks.

If you imagine dark cobblestones when you hear the word basalt, then you do actually have basalt rock in mind. The rocks of the upper 100 to 400 metres of ocean crust, however, have little to do with the dense, fine-grained rocks that are used to pave marketplaces or driveways. By contrast, these rock layers are highly porous, and in places are riddled with millimetre-sized bubbles and cracks.

This open-pored structure develops early in the formation of the six- to eight-kilometre-thick ocean crust. The crust is generated in areas called spreading zones, such as the Mid-Atlantic Ridge. These are zones on the Earth where two tectonic plates move slowly apart while hot magma from inside the Earth flows out between them. When it comes into contact with cold seawater, the surface of the magma abruptly cools and solidifies. In the process, the structure of the rock near the surface is fundamentally altered. In many places, bubbles, fissures or shrinkage cracks are formed. This creates a network of tiny hollow spaces and pathways, which from then onwards pervade the upper part of the basalt rock.

Seawater circulates through this subsurface network of pores. The upper 400 metres of basalt rock is like an extensive conduit system for fluids (liquids and gases). It constitutes the largest water-bearing rock formation (aquifer) on earth, directly beneath the ocean. Its pore spaces thus offer sufficient storage volume for the injection of enormous amounts of liquified carbon dioxide or carbon dioxide-rich water, according to specialists.

There is a distinct advantage to storing carbon dioxide in basalt rocks rather than in porous sandstone formations. Because of their chemical composition, alkaline basalt rocks react relatively quickly when they come into contact with carbon dioxide-rich solutions. The magmatic rocks contain minerals such as olivine, plagioclase, pyroxene and volcanic glass. These, in turn, contain the primary components calcium, magnesium and iron, among others.

If seawater is enriched with carbon dioxide or if injected carbon dioxide slowly dissolves in the pore waters, the water is acidified and becomes "sparkling water". When water in this state comes into contact with the basalt rock, the acid in the water corrodes the basalt surface, dissolving out the iron, magnesium and calcium components. These then react with the dissolved carbon dioxide to form carbonates, which initially remain dissolved in the water. But as the dissolution reaction continues, the water will eventually become oversaturated, and the carbonates will precipitate out to form carbonate minerals such as calcite, dolomite or ankerite. These, simply put, are mineral rocks in which the former carbon dioxide is tightly bound, in the best-case scenario, for many millions of years.

Scientists refer to this process as the mineralization of carbon dioxide. It proceeds much more rapidly and thoroughly in mafic rocks than in sandstone formations, where the injected carbon dioxide remains for a very long time as a separate phase (liquified carbon dioxide) or dissolved in the formation water. A further positive aspect of basalt rocks is that natural mineralization can be technically accelerated through the systematic input of more carbon dioxide.

Successful project on Iceland

The amount of carbon dioxide that can theoretically be stored in the upper ocean crust has not yet been thoroughly investigated, and any estimates of its capacity are therefore fraught with huge uncertainties. Currently, however, experts believe that the theoretical mineral carbon dioxide storage capacity of the mid-ocean ridges of our planet is many times greater than the amount of carbon dioxide that would be released by the burning of all the Earth's fossil resource deposits. And potentially suitable rock layers are found not only on the mid-ocean ridges but also in areas known as flood-basalt provinces, which often form underwater plateaus with high porosity or a high proportion of vesicles.

Since 2014, captured carbon dioxide dissolved in water has been injected into the upper ocean crust as part of the *CarbFix Project* in Iceland. The volcanic island lies directly on the Mid-Atlantic Ridge, so that young, still-warm and thus quite reactive basalt rocks can be accessed through comparatively shallow boreholes. The mineralization rates are correspondingly high. Because of the high reactivity of Iceland's hot crust, around 98 per cent of the injected carbon dioxide mineralizes and is thus per-manently bound in the subsurface within two years. *CarbFix* has said that by April 2023 it had injected more than 90,000 tonnes of carbon dioxide into the Earth's crust, although the process has consumed a great deal of geothermal energy and large quantities of fresh water.

An example calculation: In order to dissolve one tonne of carbon dioxide in water using the *CarbFix* procedure, a pressure of 25 bars and a water temperature of 25 degrees Celsius are required. Given the present state of research, it is difficult to estimate the amount of additional energy required for the water injection. This uncertainty factor is not of crucial importance in Iceland because the availability of renewable geothermal energy is practically unlimited. But this is far from the case in other regions. Experts therefore advise that for future storage projects in which these injection methods are considered, the costs and the availability of large amounts

8.19 > Iceland is an island where the young, reactive rocks of the upper ocean crust rise above the sea surface – recognizable by the black basalt rocks of these steep coasts.

8.20 > This pipeline is part of the *CarbFix Project* in Iceland. Since 2014, captured carbon dioxide dissolved in water has been injected into the upper ocean crust there.

of water and energy need to be taken into account during the planning stage and must be included in cost-benefit assessments.

Large basalt deposits in the deep sea

Because there are only a few places in the world where the ocean crust rises out of the water above sea level (e.g. on Iceland and the Azores), science is turning its attention to greater water depths where there are tens of thousands of kilometres of mid-ocean ridges with young, reactive basalt crust in which carbon dioxide could be stored.

This idea is reinforced by the fact that high pressures exist at greater water depths. The pressures can help to facilitate dissolution of the injected carbon dioxide in seawater that is circulating in the basalt crust, resulting in denser and heavier water – or they can promote the liquification of the carbon dioxide. The density increase is such that at a pressure of 280 bars or greater (water depths below around 2800 metres) carbon dioxide would be heavier than the seawater at a comparable depth, and no longer able to rise out of the sea floor. Thus, carbon dioxide leakage from the subsurface would be improbable, but there would be a residual risk depending on the local temperature and pressure conditions.

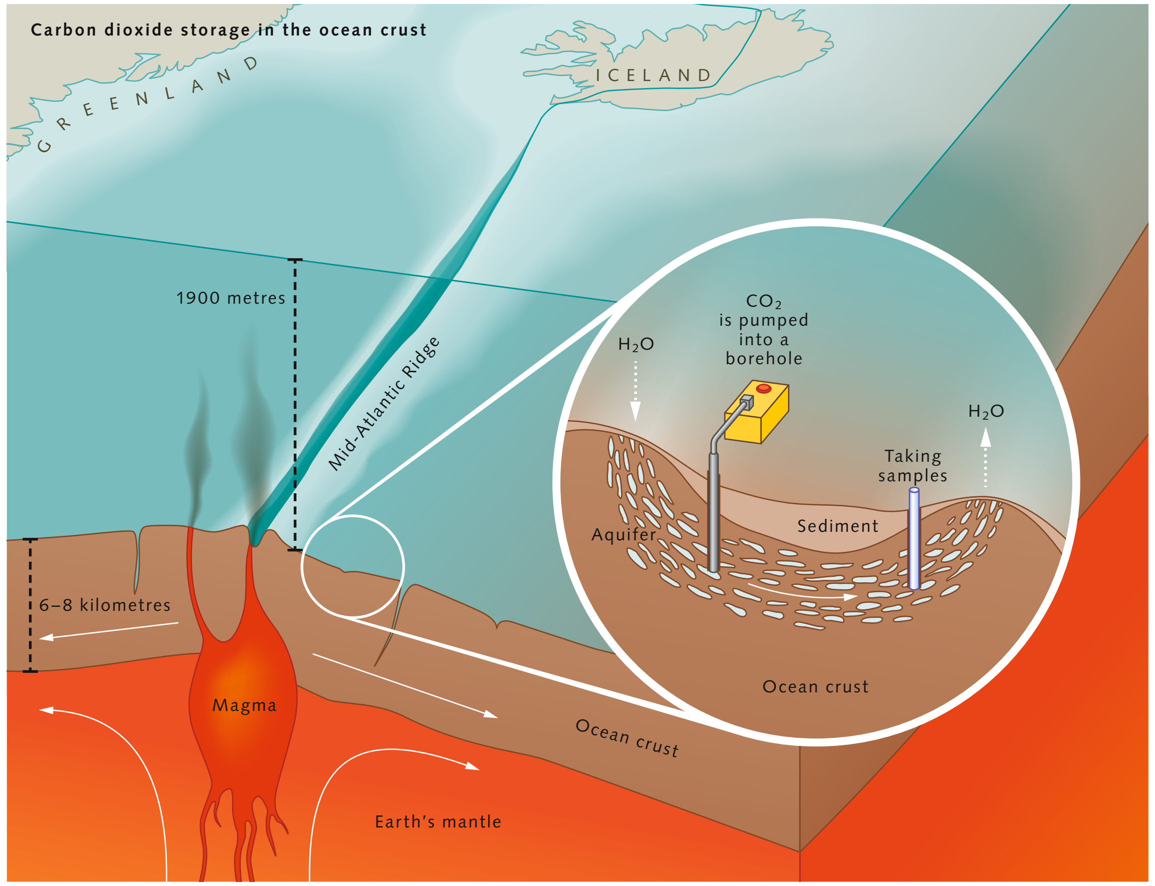
In order to be able to completely rule out the possibility of leakage over time, only basalt layers that lie beneath a layer of sediment several hundred metres thick should be selected as carbon dioxide reservoirs in the future. At large distances from the coasts, this sediment layer consists predominately of very fine clay material, which provides an effective seal for the basalt layer.

Their typically large distance from any coasts would represent still another advantage for storage at mid-ocean ridges. If the injection of carbon dioxide into the upper basalt layer of the ocean crust should trigger small earthquakes, which cannot be ruled out, their occurrence in the depths of the ocean would not endanger people or infrastructures. On land, by contrast, they would present a risk.

Carbon dioxide storage in the deep-sea subsurface, however, would also have certain disadvantages. In the cooled basalt crust, injected carbon dioxide would mineralize at a significantly lower rate than in warm rocks such as those on Iceland. In addition, many aspects of working in the deep sea would be very costly and would be pushing the limits of technical feasibility.

Due to this complex situation, the objectives of potentially storing carbon dioxide in the upper part of the ocean crust must be carefully weighed. The most cost-effective method would certainly be to dissolve carbon dioxide in seawater and inject it into the ocean crust at shallow water depths and low concentrations with high mineralization rates – as is already being done on Iceland. The few areas where a mid-ocean ridge rises above sea level, however, are generally located far from the industrial centres where large volumes of carbon dioxide are produced. The greenhouse gas would therefore have to be transported over long distances in liquified form before it could be injected into the basalt rocks.

If, on the other hand, the liquified carbon dioxide were to be injected directly into the pore spaces of the basalts at greater water depths, there would be additional advantages beyond the larger number of potential storage sites. It would also be possible to store large amounts of carbon dioxide within a short time, which, due to the ambient pressure and temperature conditions, would automatically remain in the reservoir rocks, even though it would mineralize very slowly there. The rate of mineralization, in turn, could be increased by mixing the carbon



8.21 > To test whether carbon dioxide storage in the deep sea is a technically feasible and economically viable process, scientists are conducting a deep-sea research experiment on carbon dioxide storage on a cooled flank of the Mid-Atlantic Ridge.

dioxide with seawater to dilute it – then again, with this approach it would take significantly more time to inject a given amount of carbon dioxide, because the ocean crust on the ridge flank is colder than at *CarbFix* on Iceland, for example.

Research intensifies to fill gaps in knowledge

The range of options for storing carbon dioxide in the upper basalt layer of the ocean crust is currently being examined in a number of research projects. The researchers want to find out:

- whether all theoretical prior considerations on carbon dioxide storage in the upper oceanic crust are correct and appropriate, and whether carbon dioxide injection into the deep sea floor is actually feasible;
- what concentration and amount of carbon dioxide should be injected into the basalt rocks to achieve optimal reaction processes;
- how fast injected carbon dioxide would disperse and mineralize in the rocks;
- what procedures could be used to reliably monitor the storage site over the long term and what costs they would entail;
- whether there are possible pitfalls in the conceptual considerations that have not yet been taken into account and
- whether carbon dioxide storage in the deep sea would be a more sustainable, effective, and long-term cost-effective option compared to storage on land or in the deep sandstone formations beneath the shelf seas.

These research projects are being carried out at *CarbFix* on Iceland, on the Vøring Plateau off the coast of Norway, in the Cascadia Basin off the west coast of Canada, and on Reykjanes Ridge a few hundred kilometres south of Iceland. The different project teams are working closely together and sharing scientific data on the structure, composition and geochemical processes taking place in the basalts. This knowledge is critical to determining, with the subsequent help of computer models, how much carbon dioxide can be stored at which sites in the upper ocean crust, the costs that will be incurred in the process, and what technical environmental problems, risks and damages might be involved. A concrete search for suitable sites can only begin when these numerous questions have been answered, and when society makes the conscious and informed decision to store carbon dioxide in the upper ocean crust.

The legal framework for storage of carbon dioxide under the sea

Injecting carbon dioxide into the basalt layer of the upper ocean crust or into deep-seated sandstone formations involves intervention into the ocean floor, and thus into a legal landscape that is governed by the provisions of international maritime law. Experts also point out that, under certain conditions, CCS projects in the sea could result in the escape of carbon dioxide and formation water from the sea floor and cause harm to marine ecosystems. The legal framework for carbon dioxide storage in the subsurface beneath the sea must therefore also pay particular attention to the requirements of marine environmental protection.

The provisions of international maritime law

From the perspective of international maritime law, the initial question that arises is whether states are allowed to store carbon dioxide in the seabed and, if so, where they can do it. Answers to this question are provided by the United Nations Convention on the Law of the Sea (UNCLOS). It divides the sea into different zones within which the rights of the coastal states are precisely defined.

These include:

- the internal waters and territorial seas of a state,
- the contiguous zone,
- the exclusive economic zone (EEZ),
- the continental shelf,
- the high seas and „the Area“ (the sea floor in international waters).

8.22 > On Iceland, the path of the Mid-Atlantic Ridge can be observed with the naked eye. This rift exists because the Eurasian and North American tectonic plates are moving away from each other here.

Because the internal waters and territorial seas are subject to the sovereignty of the individual coastal states, these can freely approve CCS projects there and regulate them as they wish. The legal situation becomes more complex when extended to the exclusive economic zone (EEZ), which borders on the territorial sea, and the continental shelf. These are zones in which the coastal state is only assigned particular, although exclusively sovereign, rights and jurisdictional powers. These include, among others, the exclusive right of a coastal state to drill into the marine subsurface and to construct tunnels on its continental shelf. According to experts, this also infers the exclusive right of the coastal state to subject the storage of carbon dioxide on its continental shelf to its national law, to regulate such storage under its own laws and to enforce the national provisions.

No state possesses exclusive rights in the zones designated as high seas and deep-sea floor (or simply “the Area”). At sea, both in the water column and on the seabed of international waters, the principle of freedom of the high seas is in effect. An exception to this is the research and exploitation of mineral resources on the sea floor. These activities are subject to regulation and oversight by the International Seabed Authority (ISA), which is based in Kingston, Jamaica.

The storage of carbon dioxide in the marine subsurface of the high seas, on the other hand, falls under the regime of the high seas. This gives every state the basic right to inject and store carbon dioxide in the subsurface in international waters.

Aspects of marine protection under international law

By signing the UN Convention on the Law of the Sea, all Parties have committed to protecting and preserving the marine environment. The provisions laid out in the Convention apply to all marine zones and are chiefly aimed at preventing pollution of the sea. There is now an overwhelming consensus that the precautionary principle should apply. This means that the requirements for marine environmental protection are in force when the mere possibility of pollution is present.

For a long time, it was questionable whether the injection of carbon dioxide into the marine subsurface should be considered as pollution of the seas or dumping of substances. However, these questions were resolved at the international level in 2006. Since that time, the Protocol to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter – which specifies the standards of the Convention on the Law of the Sea – has permitted the underground storage of carbon dioxide on the continental shelf of a coastal state and in other areas of the marine subsurface, provided permission is given by the appropriate authority under the relevant national law.

In order to meet the requirements of the precautionary approach, the signatories agreed to develop specific guidelines for the application of Carbon Capture and Storage. A new annex to the London Protocol now specifies three conditions that must be met when issuing the required storage permit:

- *First,* carbon dioxide may be introduced into subsurface rock formations, but not into the water column.
- *Second,* the stored gas must consist mostly of carbon dioxide.
- *Third,* the addition of other substances to the carbon dioxide intended for storage, with the purpose of disposing of these as well, is prohibited.

The London Protocol requires the Parties to meet these three requirements before the issuance of a storage permit. Moreover, the approval of carbon dioxide storage does not absolve the Parties from making further efforts to reduce the need for undersea storage.

Where the injection of carbon dioxide into the seabed is allowed, the responsible state authority must require a listing of all other substances contained in the carbon dioxide stream. Otherwise, it cannot issue a permit. Among other things, the listing must contain information on the composition, form, total amount, origin, properties, toxicity, stability and bioaccumulation potential of all substances. If the required list is incomplete or not sufficiently accurate, such that a full assessment of the risks to human health cannot be made, the injection cannot be approved.

In addition, the London Protocol requires the signatories to draw up a national action list. This should describe how the carbon dioxide stream in question and its components can be tested, for one, with respect to possible impacts on human health and the marine environment. Secondly, threshold values must be established for every substance so that a decision can be made in each individual case as to whether these are met and whether the injection of carbon dioxide can therefore be permitted. If the thresholds are not met, conditions can be imposed or the injection may be prohibited altogether.

The London Protocol also makes stipulations for the selection of the storage site. Among others, the physical, chemical and biological parameters of the water column and the marine subsurface must be evaluated, as well as any special aspects of the site and the economic and operational feasibility. When assessing the potential impacts of carbon dioxide storage, not only must the impacts of injection into the marine subsurface be considered, but also any possible disposal alternatives on land.

The impacts of carbon dioxide storage, and any work associated with it, on human health, the marine environment and other uses in the ocean should be assessed as conservatively as possible, and should also take into account contingencies such as accidents. If the assessment indicates that the impacts are too hazardous, approval should be refused. However, refusal is not mandatory.

If approval is granted for the undersea storage of carbon dioxide, the London Protocol requires the establishment of a monitoring and surveillance programme. This is to ensure that the previously assumed conditions and impacts are actually valid. Permits issued are to be reviewed regularly based on the monitoring results. If the actual developments do not correspond to the prior assumptions, the approval may be revoked.

The signatories to the London Protocol have also adopted a framework for risk assessment and risk management in relation to carbon dioxide storage in the marine subsurface. This specifies the application or implementation of monitoring requirements, and is intended, among other things, to assist official decision-making under conditions of scientific uncertainty. With respect to site selection the framework requires, for example, that storage capacity, storage security, sustainability and potential leakages as well as their effects be documented.

In the assessment of consequences for the marine environment, the sensitivity of native species and the impacts on human health, among other things, should be analysed, and the related temporal and spatial scope must be indicated. With the aid of control measurements within the storage reservoir, in the overlying marine subsurface, and at the seabed, leakages should be recognized in a timely manner and their occurrence avoided through preventive measures, but there should also be advance planning for reaction measures in case of an emergency. Even after shutdown of the borehole, the storage site should continue to be directly monitored over the long term. With growing certainty over time that carbon dioxide is not escaping from the deposit, the frequency of the measurements can be gradually decreased.

May states export carbon dioxide for offshore injection?

Whether carbon dioxide injection into the seabed is permissible at all must be distinguished from the question of whether international law allows sequestered carbon dioxide to be exported to other states for storage. Under Article 6 of the London Protocol the signatories are prohibited in principle from exporting waste and other substances to other states for dumping or incineration at sea or in the sea floor.

Article 6, however, was amended in 2009 with specific regard to the cross-border export of carbon dioxide for the ultimate purpose of storage. Because the amendment has not yet been ratified by a sufficient number of states, it has not yet entered into force. In 2019 the signatories to the Protocol therefore agreed that Article 6 can be applied provisionally.

The provisional application of an agreement in international law, however, requires a corresponding declaration by the individual state. Such a declaration has so far only been submitted by Norway, The Netherlands, Denmark and South Korea. Finland and Belgium are currently preparing these (as of: September 2022). If Germany wanted to export captured carbon dioxide to one of these two states, it would also have to submit the appropriate declaration. Moreover, if applied provisionally, the amended Article 6 of the London Protocol requires the conclusion of a specific agreement between the exporting and importing state.

Based on this legal framework, experts conclude that the signatories to the London Protocol have established all of the legal requirements for the storage of carbon dioxide in the marine subsurface and also that it may be exported for this purpose. Final decisions on the legitimacy of storage and possible carbon dioxide transport, however, will continue to be made at the national level.

How the legal framework will be applied at the national level for member states of the European Union currently also depends on the EU Carbon Capture and Storage Directive. This allows the geological storage of carbon dioxide in the territories of the EU member states, in their Exclusive Economic Zones (EEZ), and in their continental shelves, as defined by the UN Convention on the Law of the Sea. However, every storage project must be approved by the appropriate national authority.

In August 2012, the German government transposed this EU directive into national law in a very restrictive manner, in part in conjunction with the German Carbon

Capture and Storage Act (German: *Kohlendioxid-Speicherungsgesetz, KSpG*). The Act currently presents a two-pronged obstacle to carbon dioxide storage projects in the German North and Baltic Seas. Firstly, it contains a clause stating that proposals for approving carbon dioxide storage must have been submitted by the end of the year 2016. Secondly, the federal legislature grants Germany's federal states the right to exclude certain areas from possible carbon dioxide storage.

The federal states of Mecklenburg-Western Pomerania, Lower Saxony and Schleswig-Holstein have exercised this right to exclude all marine areas under their authority from subsurface carbon dioxide storage. By doing so, they have virtually imposed a ban on underground carbon dioxide storage in the coastal area of the German North and Baltic Seas.

Article 44 of the Carbon Capture and Storage Act requires that an evaluation report be produced every four years on the application of the Act and the national and international experience acquired with regard to Carbon Capture and Storage (CCS). In the current second evaluation report produced in 2022, the authors concluded that the applicable German legal framework at that time prevented the actual application of CCS in practice. At the same time, the report points out that CCS and CCU technology could contribute in varying degrees to Germany achieving its goal of greenhouse-gas neutrality by the year 2045.

The importance of procedures for carbon capture and storage, or subsequent processing, is currently (as of: summer of 2023) being discussed in the debate on a German carbon management strategy. This strategy shall include the determination of potential areas of application for CCU and CCS technology as well as the development of economic and regulatory frameworks for its rapid and large-scale implementation.

In this context, Germany's federal government recommends an expansion and adaptation of the Carbon Capture and Storage Act such that it provides a suitable legal basis for CCS and CCU, from the source of the carbon dioxide to its transport and ultimate permanent storage or use. This legal framework is urgently needed. A draft amendment to the German Climate Change Act stipulates that the storage of carbon dioxide deep underground should become an integral part of national climate policy and that, for the first time, storage targets should be set for the years 2035, 2040 and 2045 (as of: June 2023). The goals of climate protection, which include greenhouse-gas neutrality by 2045 and net carbon dioxide removal after 2050, should also be enshrined in the Act.

Pressure for action also comes from a new initiative of the EU Commission. In March 2023, the Commission announced its intention to establish by the year 2030 geological capacity for long-term storage of 50 million tonnes of carbon dioxide. The plan is part of the new Net-Zero Industry Act of the Commission, in which CCS is identified as a bridging technology for sustainable development.

In the proposed legislation, the Commission would require European Union member states to publish timely data on areas where carbon dioxide storage sites could be approved, and to report annually on the progress made in developing carbon dioxide storage projects in their territories. The necessary exploration and development work would be undertaken and financed by oil- and gas-producing companies. Simply put, this means that oil and gas producers are held accountable by policymakers. The companies rather than the states should explore more geological reservoirs to ensure the necessary storage capacity for at least 50 million tonnes of carbon dioxide per year.

The reactions to this proposed legislation were divided. While proponents of CCS welcomed the initiative, critics pointed out that it is much more important to fundamentally restrict the generation of greenhouse gases. All efforts should therefore be directed toward appropriate technologies and changes in behaviour rather than relying on CCS.

One thing is certain: the political and societal debates on CCS will continue in the coming months and years, and will very probably lead to new regulations and laws, particularly in Germany.

CONCLUSION

Carbon dioxide storage beneath the sea – a controversial practice on the horizon

Carbon dioxide can be captured either directly from the air or from exhaust streams. Both approaches are now playing an increasingly important role in the development of climate policy. Their application is hoped to offset residual emissions from industry and agriculture that are difficult to avoid, or to prevent their release in the first place. Moreover, carbon dioxide removal methods like widely-discussed combined electricity and heat production in biomass-fired cogeneration plants can similarly only contribute to offsetting emissions if the carbon dioxide produced during combustion is captured and then further processed into durable products, such as carbon fibres, or is safely stored. Carbon capture and storage (CCS) technology is therefore of vital importance in achieving the goal of greenhouse-gas neutrality by the year 2050.

The number of capture facilities operating worldwide is steadily increasing, but it is uncertain where the carbon dioxide that is removed can be permanently stored. Experts agree that most of the gas cannot be further processed over the long term, but instead must be stored, preferably underground in rock layers that are sealed by an impermeable cap rock to prevent the carbon dioxide from escaping upwards. On land, there is strong resistance to such storage plans in many locations because the injection of carbon dioxide could increase the risk of earthquakes and of groundwater pollution.

Experts are therefore now directing their search for suitable storage rocks more toward the marine subsurface. The two most promising candidates here are sandstone formations and the porous upper basalt layer of the ocean crust. The technology for carbon dioxide storage in sandstone formations has been implemented successfully since 1996, mostly in Norwegian waters. To date, carbon dioxide has only been injected into the upper ocean crust in Iceland, because the basalt rocks there rise above sea level and are thus easily accessible. In contrast, there is still much that is not known about the storage potential of basalt rocks in the deep ocean subsurface. This is now being studied in various research projects.

One fundamental difference, however, is already known: Carbon dioxide injected into sandstone may linger for many thousands of years in the pore waters of the rock before it mineralizes and is safely bound in solid form. In the more reactive basalt rocks, on the other hand, the processes that facilitate mineralization operate much more rapidly.

Carbon dioxide injection beneath the sea is not without its risks. Reservoirs must be thoroughly investigated, carefully selected, and ultimately monitored for an extended time and in an environmentally responsible manner (noise). Furthermore, under some circumstances the injection of carbon dioxide may also conflict with other kinds of marine utilization in the area.

Legally, carbon dioxide storage under the sea is regulated, for the most part, by new guidelines in the Protocol to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol). For example, it establishes what may be injected and how the monitoring of the storage site should be ensured. The final decision on approval of proposed projects, however, rests with the national authorities who are responsible for implementing the London Protocol at the national level.