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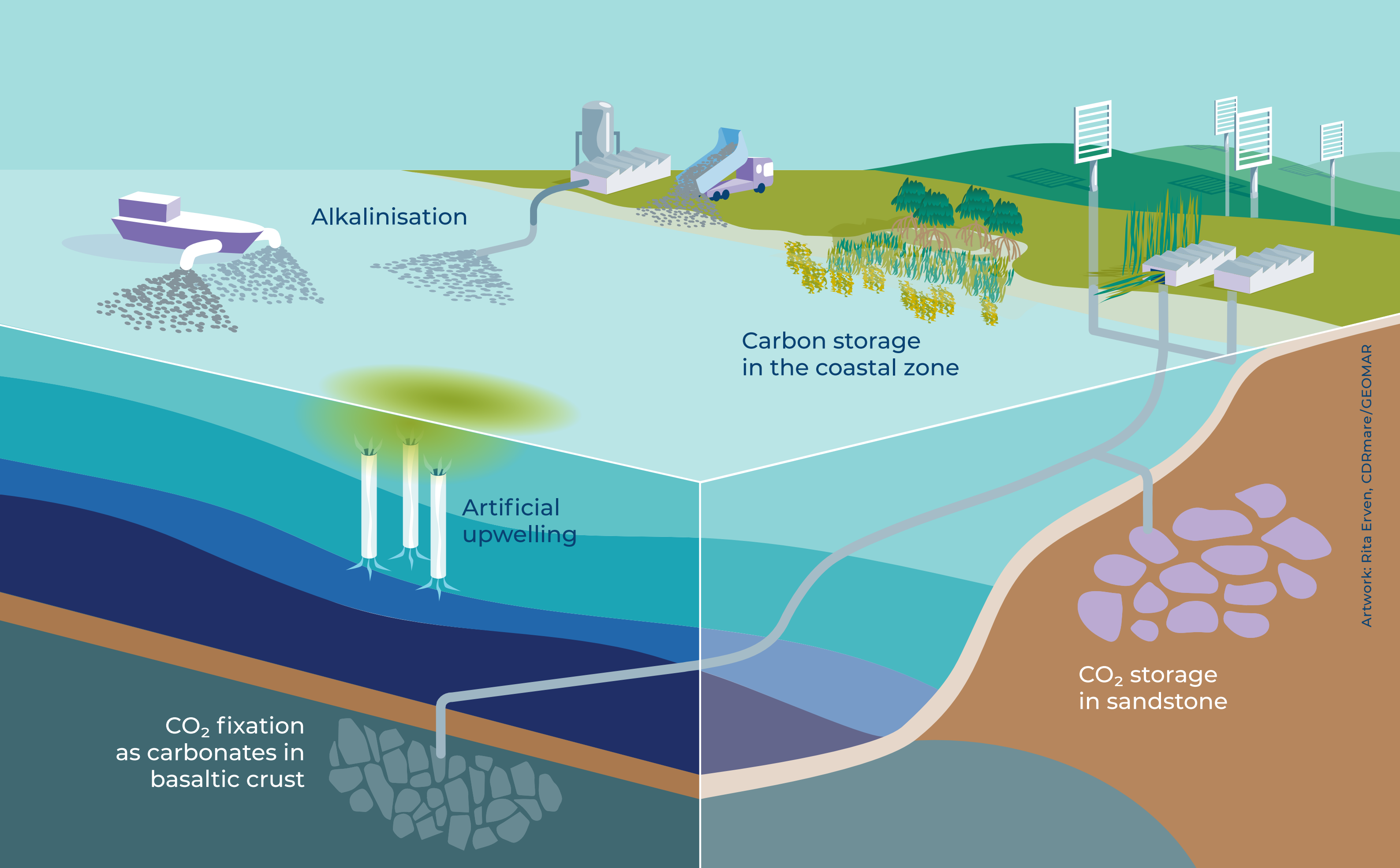
DAM GERMAN MARINE RESEARCH ALLIANCE

Federal Ministry of Education and Research

Carbon dioxide removal

What are the opportunities of ocean-based methods? And how do we explore them?



KNOWLEDGE SUMMARY

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VERSION FEBRUARY 2024

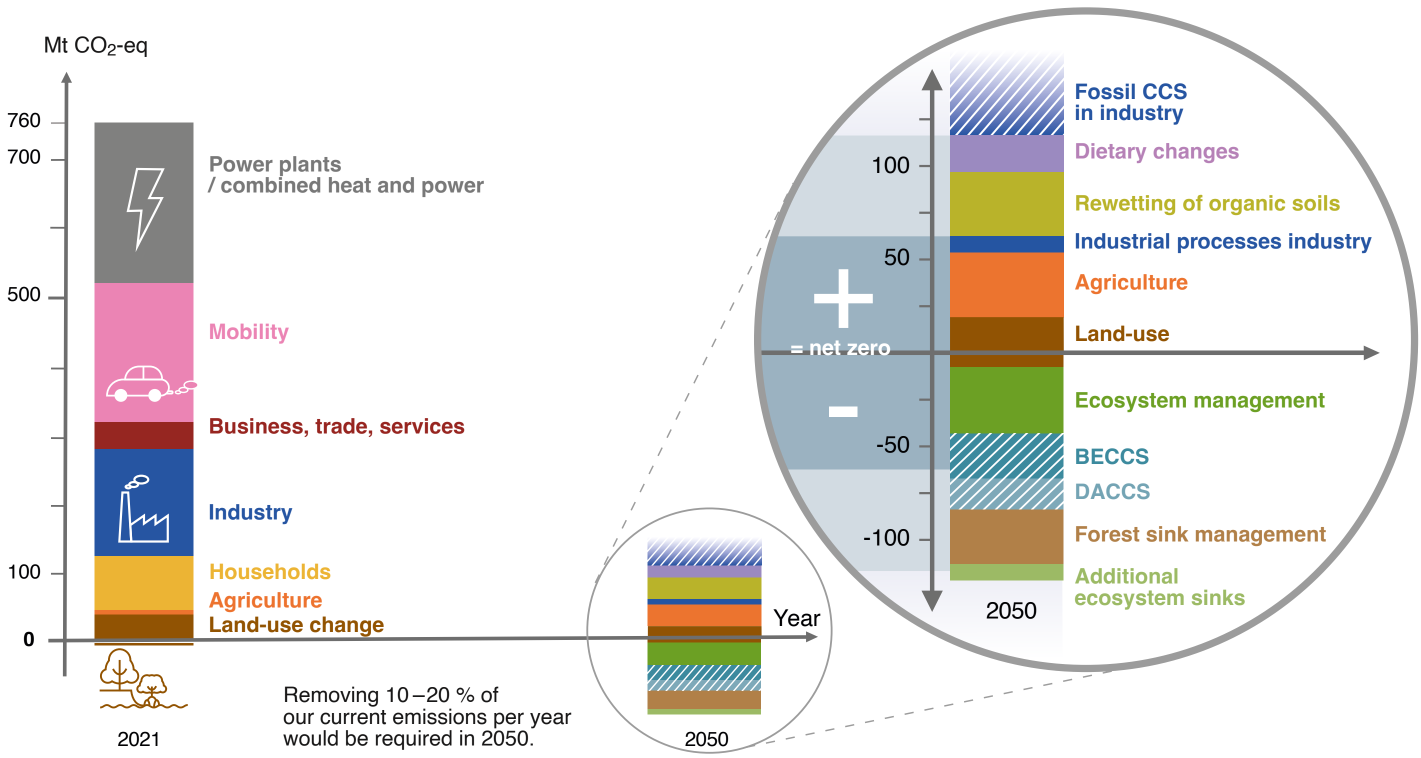
Background I: Societal pressure to act

Removing carbon dioxide from the atmosphere: urgently needed

Even with ambitious climate policies, Germany is still expected to release 10 to 20 percent of current greenhouse gas emissions within the next three decades, further driving global warming. One solution is to compensate these emissions through targeted carbon dioxide removal and storage.

The challenge: Net Zero carbon dioxide emissions

- There is a **consensus** in scientific climate research that humanity will only curb global warming and the resulting climate impacts and risks if it reduces its **carbon dioxide emissions** into the atmosphere to **net zero**.
- Human-caused carbon dioxide emissions result from the **burning of fossil fuels** such as oil, natural gas, and coal, and from **changes in land use**. So far, nobody knows how humankind can avoid 100 percent of these emissions in the future in an environmentally and socially responsible way.
- On the contrary, experts assume that Germany will still be emitting **residual carbon dioxide** and other greenhouse gases in the middle of the 21st century. In optimistic scenarios, their level is estimated at **10 to 20 per cent of current emissions**. This corresponds to annual emissions of about 60 to 130 million tonnes of greenhouse gases, most of which are methane and nitrous oxide.
- However, there is still **no social consensus** on how high possible residual emissions may be and which sectors may cause them. Currently, residual emissions are difficult to avoid, for example, in cement production, air and heavy goods transport, but also in agriculture and waste incineration.



Nadine Mengis, Rita Erven after: Anne Merfort, Miodrag Stevanović, Jessica Strefler (2023): Energiewende auf Netto-Null: Passen Angebot und Nachfrage nach CO_2-Entnahme aus der Atmosphäre zusammen? Kopernikus-Projekt Ariadne, Potsdam.

This graphic compares the emissions of the Federal Republic of Germany from the year 2021 with an emissions scenario for the year 2050, in which the country achieves its goal of a net zero emissions. The prerequisites for this are the avoidance of large quantities of emissions, a reduction in emissions in sectors that cannot completely avoid greenhouse gas emissions, and the removal of carbon dioxide from the atmosphere with the help of nature-based and technical approaches.

In search of: strategies for offsetting residual emissions

- Residual emissions will need to be offset with **some type of CO_2 removal** from the atmosphere. In addition, the release of some residual emissions can be prevented if the carbon dioxide is captured at the emission source and subsequently stored geologically. This is important for those industrial sectors that cannot currently avoid emissions of fossil origin. However, companies are not allowed to refer to the capture of carbon dioxide from fossil sources as carbon dioxide extraction. Here, a clear distinction must be made between prevented emissions and the quantities of carbon dioxide actually removed from the atmosphere.
- Many carbon dioxide removal and storage approaches are land-based. Since land is already a scarce resource, **ocean-based approaches** are being increasingly explored.

Ocean: what is its carbon dioxide uptake potential?

- The Earth's climate system has **physical, chemical, and biological processes** that remove carbon dioxide from the atmosphere and store it on land, in the ocean, or in the geological subsurface. The world ocean utilises these processes to such an extensive degree that it has buffered very large changes in atmospheric carbon dioxide concentrations throughout Earth's history. Because of its natural CO_2 uptake capacity, the **ocean is a major player in the global carbon cycle**. However, CO_2 uptake processes in the ocean and ocean floor occur on **long time scales**. Various proposed methods could accelerate such processes and thereby increase the ocean's carbon dioxide uptake rate.

CDRmare: Research provides answers

- In the interdisciplinary **research mission CDRmare**, researchers investigate a **broad spectrum of marine approaches for carbon dioxide removal and storage**.
- The scientists view the **ocean as a global, interconnected system**: changes in one area lead to interactions with other linked sub-areas and forms of use (e.g. fisheries and tourism). Only on the basis of a holistic research approach can the **potentials, costs, and risks** of human-enhanced carbon dioxide uptake by the ocean be realistically evaluated. It is important to understand which methods are applicable at all, under which local and global conditions they work, and which approaches should ultimately be eliminated. In this context, science has the task of providing **public and transparent information**. Which solutions may be used in the future must be negotiated politically and in society as a whole in an open debate.

The six CDRmare research consortia

- The research mission of the German Marine Research Alliance (DAM) CDRmare is composed of **six consortia**, in which various methods of marine carbon dioxide removal and storage are investigated and subsequently evaluated together with external experts. Important to know: All methods have **different carbon dioxide removal and/or storage potential** and have varying degrees of **technological readiness**.
- The six consortia are:
  - Carbon dioxide removal by alkalinity enhancement: potential, benefits and risks (RETAKE).
  - Searching for solutions for carbon-sequestration in coastal ecosystems (sea4soCiety).
  - Submarine carbon dioxide storage in geological formations of the German North Sea (GEOSTOR)
  - Road testing ocean artificial upwelling (Test-ArtUp)
  - Alternative scenarios, innovative technologies, and monitoring approaches for sub-seabed storage of carbon dioxide (AIMS³).
  - Assessment framework for marine carbon dioxide removal and synthesis of current knowledge (ASMASYS).

All marine research conducted within the mission is subject to German and international environmental regulations.

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Biological methods

Increased carbon storage through the expansion of marine meadows and forests

Coastal vegetated ecosystems, such as salt marshes, seagrass beds, mangrove, and kelp forests, grow on less than one percent of the ocean and coastal area, but contribute a significant portion of the natural carbon sequestration in the seabed, as well as many other ecosystem services. Plans to expand these valuable coastal habitats to enhance their natural carbon dioxide uptake sound promising. But how realistic are they really and in what ways can coastal ecosystems be expanded in a targeted way? The research mission CDRmare provides answers and ideas for solutions.

The big climate goal: a net zero of carbon dioxide emissions

> There is a consensus in climate research: even with ambitious climate policies, Germany is still expected to release **10 to 20 per cent** of current greenhouse gas emissions by the middle of the 21st century and will continue to drive global warming.

> In order to compensate for these residual emissions, humankind will either have to capture the carbon dioxide directly at its source or remove it from the atmosphere to the same extent.

Using nature-based solutions: Coastal vegetated ecosystems as carbon reservoirs

> Such **increased carbon dioxide removal** could be achieved with the help of the ocean, for example through the **(re-)establishment and large-scale expansion of coastal vegetated ecosystems** in tidal and shallow water areas (up to 40 metres water depth). These include salt marshes, mangrove forests, seagrass meadows, and kelp forests.

> Their combined areas account for less than one percent of the world's ocean area, including the intertidal zone. Together, however, the **meadows and forests of the ocean** sequester a significant portion of the carbon stored in the seabed and are thus **key players in the Earth's carbon cycle**.

Coastal ecosystems as carbon reservoirs

Costs: **approx. US$1 to US$1000 dollars per tonne of CO_2**

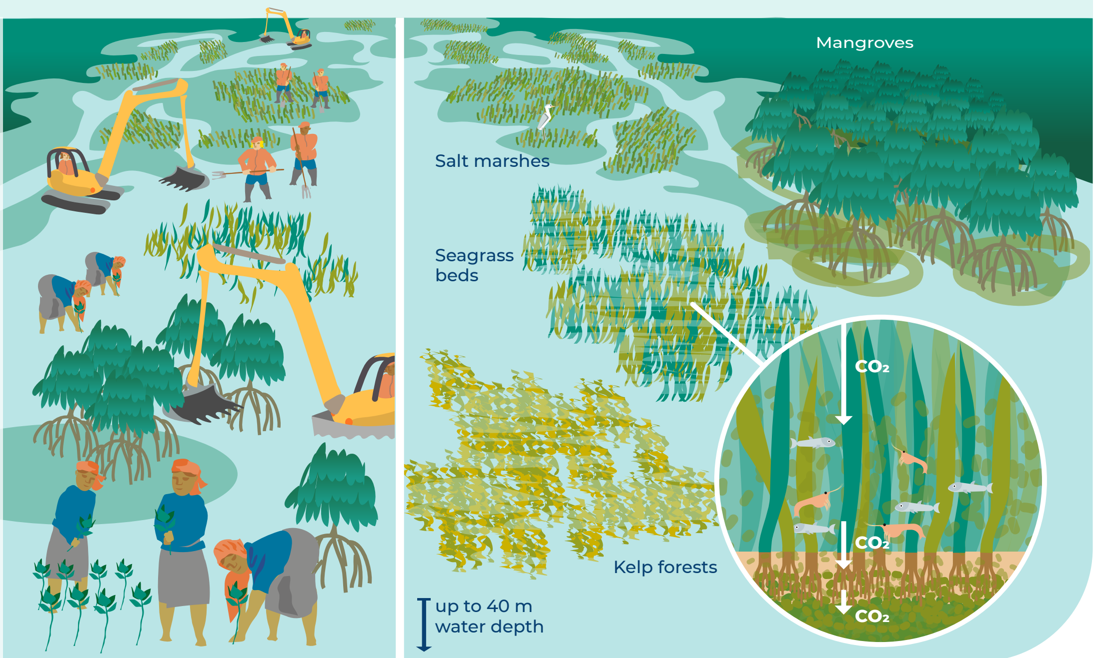
Scalability: An **extensive expansion of coastal vegetated ecosystems is theoretically possible.**

Duration of storage: **From several decades to thousands of years**

Technical state of development: Coastal ecosystems are being restored around the globe, but often only in their original areas.

A **massive expansion** of their extent is theoretically possible but has not yet been attempted practically anywhere.

The restoration and large-scale expansion of coastal vegetated ecosystems in tidal and shallow waters could enhance the carbon dioxide uptake of the ocean. These include salt marshes, seagrass beds, and mangrove and kelp forests.



Graphic: Rita Erven, CDRmare/GEOMAR

- Salt marshes, mangrove forests and seagrass beds absorb carbon dioxide from the air and seawater, bind the carbon they contain and store it underground. Over time, this creates **large carbon deposits below the plant cover**, which are preserved as long as the vegetation protecting them thrives – for up to several millennia.
- But coastal vegetated ecosystems do much more: they produce oxygen, clean the water, protect the coasts from erosion, foster biodiversity, and provide food and income for millions and millions of people around the world.

The degradation of coastal ecosystems

- The harsh reality is that **the area of coastal vegetated ecosystems is shrinking worldwide** due to climate change, coastal development, marine pollution, overfishing, and other intensive uses. In the past 100 years, up to 50 percent of all salt marshes, about a third of all seagrass beds, and about 35 to 50 percent of mangrove forests have been lost. Of the world's kelp forests, 40 to 60 percent are experiencing clear area losses.
- Where plant communities die, their belowground carbon stores also decay.
- The good news: **coastal ecosystems can be restored**. Successful restoration projects exist in many parts of the world.

Strategies to increase carbon dioxide removal by marine meadows and forests

- To effectively compensate for residual emissions, highly productive coastal habitats would not only need to be protected and restored but **expanded beyond their recently lost areas**.
- Prerequisite: Humans would have to replant mangrove forests, seagrass meadows, kelp forests, and salt marshes also in areas where they have not occurred naturally so far and implement communities of species to be planted in such a way that they achieve maximal carbon uptake and storage as an ecosystem and strengthen biodiversity at the same time.
- Experts refer to this approach as ecosystem co-design. It is believed to: (1) increase the carbon uptake and storage of coastal ecosystems; (2) promote coastal biodiversity; and (3) facilitate the adaptation of people and nature to climate change – the latter mainly because of the **many ecosystem services** provided by marine coastal ecosystems (food, coastal protection, subsistence, etc.).

Many questions, especially about the effects of climate change

- **Climate change** poses an **acute threat** to coastal vegetated ecosystems. Among other things, the question arises, in which regions of the world they will be able to contribute to climate change mitigation through their carbon dioxide uptake, and where investments in their protection and large-scale expansion would be promising for the future.
- In addition, much **detailed knowledge** is still lacking on the **ecology** of marine meadows and forests, their **carbon fluxes**, basic **storage and degradation processes** in coastal sediments, and how their carbon dioxide removal and storage could be quantified and monitored in the long term.
- It is also questionable whether the coastal population would support the massive expansion of ecosystems. Potential points of contention would be the abandonment of intensively used land and sea areas in order to be able to renature them, as well as the expansion of coastal vegetated ecosystems at the expense of sandy beaches, tidal flats, and other local ecosystems.

CDRmare provides answers and recommendations for action

- In the research mission CDRmare, scientists investigate the **basic mechanisms of carbon storage** in coastal vegetated ecosystems, their vulnerability to the impacts of climate change, and the willingness of coastal societies to support a massive expansion of marine meadows and forests.
- Based on this basic research, the experts will then develop **innovative procedures and political recommendations for action** to expand the area of coastal vegetated ecosystems, with which the carbon dioxide uptake of marine meadows and forests could be increased in an **environmentally compatible and socially acceptable way** – on German coasts as well as worldwide.

All associated research is carried out in the CDRmare research network »sea4soCiety – Innovative approaches to improving the carbon storage potential of vegetated coastal ecosystems«.

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CDRmare

Research Mission of the German Marine Research Alliance (DAM)
»Marine carbon sinks in decarboniation pathways«

KNOWLEDGE SUMMARY

Biological methods

Artificial upwelling: More power for the ocean's biological carbon pump

Algae, zooplankton and fish are among the key players in the biological carbon pump that allows the ocean to naturally remove carbon dioxide from the atmosphere and store it at great depths. However, for this mechanism to function optimally, it needs nutrients, which are lacking in many places, at least in the light-flooded surface water. By pumping up nutrient-rich deep water, humans could remedy this nutrient deficiency. But whether artificial upwelling would actually have an effect on the climate, what risks it would entail and whether it could be technically and legally implemented on a large scale, is still uncertain. The research mission CDRmare provides

The big climate goal: A net zero of carbon dioxide emissions

> There is a consensus in climate research: even with ambitious climate policies, humanity will still be emitting **10 to 20 percent** of current carbon dioxide emissions by the middle of the 21st century and thus continue to drive global warming.

> To compensate for these residual emissions, humankind will either have to capture carbon dioxide directly at its source or remove it from the atmosphere to the same extent.

Increased algae growth, enhanced transport of biomass into the deep ocean

> An **increased carbon dioxide removal** could also be achieved with the help of the sea, for example, by **increasing the biological carbon pump** in formerly less productive marine regions. This would mean increased algae growth in surface waters. After the death of the algae, its carbon-rich biomass would either sink directly or migrate through the food web and via this by-pass be transported into greater depths – not completely, however, but only to a certain extent.

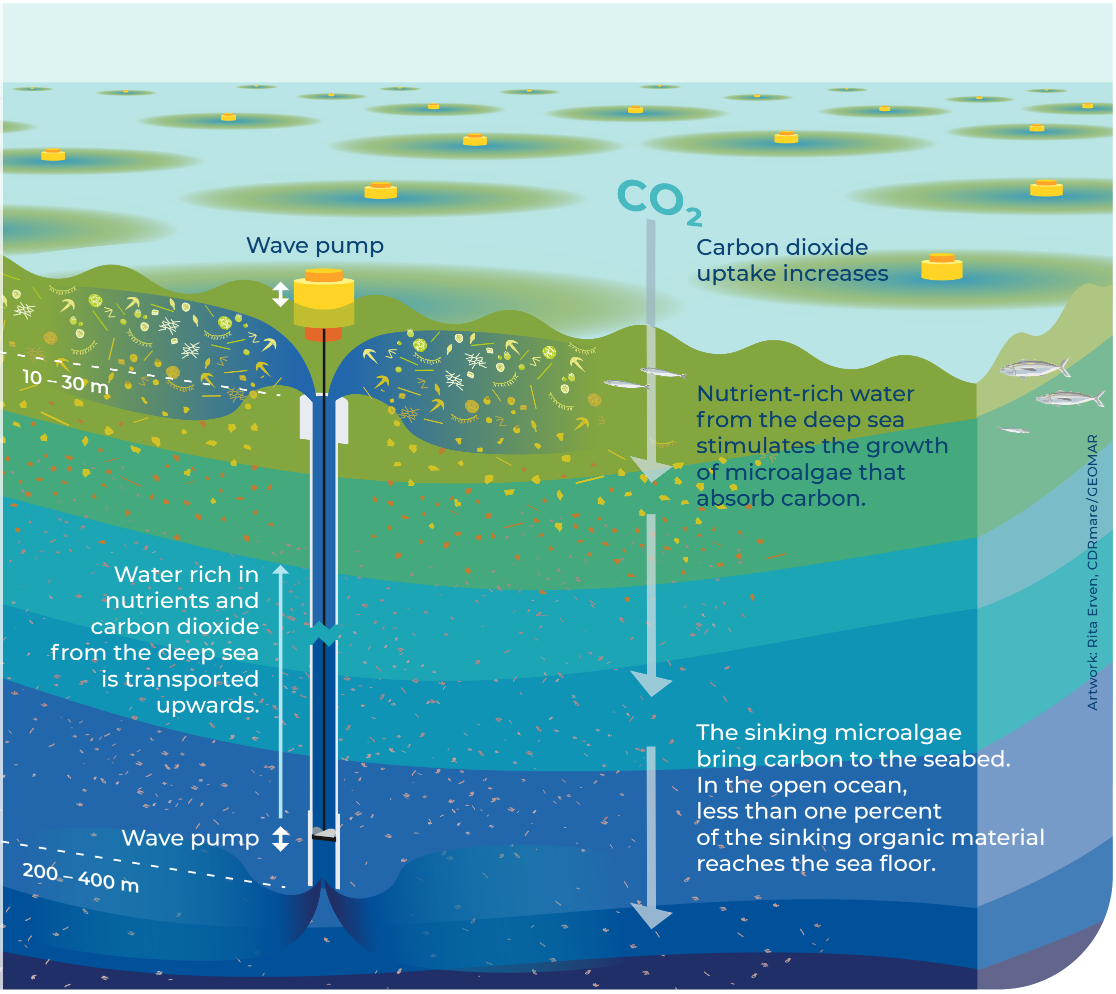
Artificial upwelling

Costs:
So far not quantifiable. Initial calculations take place within CDRmare.

Scalability: **Carbon dioxide storage on a larger scale is theoretically possible;** upwelling pumps could be used both **in the marginal seas and on the open ocean.**

Duration of storage: **for decades to centuries.**

Technical state of development:
in the early stages



> At great water depths, **the carbon contained in the biomass and possible degradation products would be trapped for decades, at best for centuries**, and would not be able to escape into the atmosphere in the form of carbon dioxide.

Artificial upwelling: Fertilizer from the deep ocean

> **Nutrients are the limiting factor** of the biological carbon pump. Where they are lacking in the surface water biomass production and thus carbon dioxide uptake by algae comes to a standstill. By **pumping up nutrient-rich deep water**, less productive oceanic regions could be supplied with sufficient nutrients.

> This approach is referred to as **artificial upwelling** because it mimics the functionality of natural upwelling areas off the west coasts of Peru, Namibia, California and Mauritania. These areas are among the most productive and fish-rich marine regions in the world. However, to achieve the same upwelling effect, **tens of thousands of upwelling pumps** would have to be operated in nutrient-poor oceanic regions.

Trial run: Testing of an optimised upwelling pump in the open ocean

> As cold, carbon dioxide-rich deep water rises to the ocean surface, it warms, which can cause **carbon dioxide to escape from the ocean into the atmosphere**. Such outgassing would reduce the climate effectiveness of artificial upwelling processes. However, the results of the research mission CDRmare suggest that, under certain circumstances, such methods have a **higher carbon dioxide removal potential** than previously thought. However, the extent to which this potential can be realised is still uncertain.

> In the research mission CDRmare, scientists for the first time conduct **comprehensive, transdisciplinary studies on the technical, ecological, biogeochemical, economic and legal and legal feasibility of artificial upwelling**. This also includes the test run of a **newly developed seaworthy wave pump** off the coast of Gran Canaria.

Extensive interdisciplinary research

> The development and test run of the upwelling pump will be accompanied by extensive **simulations of optimised flow models**, which are used to understand the basic biogeochemical processes of upwelling nutrient-rich deep water. At the same time, biologists conduct diverse experiments to test the **responses of algae and zooplankton to the increased nutrient supply** and their optimal growth- and adaptation-potential are investigated.

> In parallel, economists develop an integrated assessment model that can be used to assess the **economic and climate policy benefits of artificial upwelling**.

> Legal scholars examine the existing legal framework for such an operation and to find out which changes to the legal conventions and principles would need to be made to create an **adequate regulatory framework for the management of artificial upwelling**.

CDRmare delivers answers

> Based on the several analyses, the researchers will compile **options for action for decision-making in politics, businesses and society**. This knowledge will enable all stakeholders to make **fact-based** decisions about the benefits and risks of a possible use of artificial upwelling to increase the ocean's carbon dioxide uptake.

All research activities described here are carried out within the CDRmare consortium »Test-ArtUp – Road testing ocean artificial upwelling«.

 // **Cite as:** CDRmare (2023): *Knowledge summary, Artificial upwelling: More power for the ocean's biological carbon pump*, CDRmare Research Mission, pp. 1-2, DOI 10.3289/CDRmare.30

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Chemical methods

Minerals for enhanced carbon dioxide uptake by the ocean

The amount of carbon dioxide that the ocean can absorb without becoming highly acidic depends on the alkalinity of its surface water. This term refers to the amount of acid-binding mineral components of mineral origin that were previously dissolved from weathered rock and washed into the ocean. The question now is: could a targeted input of such minerals help to increase the marine carbon dioxide uptake without unbalancing the chemistry and life in the ocean? This approach does work in simple model calculations. However, field experiments are still lacking, as are realistic simulations and detailed knowledge about the consequences and risks of an increase in alkalinity. The research mission CDRmare investigates the potentials, feasibility and side effects of the various methods.

The big climate goal: a net zero of carbon dioxide emissions

> Even with an ambitious climate policy, Germany is still expected to release **10 to 20 per cent** of its current greenhouse gas emissions in three decades, further driving climate change. One possible way out: **offset the remaining emissions** – for example by increasing carbon dioxide uptake and storage by the ocean.

> There is a constant exchange of carbon dioxide between the ocean surface and the atmosphere, which equalises any pressure differences between the carbon dioxide dissolved in the seawater and the carbon dioxide in the atmosphere. If the carbon dioxide concentration in the atmosphere increases, the ocean also absorbs more carbon dioxide.

> In recent decades, the **world ocean** has absorbed about 25 per cent of anthropogenic carbon dioxide emissions from the atmosphere, thus significantly **slowing down global warming**.

The laws of marine chemistry

> When carbon dioxide dissolves in seawater, some of the gas undergoes a **series of chemical reactions** during which it is chemically bound as hydrogen carbonate so that the ocean can absorb new carbon dioxide. However, this reaction chain also releases protons that **acidify the ocean**. The extent to which this happens depends on the amount of acid-binding minerals in solution in the

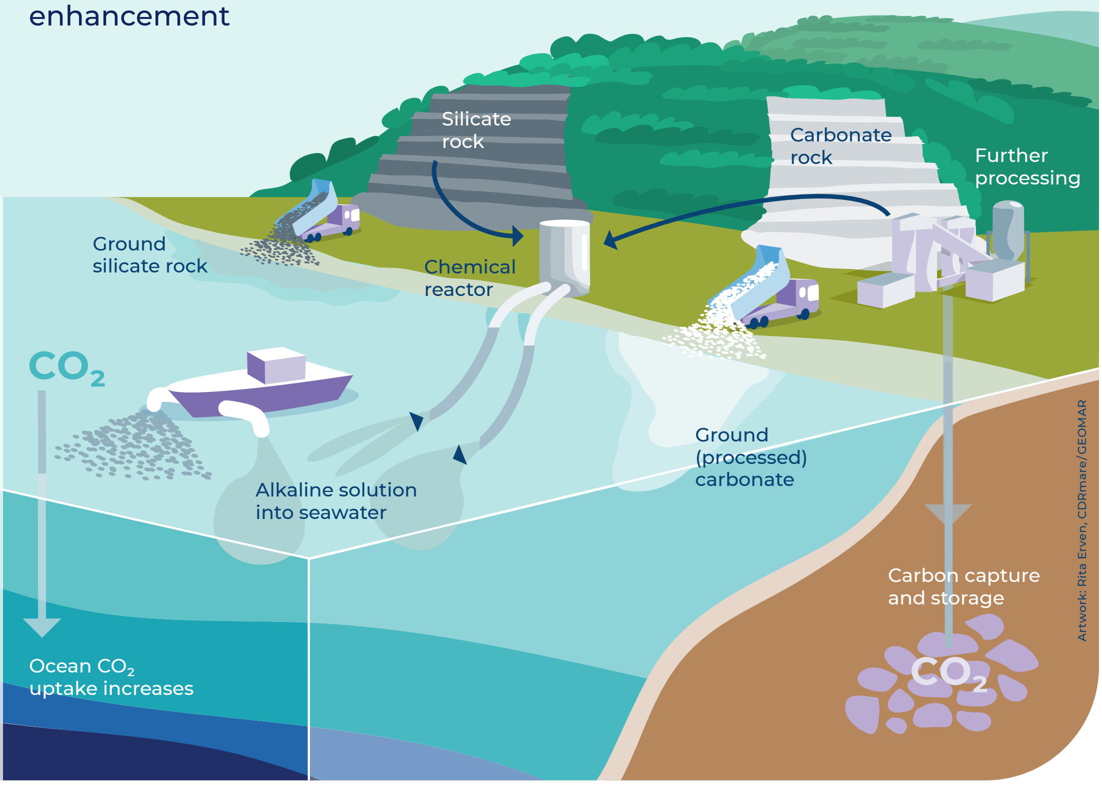
Costs: Estimates range from **US$40 to US$260 per tonne of carbon dioxide**

Scalability: **Carbon dioxide extraction on an industrial scale is theoretically possible.**

Duration of storage: **Many hundreds to hundreds of thousands of years**

Technical state of development: For the ocean, the method has so far **only been simulated in computer models and tested in individual laboratory experiments**. Extensive **laboratory and field tests** as well as **knowledge on risks and side effects for humans and the environment are lacking.**

Marine alkalinity enhancement



water, which were previously dissolved from weathered rock and washed into the ocean. Experts speak of the degree of alkalinity as a measure of the **acid-binding capacity** of seawater.

- Rock weathering on land and the subsequent storage of the acid-binding solution products in the ocean are comparatively slow natural processes. Nevertheless, they remove about **1 billion tonnes of carbon dioxide** from the atmosphere annually. On a long-term average, this amount corresponds roughly to the amount of carbon dioxide that enters the atmosphere through volcanic activity and mineralisation processes in the Earth's mantle and in the ocean.
- In order to fully compensate for man-made residual emissions from 2050 onwards, the **ocean's natural carbon uptake would have to increase fivefold**.

The idea: an acceleration of natural weathering

- According to modelling studies, an increase in oceanic carbon uptake would be entirely possible if mankind were to accelerate the natural weathering of mineral-bearing rocks and deliberately increase the alkalinity of seawater.
- Such an intervention in ocean chemistry would have the advantage that **the ocean could absorb more carbon dioxide without acidifying**. At the same time, an increase in alkalinity in highly acidified ocean regions would lead to free protons being bound, thereby decreasing their acidifying effect. This in turn would facilitate the **protection and restoration** of coral reefs, mussel beds and other important marine habitats.

Alkalinity enhancement: A method in its infancy

- **Various processes** are currently being developed that could accelerate the natural weathering of mineral-bearing rocks and increase the alkalinity of seawater.
- However, most knowledge about the chemical and biological consequences of alkalinity enhancement has so far come from model studies (computer simulations). **Conclusive laboratory or field studies** on local, regional and global impacts of industrial-scale mineral inputs on the environment and humans are **still largely lacking**.
- It is also not clear in which marine regions the appropriate techniques would have to be used in order to achieve the greatest possible benefit and whether alkalinity enhancement methods are ultimately more effective and expedient than other marine or land-based processes that increase carbon dioxide removal from the atmosphere.

CDRmare provides answers

- In the interdisciplinary research mission CDRmare, scientists for the first time comprehensively investigate the **carbon dioxide removal potential, feasibility and possible ecological and social side effects** of the various methods of marine alkalinity enhancement.
- They combine local laboratory and mesocosm experiments with model studies for selected regions as well as the world ocean. They review the legal framework, consider social aspects and the compatibility of a deployment with the UN's sustainability goals, and analyse whether the benefits that might be achieved could justify the effort, the costs and any environmental impacts that might arise.
- They also address the question of how permanent an ocean carbon dioxide removal achieved through alkalinity enhancement would be and how it could be measured, monitored and attributed to specific measures.
- Its aim is to provide policy-makers and society with **scientifically sound information** on whether and in what form marine alkalinity enhancement can be a viable method to permanently remove significant amounts of carbon dioxide from the atmosphere in an environmentally safe and socially responsible manner.

All research activities described here are carried out within the CDRmare consortium »RETAKE – CO_2 removal by alkalinity enhancement: potential, benefits and risks«.

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Geological methods

Carbon dioxide storage in geological formations below the German North Sea

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

Storage for captured carbon dioxide emissions

> There is a consensus in climate research: Even with ambitious climate policies, Germany is still expected to release **10 to 20 percent** of current greenhouse gas emissions by the middle of the 21st century, further accelerating climate change.

> To offset these emissions, humans will have to remove the same amount of carbon dioxide from the atmosphere. The gas must then be stored safely. Some of the residual emissions can also be avoided from the outset. To do this, fossil carbon dioxide is captured directly at the emission source and then stored underground. The gas must then be safely stored. This technique is called **carbon capture and storage** (CCS).

> Carbon dioxide is a long-lived gas. Its extraction and storage must therefore be **effective and permanent**. Some key CO_2 removal methods, such as direct air capture and bioenergy generation with carbon capture and storage (BECCS), rely on **deep underground storage**.

CO_2 storage in sandstone formations of the German North Sea

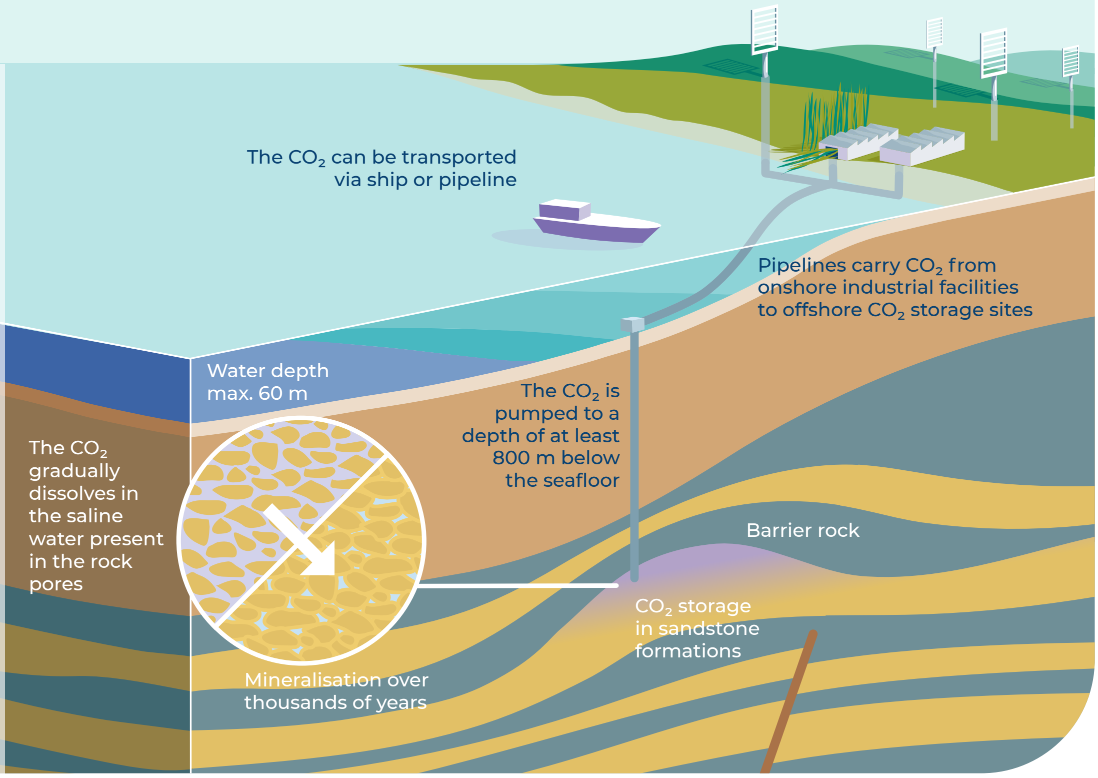
Costs associated with capture, liquefaction, transport, storage, monitoring: **approximately 150 to 250 euros per ton of carbon dioxide**

Scalability: **CO_2 storage at industrial scale is possible**

Duration of storage: **permanently possible, monitoring required**

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

For storage in the ocean's subsurface, liquid carbon dioxide is transported by pipeline or by ship to the relevant ocean site and injected through one or more boreholes into deep porous sandstone formations. In the rock pores, the carbon dioxide then spreads and collects at the highest point of the reservoir under the barrier layer. Over time, the carbon dioxide dissolves in the formation water and reacts with minerals contained in the surrounding sandstone. In this process, minerals (carbonates) are formed in which the carbon dioxide is permanently bound. However, several centuries pass before this happens.



Technically feasible, planned in many locations

- The safe and permanent storage of large quantities of carbon dioxide in the deep subsurface of the North Sea is **technically feasible** and has already been successfully practiced under Norwegian waters for more than two decades.
- In the Netherlands, Denmark, Great Britain as well as in Norway, various companies are currently planning **further large-scale projects in the North Sea** because the capture and storage of carbon dioxide in the seabed is now economically viable due to the rising prices for CO_2 emission certificates.

The geological subsurface of the North Sea offers great CO_2 storage potential

- The North Sea has massive sandstone formations in its deep subsurface and thus offers good **geological conditions** for carbon dioxide storage. Its shallow water depth also facilitates the installation of the necessary technical infrastructure.
- It is estimated that around **150 billion metric tons** of carbon dioxide could be stored in the deep subsurface of the entire North Sea. The potential storage reservoirs in German waters would account for 3.6 to 10.4 billion metric tons. To put this into perspective, it is estimated that Germany will produce residual emissions of 0.06 to 0.13 billion metric tons of carbon dioxide per year in the future.

Risks are known, but strategies for solving them are missing

- The **risks** of the technology to humans and the environment are well known. They include:
  - the unintentional **escape of the stored carbon dioxide** from the reservoir rock (leakage) and the resulting acidification of near-bottom water masses;
  - **contamination of the marine environment** by very salty formation water, as well as by **heavy metals and other substances harmful to the environment** that could be contained in the formation water displaced from the reservoir rock in the course of carbon dioxide injection;
  - **seismic events** at depth, which could threaten the functionality and stability of seabed-anchored infrastructure; and
  - **noise disturbance** to marine organisms during the search for suitable storage structures, construction of the facilities, and long-term monitoring of the carbon dioxide storage facilities.

Monitoring and mitigation concepts have been developed for CCS projects in neighboring countries, but they must now be adapted to conditions in the German North Sea and, if necessary, supplemented. In addition, **strategies for dealing with possible conflicts** of use in the North Sea (e.g. offshore wind farms) are needed.

Germany's legal position on carbon dioxide storage in the seabed is in need of clarification

- International agreements allow coastal states to store carbon dioxide in the geological subsurface of marine areas under their jurisdiction. In Germany, however, **the legal situation requires clarification** and makes CO_2 storage projects difficult. In order to be able to carry out such projects, it would be necessary, among other things, to **amend the Carbon Capture and Storage Act**. In addition, experts recommend that German marine spatial planning be extended to the deep subsurface.

CDRmare provides answers, and concepts for safeguarding and action

- As part of the research mission CDRmare, **solutions and options for action** are developed for open geological, technical and legal questions of CO_2 storage in the deep subsurface of the German North Sea. **Monitoring and precautionary concepts for risk mitigation** are also investigated. Moreover, the researchers estimate the **costs** involved. By doing so, they create the scientific basis for a comprehensive demonstration project.

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

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Geological methods

A deep-sea experiment on carbon dioxide storage in oceanic crust

On Iceland, water enriched with carbon dioxide has been injected into the upper ocean crust since 2014 – and successfully. The carbon dioxide mineralises within a short time and is firmly bound for millions of years. However, since ocean crust only rises above sea level in a few places on Earth, researchers are currently investigating the option of injecting carbon dioxide into ocean regions where huge areas of suitable basalt crust lie at medium to great water depths. One possible advantage: In the deep sea subsurface, the carbon dioxide would either be stable as a liquid or dissolve in the seawater circulating in the rock.
Due to the high pressure, both the liquid carbon dioxide and the carbon dioxide-water mixture would be heavier than seawater, making leakage from the underground unlikely. But would carbon dioxide storage in the deep sea subsurface be technically feasible and ultimately also economically viable? The research mission CDRmare provides answers – with the help of the world's first deep-sea research experiment on carbon dioxide storage on cooled flanks of the Mid-Atlantic Ridge.

The big climate goal: a net zero of carbon dioxide emissions

> There is a consensus in climate research: Even with ambitious climate policies, Germany is still expected to release **10 to 20 percent** of current greenhouse gas emissions by the middle of the 21st century, further accelerating climate change. However, there is still no social consensus on how high possible **residual emissions** may be and which sectors may cause them. Currently, residual emissions are unavoidable, for example, in cement production, air and heavy goods transport, but also in agriculture and waste incineration.

> To compensate for these residual emissions, humankind will have to either capture carbon dioxide directly at its sources or remove it from the atmosphere to the same extent. The gas must then be safely stored underground. **Carbon capture and storage** processes are also known as CCS. The abbreviation stands for carbon capture and storage.

Carbon dioxide storage in oceanic crust

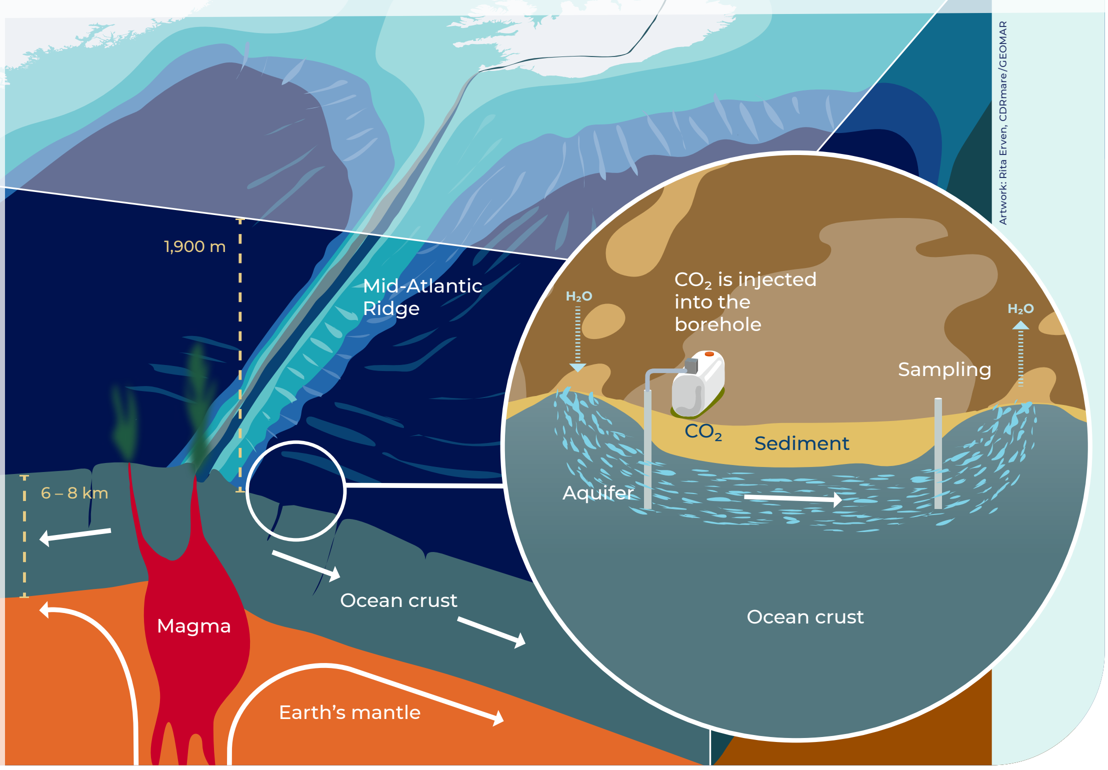
Cost: on Iceland ca. 25 to 45 US-Dollar per metric ton CO_2, but for **deep water settings so far unknown**.

Scalability: A **carbon dioxide storage at industrial scale is in principle possible** (but may be an expensive option.

Duration of storage: After mineralisation the CO_2 is fixated for **many millions of years** as carbonate.

Technical level of development: On Iceland, seawater enriched with carbon dioxide has been successfully injected into the upper ocean crust since 2014. **This process has not yet been sufficiently tested in greater water depths.**

The highly porous and reactive basalt rock of the Earth's upper crust is an ideal storage site for captured carbon dioxide. In a first carbon dioxide injection experiment in the deep sea, researchers are now investigating whether this is also the case under deep-sea conditions and how the injected carbon dioxide is distributed in the basalt rock and mineralised there.



> Carbon dioxide is a long-lived gas. Its extraction and storage must therefore be **effective and permanent**. Some key carbon capture methods, such as direct air capture and bioenergy generation with carbon capture and storage (BECCS), rely on **deep underground storage**.

Porous and reactive: the upper ocean crust as a carbon dioxide reservoir

> The **upper, 400-metre-thick basalt layer of the oceanic crust** lends itself to storing captured carbon dioxide. This basalt rock is **hot, highly porous and very reactive**. This means that, on the one hand, it offers a lot of space. On the other hand, it contains many minerals that react with the carbon dioxide dissolved in the seawater and **bind it firmly by forming new minerals (= rock) – for millions of years**.

Successful project on Iceland: 98 percent of carbon dioxide mineralises

> On Iceland, carbon dioxide that has been separated and dissolved in fresh water has been injected into the upper ocean crust for eight years. The volcanic island lies exactly on the axis of the Mid-Atlantic Ridge, so that the ocean crust here reaches above the sea surface and young, still warm and thus very reactive basaltic rock can be reached even by comparatively short drill holes. The mineralisation rates are correspondingly high: **within two years, 98 per cent of the injected carbon dioxide mineralises**.

In search of the optimal solution: A carbon dioxide discharge experiment in the deep sea

> Places where the ocean crust rises above sea level, as in Iceland, are scarce and usually far from industrial centres where many carbon dioxide emissions occur. Researchers therefore investigate the option of injecting carbon dioxide into ocean regions where **huge areas of suitable basalt crust lie at medium to great water depths**. One possible advantage is that the carbon dioxide would either be stored as a liquid in the underground in the deep sea, or dissolve in the seawater circulating in the rock before it mineralises. Due to the high pressure, however, both the liquid carbon dioxide and the carbon dioxide-water mixture would be **heavier than seawater, making leakage from the subsurface unlikely**.

> In the research mission CDRmare, geologists and engineers conduct **a scientific carbon dioxide injection experiment in the North Atlantic deep sea** for the first time. On the one hand, they want to use it to define the spectrum of conceivable carbon dioxide storage options along mid-ocean ridges. On the other hand, the aim is to close existing knowledge gaps on carbon dioxide storage in oceanic crust and to find out whether carbon dioxide storage in the deep sea would be a more sustainable, effective and, in the long term, more cost-effective option compared to geological storage on land.

> In addition, the scientists develop and test **new sensor technology suitable for deep-sea** use as well as modularly deployable **underwater robots**. They are the prerequisite for the large-scale investigation of the deep-sea floor around the injection site for possible leaks and could also be used in the long term to **monitor other approaches for carbon dioxide storage in the ocean floor**.

> The deep-sea research experiment is scheduled to take place in summer 2025 in international waters of the North Atlantic, 300 to 800 kilometres south of Iceland, in the area of the **eastern flank of the Reykjanes Ridge**.

> The scientific drilling and associated experiment planned as part of the CDRmare mission are carried out for research purposes only.

CDRmare provides answers

> Based on the results of the deep-sea experiment and subsequent numerical modelling, the researchers will conduct cost-benefit analyses and for the first time **derive options for action for the entire spectrum of possibilities along mid-ocean ridges** – starting with a possible carbon dioxide injection in basalt rock on land to storage projects in medium and deep water.

> This action knowledge should enable decision-makers from politics, business and civil society to discuss the various options for carbon dioxide storage in the ocean floor in a **fact-based manner**.

All research activities described here are carried out within the CDRmare consortium »AIMS³ – Alternative Scenarios, Innovative Technologies and Monitoring Approaches for Carbon Dioxide Storage in Oceanic Crust«.

AIMS³ aims3.cdrmare.de

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Research Mission of the German Marine Research Alliance (DAM)
»Marine carbon sinks in decarboniation pathways«

KNOWLEDGE SUMMARY

Synthesis

An assessment framework for marine Carbon Dioxide Removal Methods

More research is currently being conducted on marine carbon dioxide removal methods than ever before. Expertise on each approach continues to grow. At the same time, policymakers are relying on carbon dioxide removal methods to meet national climate goals. What is missing is a tool to bring together research results and evaluate methods - in a transparent way that everyone can understand. In the research mission CDRmare mission, an interdisciplinary team of scientists develops an evaluation framework, a guide to make this possible. It not only asks whether a method is technically, legally, or politically feasible, but also whether its use can be described as »desirable« in terms of the ethical and moral principles of our society – a fundamentally important contribution to future debates.

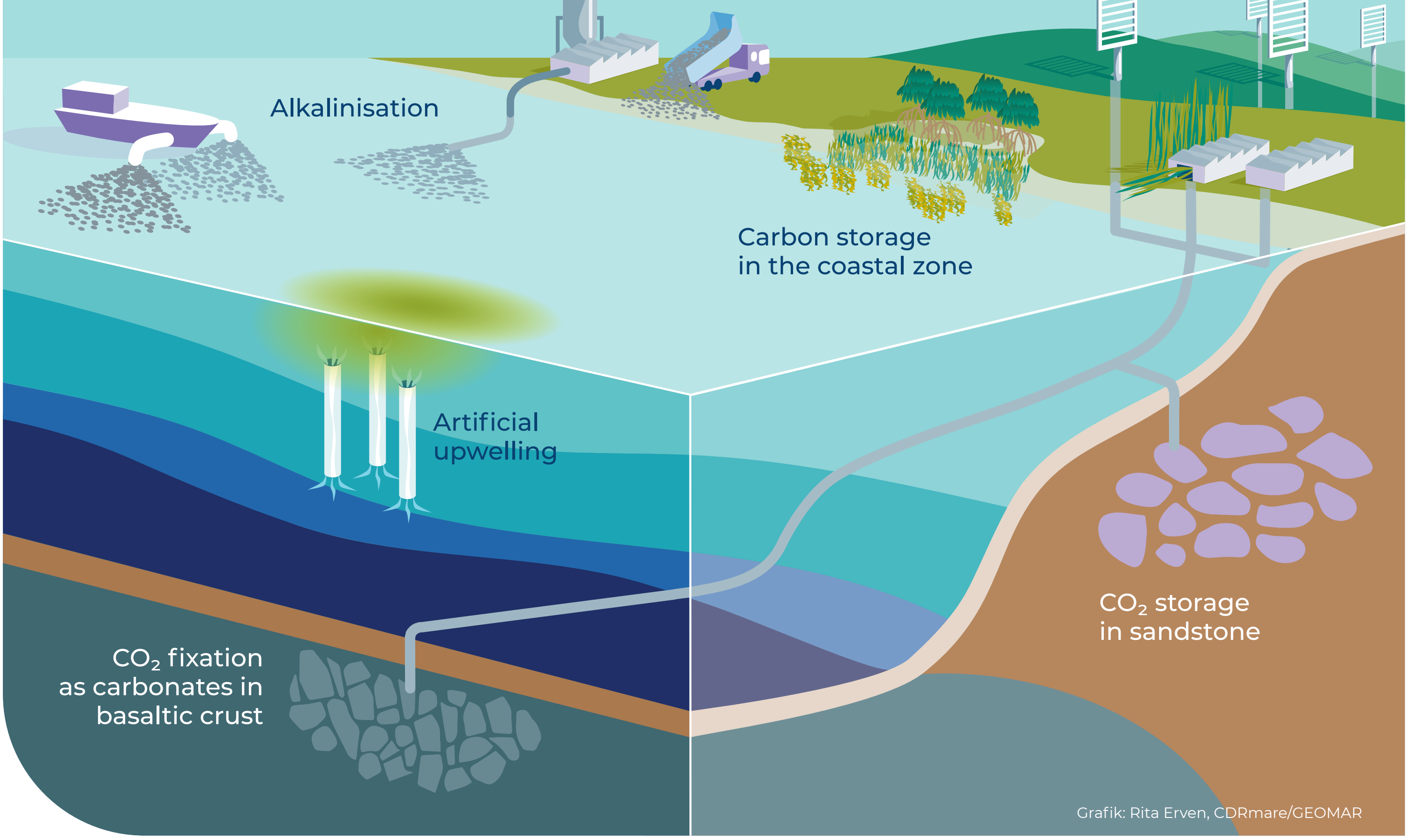
The big climate goal: net zero

> There is a consensus in climate research: even with ambitious climate policies, humanity is still expected to **release residual amounts of carbon dioxide and other greenhouse gases** by the middle of the 21st century, which will contribute to further global warming.

> To offset these residual emissions, and thus their climate impact, humanity would need to **remove carbon dioxide from the atmosphere at the same rate.**

> Many known **carbon dioxide removal (CDR)** methods are land-based. However, because land is a scarce resource, **ocean-based methods** are now being increasingly explored.

Ocean-based methods of carbon dioxide removal from the atmosphere



Difficult decisions for society and politics

- Human interventions in the ocean system to **increase carbon dioxide uptake** are, among other things, changing ocean chemistry or ecosystems and thus the living conditions for many marine organisms.
- **The ocean** is also a **space intensively and diversely used** by mankind – and our demands on the services of the oceans continue to increase. In the long term, they should provide a growing world population with food, energy and raw materials (also for the energy transition) that can no longer be produced on land to a sufficient extent.
- **Any use** of and intervention in the sensitive ocean system **must therefore be carefully considered** and it must be ensured that the oceans and their ecosystems are not harmed.
- If the **carbon dioxide removal required to offset residual emissions** were to be done increasingly by ocean-based methods, this would require **large-scale interventions over long periods of time.** This would necessitate the emergence of international industries and associated governance and regulatory structures whose purpose would be to increase ocean carbon dioxide uptake and storage.
- This complex baseline situation poses an enormous **challenge** to society and its decision-makers. The task is to effectively limit climate change while at the same time ensuring sustainable development and thus a future worth living for all people on earth.

Answers are needed

- To meet this challenge, political actors need **understandable and transparent information** about whether marine carbon dioxide removal methods actually work to the extent hoped for, whether they would be politically, legally, socially, and financially feasible, what benefits and risks they pose to humans and the environment, and whether their use and all associated impacts are actually desirable in the long term.
- Answers to these questions can support decision-making processes before marine CDR methods are potentially implemented on a large scale.

An assessment framework for marine carbon dioxide removal methods

- In the research mission CDRmare, scientists from the natural sciences, social sciences, humanities, law, and economics develop **an urgently needed assessment framework** for marine CDR methods.
- It not only asks **which methods work** and can actually be technically implemented, but also examines **whether the effects achieved are desirable** and whether we can use marine CDR methods to help achieve the net-zero goal **without compromising internationally recognized goals and standards in other areas** – such as the UN Sustainable Development Goals.
- The new assessment framework will cover the many dimensions of the issue of carbon dioxide uptake and storage in the ocean and will enable decision-makers, politics, business, and civil society to make a **fact-based and comprehensible judgment** on individual methods or future projects.
- It is also intended to **synchronise the framework with approaches to assessing land-based carbon dioxide removal methods** so that it can compare ocean-based carbon dioxide removal methods with land-based methods.

The development of the assessment framework described here is being conducted within the CDRmare research consortium »ASMASYS – Unified assessment framework for proposed methods of marine CDR and interim knowledge synthesis«.

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