Policy Paper

ENERGYWATCHGROUP

Cooling our planet with ocean farming: CO_2 removal as the third pillar of climate protection

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Management Summary

I. The Earth is already overheated and expected to exceed the 2°C limit in the 2030s, triggering further tipping points with serious consequences for the climate, biodiversity, oceans, and human wellbeing.

II. Even if climate neutrality were achieved today, too much CO_2 would remain in the atmosphere to stop global warming. For a stable climate, the CO_2 concentration must be reduced from 425 ppm today to below 350 ppm. That is why reducing emissions to zero is not enough. Targeted climate adaptation and carbon removal are just as necessary.

III. Based on scientific findings and our own calculations, we propose a removal target of at least 450 gigatons of carbon (1,700 Gt CO_2).

IV. Existing methods are not sufficient to reliably achieve this scale. Ocean farming with free-floating seaweeds may fill the gap. It also offers novel technical, economical, and ecological perspectives.

V. Seaweeds grow very quickly, especially when supplied with nutrient-rich deep water. In the vast, currently unused subtropical gyres, large seaweed farms can be created that permanently remove CO_2 and create new marine habitats.

VI. The biomass produced can replace fossil fuels and fossil fuel based raw materials as well as increase global food security. This creates a sustainable marine economy – with opportunities especially for countries in the Global South and for funding large scale carbon removal

VII. Time is of the essence: we call for a legally binding carbon removal target to be agreed and for the necessary steps to be taken, as outlined in the #BioOcean2040 strategy, to test open-ocean seaweed farming on a large scale.

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Table of Contents

1. Introduction: Carbon removal, oceans, and seaweeds - why we want to talk about this now

Even if we stop burning fossil fuels such as gas, oil, and coal, and if no more greenhouse gases are emitted from thawing permafrost or cattle stomachs, we still need to develop and apply an essential capability: removing carbon from the atmosphere on a large, industrial scale. If it remains there, global warming will continue unchecked. Warming and extreme weather events threaten millions to billions of people, depending on the continent.

The Paris Climate Agreement contains commitments to reduce CO_2 emissions, but hardly addresses carbon removal for the necessary cooling of the Earth. As a result, there is a lack of political ambition and quantified targets commensurate with the task at hand.[1]

In the current debate, carbon removal technologies are mainly seen as tools to offset remaining emissions, e.g. from agriculture, after comprehensive decarbonization, and thereby achieve the net-zero target. Accordingly, the Paris Agreement calls for carbon removal at scale beginning mid-century to compensate for unavoidable CO_2 emissions.

That is why the climate policy debate on large scale carbon removal is still in its infancy and not in line with the actual task, that is many times greater. In addition, proponents of carbon removal are often considered supporters of the fossil fuel industry or accused of harmful geoengineering. This is likely to keep scientists and others from speaking out on the need to act.

If carbon removal is to become effective at scale before mid-century and help cool the earth, the decisive years are now[2]. Now is the time to reexamine old beliefs, reassess risks, be open to competing technologies, enable innovation and research, and test solutions so that we can then focus all our resources and energy on the most effective levers.

The net-zero target is not sufficient, since the atmospheric concentration of CO_2 is already well above the safe level of the pre-industrial era and above the planetary limit. It is therefore far from enough to aim for and achieve net zero; CO_2 must be removed on a much larger scale – and earlier – in order not to exceed planetary tipping points and to counteract problems such as sea level rise and the melting of the polar ice caps. Essentially, what is needed over the next 10

[1] European Union 2016 Article 4
[2] Fuss et al. 2021

to 15 years is a political impetus in several policy areas to ensure that industrial-scale carbon removal can and will take place.

In terms of climate policy, there are three major mission goals:

- rapidly reducing greenhouse gas emissions to net zero,
- developing and implementing climate adaptation measures at local, national, and global levels
- removing 450 Gt carbon from the atmosphere to return to the "climate-stable level" of 350 ppm.[3]

What makes our study unique is that it thinks far beyond the net-zero target and presents one of the most promising approaches for rapid carbon removal in large quantities: large-scale seaweed farming as a new approach.

In addition to the technical approaches discussed in the media, two biological, nature-based measures stand out: planting trees and growing seaweeds. Seaweeds are a massively underestimated lever in this context. Like trees, they absorb CO_2 from the ocean and the atmosphere as they grow, but their growth rate is many times higher than that of most land plants. Their doubling rate of up to 10 days[4] is comparable to the legend of the chessboard and the grain of rice and makes them an extremely effective tool for carbon removal. After doubling 63 times, the seaweed population grows to 9,223,372,036,854,775,808 (9 trillion 223 quadrillion 372 billion 36 trillion 854 million 755 thousand 808). Other plant and tree species on land and all technical processes lag far behind such a removal rate. This is why seaweeds can have an enormous removal effect.

In an assessment of various ocean-based carbon removal methods, the US *National Academies of Science, Engineering, and Medicine* found that the cultivation of large algae is a promising method for binding large amounts of CO_2, storing it permanently, and creating new jobs as an added benefit.[5]

This focus on the untapped potential of the oceans for CDR is a visionary approach[6]: In the vast, nutrient-poor subtropical gyres (large scale circular currents) - the "deserts of the seas" that make up 50 percent of the Earth's surface - nutrient-rich water from depths of 400 to 1,000 meters could be pumped to the surface to promote the extremely rapid growth of large algae, which could then be "harvested." Some of the technologies required to carry out such projects are

[3] See Chapter 2 for the derivation of the 450 Gt C removal target and the urgent appeal in the essay by Breyer et al. 2023
[4] Lapointe 1986, Lapointe et al. 2014, Xiao et al. 2019, Magaña-Gallegos et al. 2023
[5] See National Academies of Sciences, Engineering, and Medicine 2022
[6] See Smetacek et al. 2024 and Smetacek 2024

already in proven industrial use, for example in offshore drilling and wind power plants. Further components are currently being developed by various start-ups.

With this policy paper, the Energy Watch Group aims to open the general discussion on the necessary carbon removal and, with the #BioOcean2040 strategy, bring a roadmap for the potential of seaweed into the political debate.

This policy paper also supports the objectives of the international Holocene Project: to promote policies that ensure zero emissions and return to the safe climate limit of 350 ppm CO_2 with the necessary carbon removal. The Holocene Project brings together leading scientists from around the world to develop strategies for a sustainable transformation within planetary boundaries.[7]

This paper identifies the removal gap of at least 450 gigatons of carbon and ways of closing it. It weighs the risks of a responsible marine carbon removal industry against the risks of action and inaction – both for life on land and in the water. The policy paper highlights the growth and carbon removal potential of seaweeds and ocean aqua farms as the most promising approach. With the #BioOcean2040 strategy, the study also provides climate policy impetus to give the urgently needed discussion on effective and sufficiently scaled removal strategies an appropriate platform.

As the team of authors, we would like our readers to first set aside any opinions and preconceptions, take the following arguments in with an open mind and then reconsider their own position. We invite you to weigh the consequences of action and inaction and, ideally, to develop a new view on the political task of forming carbon removal. And no, you don't have to love seaweeds after reading this paper - but a new appreciation would be helpful.

[7] Holocene Project 2025 (scientists listed in the top 2 percent of scientists by Stanford/Elsevier)

2. Paris, we have a problem – the 450 gigaton gap

Our climate is like a ship hull that has a large leak. Water is pouring into the ship through the leak, increasingly threatening its stability. To prevent it from capsizing and sinking, the leak must be sealed quickly – in other words, CO_2 emissions must be reduced to zero through complete decarbonization in all sectors of society. But it is not enough to simply plug the leak. The water that has already entered – the CO_2 of the last decades – must be pumped out again. Both must happen at the same time, otherwise the ship will remain unstable. It would be neither logical nor responsible to wait until the leak is completely sealed before pumping out the water. As long as the two measures do not interfere with each other, they must be carried out simultaneously. The later the plugging and pumping, the more unstable the ship – i.e. our climate system - will become, with increasingly extreme weather events.

Despite this urgency, the second necessary step – pumping out the water that has entered, i.e. actively removing CO_2 beyond net zero, has so far been surprisingly low on the agenda in the climate policy debate. For example, there are hardly any studies that quantify the "amount of water," i.e., the amount of CO_2 that would have to be pumped out of "the leaking ship."

The Paris Agreement and the IPCC reports emphasize the need to reduce CO_2 emissions to zero in order to limit global warming to 1.5 °C and recognize that fossil CO_2 must be removed from the atmosphere to achieve that. What remains to be done is to establish political and legal frameworks for the scale, measures, and timeframes. As long as CO_2 levels remain well above those necessary for a stable climate, the decline in ice-covered areas on land and in the oceans will continue, further accelerating negative developments.

There are currently few studies that quantitatively discuss and outline the removal of gigatons (Gt) of CO_2 or carbon.[8] We consider it essential to clarify these quantitative relationships and raise awareness of the orders of magnitude involved in CO_2 removal (see Figure 1).

[8] We refer primarily to one of these studies: Keiner et al. 2023

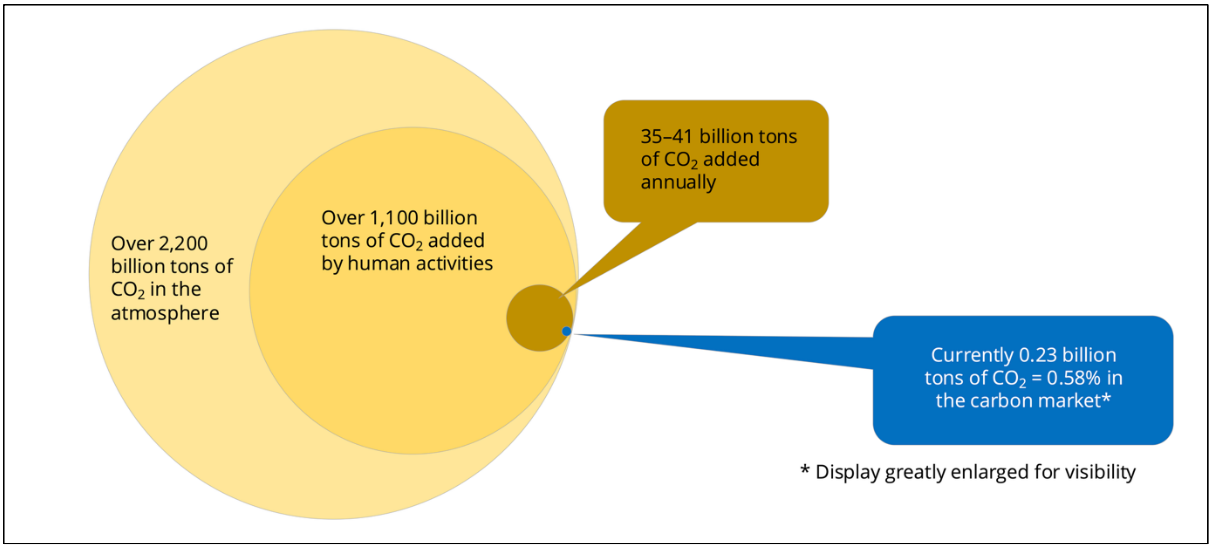

Figure 1: The scale of the CO_2 removal task compared to current emissions and the volume of the carbon market.[9]

Unfortunately, particularly climate scientists resist that clarification, presumably out of concern that it will raise false hopes that carbon removal alone will suffice for achieving net zero and existing CO_2 emissions can continue. Instead, CO_2 emissions must be reduced to "zero", but that is not enough. To ensure climate stability, large-scale carbon removal is unavoidable – despite all the uncertainties and risks associated with implementation. There is also a lack of political dialogue on this issue, as the debate is often overshadowed by fears that carbon removal will support the illusion of a "business as usual" strategy. But without effective removal, we will not return to a "safe climate harbor" globally.

Quantifying the current situation and the ppm target level

To estimate, how much CO_2 needs to be removed, the current CO_2 concentration of 425 ppm in the atmosphere is the starting point (see Figure 2).

[9] Graph based on Barnard 2024

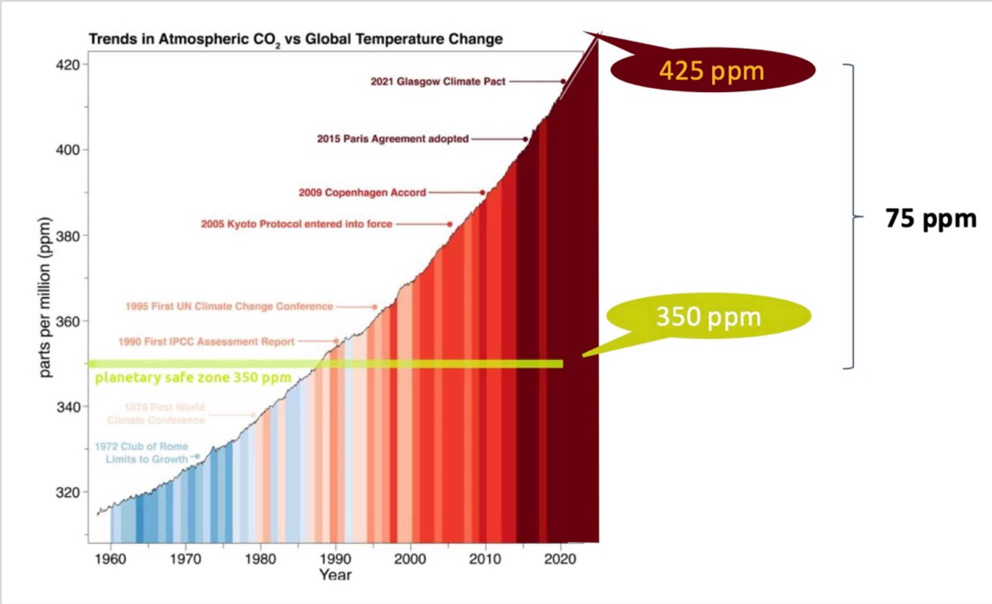

Figure 2: Development of global CO_2 concentrations- with 425 ppm currently well above the safe planetary limit of 350 ppm.[10]

Ideally, we would return to the pre-industrial level of 280 ppm and 0.0 °C global warming. But we should at least achieve 350 ppm, corresponding to a temperature increase of 1.0 °C above pre-industrial levels, to halt the shrinking of ice masses and the retreat of glaciers.
This is based on the *planetary boundaries*[11] which were developed in 2009 by an internationally renowned team of researchers. The German government, in agreement with numerous experts, considers a CO_2 concentration of 350 ppm the critical threshold for dangerous climate change.[12]

This threshold was already exceeded in 1990.[13] Above this threshold, tipping points are increasingly expected, such as the melting of the polar ice caps and the Greenland ice sheet, or the collapse of the Gulf Stream, to which Europe owes its warm climate. These tipping points can in turn trigger uncontrollable chain reactions that plunge the global climate system into increasingly "chaotic" states.[14] It is therefore necessary to keep CO_2 levels below 350 ppm.

[10] See Holocene Project 2025 (and the description in Solarify 2024) and, for the 425 ppm, which is now 430 ppm, UC San Diego 2024 and Auer 2025 on the CO_2 clock; in the calculations for this project, we are still using the slightly older value of 425 ppm.
[11] See UC San Diego 2024 and Rockström et al. 2009
[12] See Federal Ministry for the Environment, Climate Protection, Nature Conservation and Nuclear Safety 2024
[13] tagesschau.de 2024
[14] See Global Tipping Point Report 2023 and Statista 2025

The order of magnitude of carbon removal

To estimate how much CO_2 needs to be removed to get back to 350 ppm, several points must be considered:

1. the amount of CO_2 currently in the atmosphere that needs to be removed
2. the CO_2 that the oceans will additionally release back into the atmosphere, when atmospheric CO_2 concentrations decrease
3. the CO_2 that plants on land will additionally release, when atmospheric CO_2 concentrations decrease
4. the CO_2 that will be emitted from now until net zero is achieved

Amount of CO_2 currently in the atmosphere

This requires a conversion from ppm to gigatons of CO_2:[15]

1 ppm CO_2 in the atmosphere corresponds to approx. 2.12 gigatons of carbon (C)

The difference between the current concentration and the target value is calculated as follows:

425 ppm - 350 ppm = 75 ppm

This can be converted into gigatons of CO_2 and the required removal amount:

*75 ppm * 2.12 Gt C ≈ 159 gigatons C*

*159 gigatons C * 3.67 = 583 gigatons CO_2*

In the rest of this text, we will round the 159 gigatons to 150 gigatons of C.

CO_2 in the ocean and atmosphere – these carbon reservoirs are coupled

Most models only take the carbon emissions into account that are currently in the atmosphere. However, they do not consider the carbon absorbed by the oceans (see also Figure 3 on heat absorption) and land ecosystems. Most of this absorbed carbon is not stored long-term and can return to the atmosphere in various ways. Two factors are particularly important for the oceans' carbon absorption capacity: the temperature and the CO_2 concentration in the atmosphere (partial pressure).[16]

[15] See Friedlingstein et al. 2023; factor 3.66 for converting C to CO_2

[16] See Canadell et al. 2021

We are all familiar with the effect of temperature: when we drink carbonated beverages, we experience a tingling sensation in our mouths. This is partly caused by a chemical reaction in which CO_2 reacts with water to form carbonic acid, which stimulates the sensory cells, and partly by the formation of gas bubbles. As the drink warms up, the solubility of CO_2 decreases, causing it to escape more easily. Cold water can absorb more CO_2 than warm water; for example, water at 0 °C can bind about twice as much CO_2 as water at 20 °C.

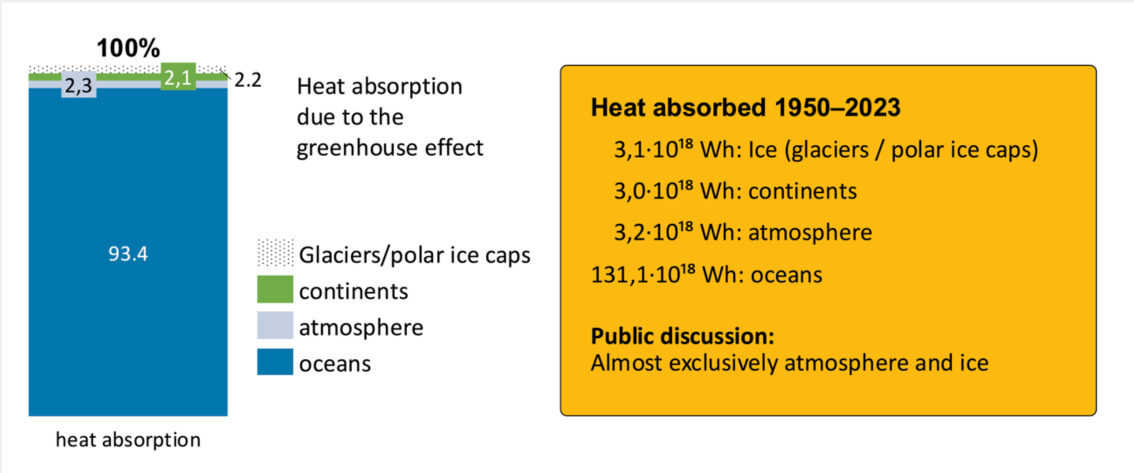

Figure 3: 93 percent of the additional heat stored by human greenhouse gas emissions is absorbed by the oceans.[17]

The CO_2 concentrations in the atmosphere and in the surface layer of the oceans are therefore linked by equilibrium reactions:

- If the concentration of CO_2 in the atmosphere increases, the partial pressure rises, and the oceans absorb more CO_2 to restore equilibrium with the atmosphere. This is the main reason why the oceans have absorbed around 200 Gt C in the form of CO_2 over the last 150 years. This corresponds to around 30 percent of the anthropogenic CO_2 emissions.
- Since only a small portion of the anthropogenic CO_2 emissions absorbed by the oceans has been transported to the deep sea by ocean circulation, most of it remains in the surface layer, which is in direct contact with the atmosphere.
- If the CO_2 concentration in the atmosphere decreases through CDR, this process is reversed – the ocean then becomes a source of CO_2. To date, this scientific fact has been largely ignored.

If the CO_2 concentration in the atmosphere falls from 425 ppm to 350 ppm, i.e. if the increase since pre-industrial times is halved, the oceans will also release half of the CO_2 absorbed since pre-industrial times back into the atmosphere –

[17] OneOcean 2019 and IPCC reports

around 100 Gt C.[18] This amount would also have to be removed from the atmosphere in addition to the above 150 gigatons of carbon.

CO_2 in terrestrial vegetation – feedback loops with atmospheric carbon

Similarly, the carbon stored in all land plants, is estimated at 450 Gt C. This amount has increased by 200 Gt C in the last 150 years since industrialization,[19] because the rising CO_2 concentration in the atmosphere leads to "CO_2-fertilization" of land plants – the plants can absorb carbon more easily and grow faster thanks to the additional CO_2. If there is less CO_2 in the atmosphere, the growth of trees and plants is reduced accordingly. If the CO_2 concentration in the atmosphere falls from 425 ppm to 350 ppm, halving the increase since pre-industrial times, it is also to be expected that around 100 Gt C of the 200 Gt C absorbed since pre-industrial times will be released back into the atmosphere. This amount would also have to be removed from the atmosphere.

Removal of future anthropogenic CO_2 emissions

Until net zero is achieved, fossil fuels such as gas, coal, and oil will continue to be burned, meaning that CO_2 will continue to be emitted. In order to achieve 350 ppm, this CO_2 must also be removed from the atmosphere. With a steady reduction of today's emissions to zero in 20 years, this adds up to about 380 Gt CO_2 or around 100 Gt carbon more in required removal.

Total removal required and proposed removal target

As a result, we must expect to remove 450 Gt carbon or 1,700 Gt CO_2 in order to draw atmospheric CO_2-levels back down to 350 ppm (see Figure 4).[20] This does not account for potential additional CO_2 emissions, such as those resulting from the thawing of permafrost soils.

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[18] Smetacek 2024
[19] See Friedlingstein et al. 2025
[20] 450 gigatons of C * 3.67 = 1,651 gigatons of CO_2 rounded to 1,700 gigatons of CO_2 in the rest of the text

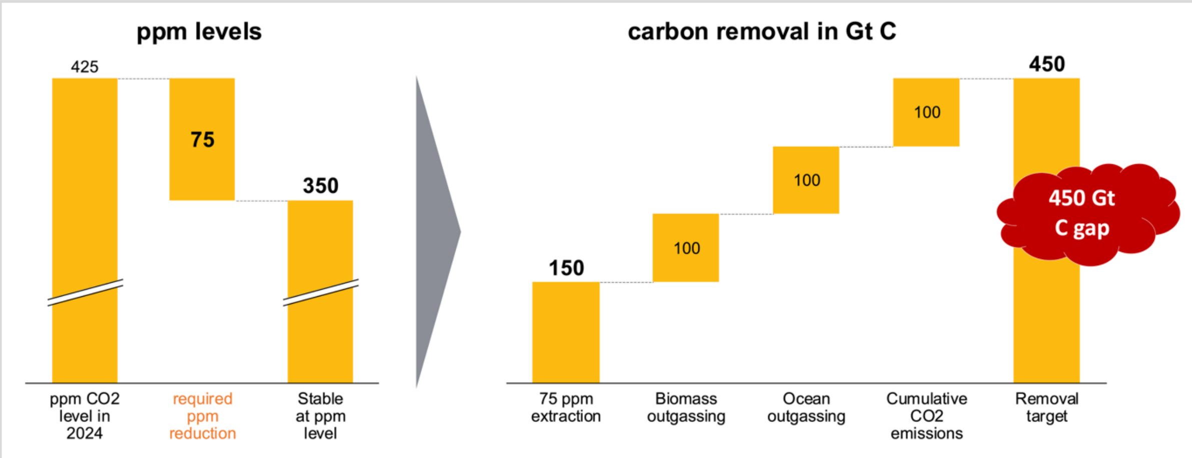

Figure 4: Schematic composition of the 450 gigaton carbon removal for returning to a safe climate level.[21]

This order of magnitude 1.700 gigatons of CO_2 is consistent with a simulation by Prof. Dr. Christian Breyer, who determined that CO_2 removals of 1,750 Gt CO_2 are necessary to reduce global warming to 1.0 °C compared to pre-industrial levels.[22]

The gigaton carbon removal gap in climate protection

The Paris Agreement and the IPCC reports emphasize that emissions must be reduced to zero. And it is recognized that CO_2 must also be removed from the atmosphere.[23] In view of the rapid acceleration of CO_2 concentration in the atmosphere, we call for a timely and clear answer to the crucial questions of carbon removal: how much, how fast, and by what means?

As long as CO_2 levels remain well above the safe 350 ppm, polar ice melting, extreme weather, and other tipping points will continue to progress. Although the IPCC discusses removal quantities, there is a lack of clear targets in climate policy that can serve as a basis for action in politics, business, and society.

The two likely main reasons for this "political removal gap":

- The temperature limit for global warming has been too high. The IPCC and the Paris Agreement maintain that 1.5 °C is the threshold. But it has become sufficiently clear that 1.5 °C is no longer a safe limit. The planetary limit is closer to 1.0 °C or 350 ppm CO_2.
- The underestimated speed of global warming, i.e. the assumption that we have not yet “permanently” reached 1.5 °C. An evaluation by the Energy Watch Group shows that this threshold has already been exceeded.

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[21] Friedlingstein et al. 2023

[22] Breyer et al. 2023

[23] p. 123, IPCC 2018

According to mathematical extrapolation of the historical data, the next threshold of 2.0 °C will be reached as early as 2032.[24]

Carbon removal must not remain a taboo subject or a vague plan for the future. The world is already in "overshoot" mode, i.e. beyond safe CO_2 limits. According to the IPCC, this state should be kept as short as possible, since the consequences are serious and, in part, irreversible. Carbon removal must therefore begin immediately and be scaled up rapidly.

With all seriousness and sense of responsibility, we call for establishing a politically and legally binding carbon removal target as the new benchmark for climate policy.

In our opinion, it is imperative to close this "gigaton gap" in climate targets, so the removal targets can serve as an anchor point for the global expert community and thus also for political decision-makers. The calculated carbon removal requirement should also include a buffer for the expected breach of the 2.0 °C limit[25] and for resulting tipping points such as the thawing of permafrost soils.

Those who fail to act now risk closing the window of opportunity for a safe return below critical thresholds, with irreversible consequences for present and future generations.

Proposed timeline

In addition to resolving technological issues, timing is crucial for effective carbon removal. It would be desirable and necessary to achieve removal of 450 Gt carbon over the next 20 years in order to keep global warming well below the 3.1 °C expected under current policies and to limit the severity and duration of damage caused by exceeding the planetary boundary of 1.0 °C warming (see Figure 5). However, that does not appear to be feasible - politically, technically, or financially - on that scale in that timeframe.

[24] Fischer, Schwarz & Fell 2025

[25] UN Environment Programme 2024: In this report, the United Nations predicts that global warming will reach 3.1 °C with existing climate policy measures.

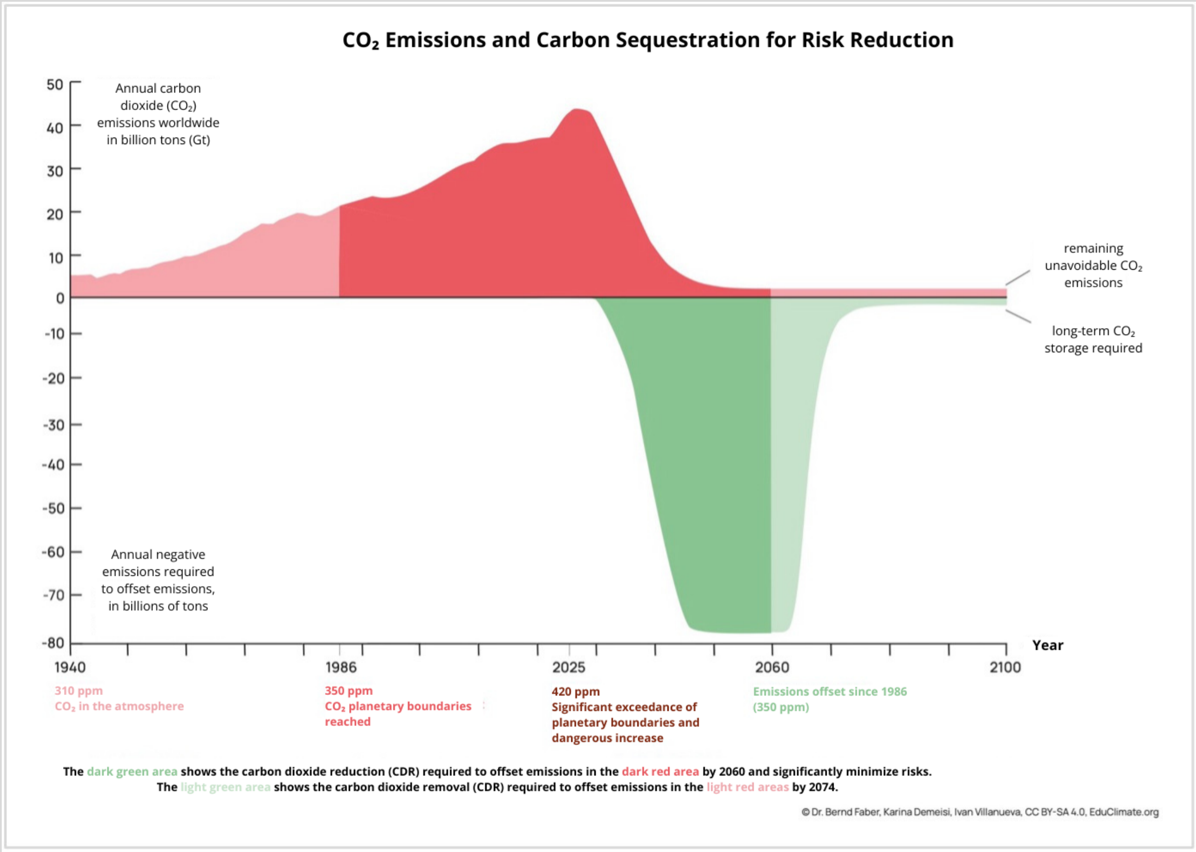

Figure 5: CO_2 reduction pathways and CO_2 removal pathways as well as the removal gap; unpublished graphic by Karina Demeisi and Dr. Bernd Faber, EduClimate gUG, based on Sovacool et al. 2022, schematically corrected to reflect actual quantities, translated by German by Energy Watch Group.[26]

Therefore, for the purposes of this paper and future climate policy, the following key parameters are used as a basis and recommendation:

- 450 Gt of carbon or 1,700 Gt of CO_2 must be removed.
- The technical and economic maturity and scalability of technologies to achieve removal at that scale should be reached by 2035 to 2040 at the latest.
- This should be followed by a forty-year phase of intensive removal on an industrial scale.
- Removing a total of 450 Gt of carbon or 1,700 Gt of CO_2 in 40 years, requires an average annual removal rate of approx. 10 Gt of carbon or 40 Gt of CO_2.

[26] Unpublished graphic by Karina Demeisi and Dr. Bernd Faber, EduClimate gUG, based on Sovacool et al. 2022, schematically corrected to reflect actual quantities.

3. Approaches to CO_2 and carbon removal

The goal of removing 450 gigatons of carbon from the atmosphere leads to the various technical and biological removal methods currently being discussed and developed.

Politicians and the public often discuss so-called "negative emissions" – a concept based on carbon capture from industrial processes during and after the combustion of fossil fuels. However, this is completely different from carbon removal, as it merely reduces emissions but does not remove carbon from the atmosphere. The decisive factor is not only to release fewer pollutants and reduce emissions to zero, but, as already mentioned, to remove the carbon that has already been emitted. We will therefore not use the term "negative emissions" in the following.

This is because carbon capture has no effect on the concentration of CO_2 already present in the atmosphere.

Carbon removal means extracting carbon from the atmosphere that has already been emitted

Carbon removal means extracting carbon that has already been emitted from the atmosphere, binding it, and thus permanently removing it from the atmosphere. This can be achieved through natural carbon sinks on land (intact forests, humus formation, rewetting of wetlands), on coasts (mangroves, seagrass), and in the oceans through increased seaweed growth.[27] Technical processes from the field of carbon capture and storage (CCS), *direct air capture* (DAC) or in combination with bioenergy (BECCS) are also being discussed in this context.

To reduce atmospheric concentrations, it is essential to extract CO_2 that has already been emitted from the air. Only large-scale carbon removal can close the 450 gigaton gap and stabilize the climate in the long term. This is the political, legal, and technological task at hand.[28]

The permanent storage of the captured CO_2 is an essential part of the process. This can be achieved by storing it in geological formations, provided these are truly safe, or by binding it in long-lasting products such as building materials. In

[27] See the Öko-Institut's brief study on structuring the complex LULUCF sector and on the necessity, interrelationships, and potential of emissions to be captured and effective removal, DENA 2021

[28] See Markus et al. 2023, p. 2 and Sovacool et al. 2022

contrast, the use of captured CO_2 in short-lived products such as fuels does not lead to sustainable carbon removal, but merely delays emissions[29].

Clarifying the term "removal" in the climate policy debate

This policy paper has no intention of supporting the argument, that carbon removal would allow mankind to reach net zero while continuing to burn fossil fuels. This argument suggests that it is virtually impossible to avoid all man-made greenhouse gas emissions by the middle of the century. Emissions that are difficult to avoid occur, for example, in cement and fertilizer production, in construction machinery, in air and heavy transport, in agriculture, and in waste incineration. Methane and nitrous oxide emissions, especially in the agricultural sector, are also difficult to avoid, or their avoidance entails high economic and social costs. It is regularly claimed that there are no other solutions, but these are often already available, such as the production of green steel using electric arc furnaces or the replacement of Portland cement with innovative carbon-binding cement types. In addition, there is no consensus on how high these residual emissions may be and how they should be distributed among the various sectors. Offsetting measures would be necessary to neutralize unavoidable residual emissions, and carbon removal is being given the red-carpet treatment for that purpose.[30]

This is not wrong, but it is also not right. The actual removal effort consists of having to extract 450 gigatons of climate-impacting carbon that has already been emitted from the atmosphere. If this focus is blurred, the priorities and the necessary political decisions become blurred as well. Our aim is to promote the threefold political thrust towards zero CO_2 emissions, climate adaptation, and carbon removal to avoid the escalating effects of the climate tipping points.

Scientific and emotional skepticism instead of political ambitions

In addition to technological and economic challenges, there are also major obstacles in the political environment surrounding this issue. With our paper, we want to help open new discussions and overcome deadlock in ongoing discussions.

Various sectors of society repeatedly express concerns about large-scale carbon removal technologies, which hinders serious political and strategic discussion:

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[29] However, making products from captured CO_2 that can replace fossil raw materials is an important prerequisite for achieving the net-zero target.

[30] See also the argumentation in the foreword to the report on the research mission of the German Alliance for Marine Research (DAM) "Marine carbon sinks as a path to decarbonization" by the Federal Ministry of Education and Research in CDRmare 2024

- Science: Many scientific experts warn that large-scale carbon removal is both technologically and ecologically risky. They emphasize that the focus should be on rapidly and comprehensively reducing emissions rather than relying on immature technologies that only intervene after CO_2 has been emitted. There are also concerns that the expansion of carbon removal methods weakens the political and economic resolve to reduce emissions. Critics fear that companies and lobby groups could use carbon removal as a pretext to keep fossil fuels in use for as long as possible – with potentially absurd consequences such as the marketing of "emission-free oil." People would rather not open this Pandora's box in the first place – but in consequence the urgently needed scaling of carbon removal methods gets put off.
- Lobby research organizations: These organizations compete for larger research grants and tend to exaggerate the potential of some carbon removal technologies while downplaying others. As a result, politicians tend to wait until a generally accepted position has developed so as not to be responsible for public investment in the wrong technological path.
- Nature conservationists: They warn that humans have already deeply interfered with ecosystems and caused considerable damage. In their view, any further manipulation of nature through large-scale CDR could have further unpredictable consequences.

In part, these concerns and attitudes omit the much more concrete dangers posed by the carbon that has already been emitted remaining in the atmosphere. Without carbon removal, even if emissions are successfully reduced, there is a risk of exceeding several tipping points in the climate system – such as the destabilization of the Atlantic Meridional Overturning Circulation (AMOC) or further overheating and acidification of the oceans, which would result in the death of marine ecosystems such as coral reefs. [31] Land biodiversity is also declining as a result of further warming of the atmosphere.

No "waste handling of further emissions," but carbon removal from the atmosphere

To put it clearly and unequivocally: this is not about "waste handling" of further fossil fuel emissions such as capturing CO_2 from industrial plants and power stations, but about removing carbon that has already been emitted: these 450 Gt of carbon must be removed from the air. There is no other way to return to a safe temperature level.

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[31] The Atlantic Meridional Overturning Circulation (AMOC) regulates the climate. High freshwater inflows from melting Greenland ice could destabilize it. A collapse would have drastic consequences: colder winters in Europe, droughts in Africa, and rising sea levels on the US East Coast. Studies warn of a standstill between 2050 and 2100—with irreversible climate consequences.

Offsetting CO_2 emissions may buy valuable time but is not an alternative. That is why the period until 2040 is crucial for introducing, developing, and deploying these technologies on the necessary scale.

However, the development and expansion of carbon removal is currently suffering from a significant deficit in innovation, research, funding, and political support.[32] This is hampering progress and also carries the risk that the necessary scaling will not be achieved in time. Focused investment and changes in the political framework are needed to drive these technologies forward, to create markets willing to pay, and simultaneously generate the necessary social support.[33]

It should be emphasized to associations, politicians, and the media that carbon removal does not replace the necessary drive to achieve net-zero emissions, but rather complements it, especially regarding non-reducible residual emissions. The smaller this base is, the fewer offsetting measures are required. CDR can then remove emitted CO_2 from the atmosphere more quickly – an evident mathematical correlation.

This perspective is also shared by leading research institutions such as the Mercator Research Institute and the Potsdam Institute for Climate Impact Research. In their study on “CO_2 Removal – Necessity and Regulatory Options," commissioned by the Science Platform Climate Protection they come to the clear conclusion: "*Due to the German Climate Protection Act, CO_2 removal options must be scaled to relevant quantities by 2040*."[34]

As a logical consequence, in analogy to the Climate Protection Act and modern policy planning and transformation laws[35] , carbon removal goals should be defined in annual steps in order to do justice to the magnitude of the task and not lose time for acting on it.

For humankind and our future generations, our paper calls for a new common stance on decisive action:

Those who allow more time to pass before engaging in large-scale expansion of carbon sinks are responsible for permanent global warming of at least 3.1°C. This is the UN’s prediction of where current commitments and measures will lead, aptly described by the UN Secretary-Generalas "climate hell".

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32 See Sovacool et al. 2022
33 See also Ma & Merrill 2025
34 See Fuss et al. 2021 (p. 5)
35 See dissertation project Neubauer 2025

Of the sixteen tipping points identified for the Earth's climate system, five may already have been triggered at the current level of warming around the 1.5°C threshold. These include the death of tropical coral reefs, the abrupt thawing of permafrost soils, the melting of ice sheets in Greenland and West Antarctica, and an abrupt collapse of the current in the Labrador and Irminger Seas in the North Atlantic.[36]

Waiting and hoping will not help – this is not a strategy or a solution to the scientifically proven correlations described above.[37]

The scale and relevance of carbon removal approaches

The amount to be removed, 450 Gt carbon or 1,700 Gt CO_2, draws attention to all the technical and nature-based ideas, processes, and methods being discussed. Among these, those are relevant that can make a sufficiently large contribution towards meeting the target at reasonable cost beginning 2040 or earlier.

1,700 gigatons of CO_2 correspond to:

- 1,700 billion tons or
- 1,700,000 million tons or
- 1,700,000,000,000 tons.

The processes used would need to have a carbon removal potential of a gigaton or more per year.[38] And some 40 gigaton-processes would be needed to achieve the required carbon removal within 40 years. These processes need be set up and working within the next decade.

Overview of options

There are various approaches to carbon removal, which are presented in Figure 6 and described in more detail later in the text.[39]

[36] Armstrong McKay et al. 2022
[37] Wunderling et al. 2021 and Schellnhuber et al. 2016
[38] See argumentation on the order of magnitude in the overview article by Barnard 2024
[39] More detailed descriptions can be found on p. 1275/1276ff, IPCC 2023 Full Report, among others.

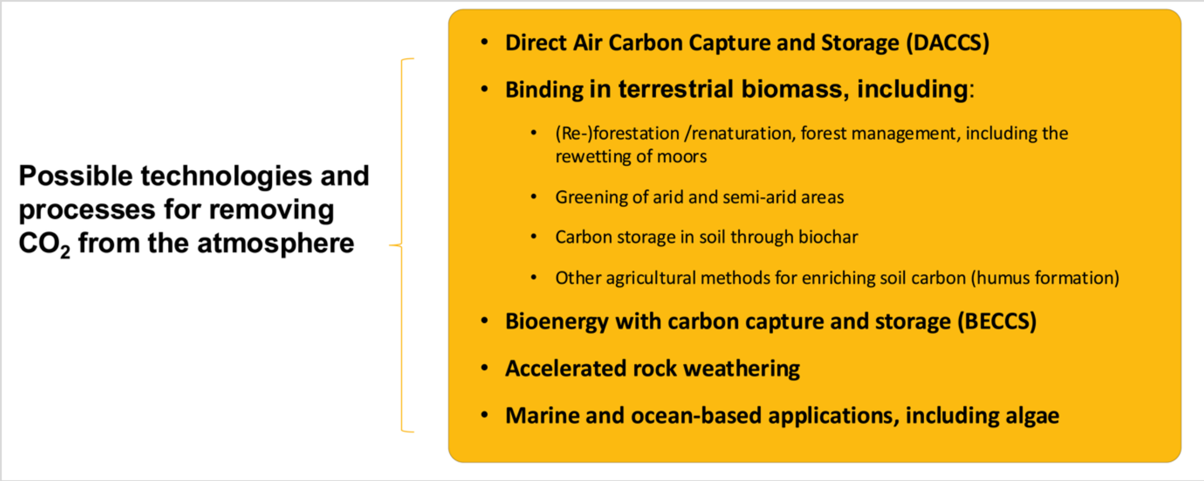

Figure 6: Overview of possible technologies and processes for removing CO_2 already emitted from the atmosphere (the technologies and processes printed in bold are described in more detail below).

The options currently under discussion in politics and science are still in their infancy in terms of extraction volumes on a gigaton scale. In addition, considerable technical, economic, and ecological challenges must be overcome before they can be implemented on a large scale.[40]

Their costs are currently difficult to quantify, partly due to a lack of scaling experience, and are therefore still estimated by the IPCC to range from EUR 40-50 to EUR 200-300 per ton of CO_2. This uncertainty in costs ranges does not provide a clear cost-benefit prioritization of options.[41,42] To give an idea of the relevance of these cost rates: at USD 100 per ton of CO_2 removed, the removal of 1,700 Gt of CO_2 would cost around USD 170,000 billion. This is almost twice the current annual global gross domestic product.[43] When you consider how long it took industrialized countries to commit less than 0.6 thousandths of this amount (USD 100 billion) to climate protection and climate adaptation in the Global South, it becomes clear how challenging financing carbon removal will be and how crucial cost-effective removal methods will be.

We advocate that, for the time being, all options should be pursued responsibly and without prejudice to any particular technology, as none of the options are yet sufficiently reliable for use on a gigaton scale and their financial viability on the scale required is still unclear. In addition, greater attention should be paid to biological options, as these can make other important contributions to sustaina-

[40] See Sovacool et al. 2022

[41] p. 1275/1276ff, IPCC 2023 Full Report, column Cost (USD/tCO_2)

[42] These cost considerations do not take into account the contributions of carbon removal options to food security, combating the causes of migration, and much more, and therefore cannot be the sole evaluation criterion.

[43] Approximately USD 100 billion per year, see Federal Agency for Civic Education 2024

bility (biodiversity, food security, habitat preservation, desert greening) in addition to their contribution to carbon removal.

The goal must be to identify sufficiently scalable options with the best cost-benefit ratio and acceptable risks in order to then set priorities and push ahead with the necessary scaling of the key technologies at the political level.

Some key features of a non-exhaustive selection of options currently under discussion are:

Direct air capture (DAC)

Direct Air Capture, in which CO_2 is removed directly from the ambient air through chemical processes, is a much-discussed technology. Although it still faces considerable challenges, billions are already being invested in this technology, driven by companies such as Microsoft, Amazon, and Airbus, among others.[44]

DAC requires a great deal of energy. Estimates range from around 1,000[45] to over 5,000 kWh[46,47] per ton of CO_2 captured.

This is one of the reasons why, according to operator Climeworks, carbon removal at the world's largest DAC plant in Iceland currently costs between USD 500 and USD 1,000 per ton of CO_2 and will not fall below USD 300 per ton in the long term.[48]

At the yet unachieved price of USD 300 per ton, the cost of removing 1,700 Gt of CO_2 would be USD 510,000 billion – around five times the current global gross domestic product.

Furthermore, DAC does not yet appear to be ready for scaling up. Even in its third year of operation, the Climeworks plant Orca is still far below its full capacity of 4,000 tons of CO_2 per year, with a removal rate of 900 tons of CO_2.[49] Even with a rather optimistic estimate by the International Energy Agency[50] , the current DAC performance is a maximum of 0.00006 Gt CO_2 per year, or 0.2

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[44] Ma & Merrill 2025
[45] BDEW 2022
[46] 2,650 kWh, Chalmin 2021
[47] 4,000-5,000 kWh, p. 3041, Jacobson et al. 2025
[48] De Luna 2024
[49] Alexandersson & Grettisson 2025, Haitsch 2025
[50] IEA 2025. This estimates the current global DAC removal capacity to be 10,000 t CO_2 per year. Of this, 5,000 t CO_2 is attributed to the Climeworks plant in Orca. However, this corresponds more to the nominal capacity of 4,000 t CO_2 than to the actual removal capacity of currently around 900 t CO_2 per year (see Alexandersson 2025).

millionths of the removal requirement of around 40 Gt CO_2 per year derived in Chapter 2. Furthermore, questions regarding the long-term and safe storage of CO_2 remain unanswered. In this respect, it is currently still uncertain from an operational, energy, and financial perspective whether DAC can make a relevant contribution to the removal of 1,700 Gt CO_2. To clarify these questions, it is important to continue pursuing the scaling and development of DAC.

Sequestration in terrestrial biomass

The sequestration of CO_2 in terrestrial biomass has existed since plants have existed on land. Its effectiveness is also demonstrated in the above-mentioned increase of some 200 Gt of carbon bound in terrestrial biomass over the last 150 years, parallel to the rising CO_2 content of the atmosphere. This increase is largely attributed to the "fertilization effect" caused by the higher CO_2 concentration.[51] This biomass sequestration can be achieved through reforestation, humus formation, and greening of previously arid and semi-arid areas, among other measures. The carbon is then stored in the living biomass or, for example, by conversion into biochar.

However, there are limits to this removal process. Although forests still are major carbon sink among the terrestrial sequestration options, their contribution has declined in recent years in some regions due to deforestation, forest fires, and climate change stressors such as higher temperatures and longer dry periods.[52] In addition, conflicts over land use with agriculture and forestry, as well as with housing and infrastructure development, need to be renegotiated on an ongoing basis.

Even if these challenges do not turn forests in a net carbon source: if the CO_2 concentration in the atmosphere is reduced to 350 ppm, it is expected that terrestrial biomass will become a carbon source equivalent to about 100 Gt of carbon, as explained above. This is the equivalent to ten more years of current global CO_2 emissions.

Blue carbon systems, coastal ecosystems with carbon removal potential

In addition to land-based options, there are other methods using biological systems in oceans. Today, the term *"blue carbon systems"* refers to plants and algae in coastal and marine ecosystems that store significant amounts of carbon, although this is limited by the restricted area available for this purpose. These include:

[51] p. 566, Pan et al. 2024
[52] p. 567, Pan et al. 2024

- Mangrove forests: Coastal forests that thrive in salty water and store large amounts of carbon in their roots and sediments.
- Seagrass beds: Underwater plants that grow along coasts in shallow waters and bind carbon both in their leaves and sediments.
- Salt marshes: Coastal wetlands that are flooded at high tide and store considerable amounts of carbon in the soil.

These forms of blue carbon systems store organic material for centuries in carbon layers up to 10 meters thick. Both the carbon storage in the root system and the airtight enclosure of animal and plant residues accumulate more and more carbon-containing organic material over time. This removes climate-damaging greenhouse gases from the atmosphere. They store up to 30 times more carbon per area than tropical rainforests. Outside of marine research, this capacity and efficiency is largely unknown in comparison to the carbon uptake and storage of forests on land.

Currently, seaweeds near the coast are the subject of intense and frequent discussion, along with other coastal ecosystems such as mangroves, seagrass beds, and salt marshes. There are a number of studies and literature on this topic as well as innovation and research projects that can be found under the keywords *Blue Carbon Systems* or *Blue Carbon Dioxide Removal* (blueCDR).[53 and 54] Although the term 'blue carbon' has not yet been consistently defined scientifically, it is becoming increasingly important in international climate policy.

According to the IPCC overview, the potential of blue carbon systems for carbon sequestration is estimated to be rather low, at 1 to 3 Gt CO_2 per year.[55] Coastal blue carbon competes with other uses such as shipping and suffers from pollutant discharges from industry, agriculture, and wastewater. At the same time, it can compensate for overfertilization and create new habitats for fish stocks, thereby contributing to food security. CO_2 is sequestered via living biomass in the short term. Long-term storage only occurs through death and sedimentation, with limited efficiency, because most of the living biomass is converted back to CO_2 after the death of the organism through decomposition. Nevertheless, these ecosystems are important building blocks of marine carbon removal.[56]

Significantly greater opportunities are opening up in the open ocean. This is where so-called *ocean carbon systems* come into play, which aim to cultivate fast-growing, free-floating seaweed on an industrial scale – far away from coasts, with

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[53] Mengis et al. 2023; see also Brooks et al. 2024

[54] Macreadie et al. 2019, Lovelock & Duarte 2019, Gao et al. 2022, Röschel et al. 2022, Peter et al. 2024

[55] p. 1275/1276ff, column "Mitigation Potential," IPCC 2023 Full Report; see also Öko-Institut 2024

[56] p. 1271, IPCC 2023 Full Report

less competition for space and significantly higher scaling potential. In an additional step, the biomass produced is largely and permanently bound, unlike in the blue carbon systems described above.

A look at the carbon removal methods discussed so far – such as direct air capture (DAC), land- and forest-based methods, as well as blue carbon systems – shows that none of these solutions alone is sufficient to reliably capture the necessary amounts of CO_2. Therefore, additional options need to be developed urgently. Ocean carbon systems promise exactly that – a new, scalable carbon sink strategy with economic and ecological added value.

4. Blue potential – how seaweeds and Ocean Carbon Systems can improve the global carbon footprint

Around 70 percent of the Earth's surface is covered by oceans. Of the approximately 100 gigatons of carbon that are bound temporarily in biomass on our planet every year by means of solar energy, half is produced by land plants and half by algae, consisting of seaweed and microalgae, in the world's oceans[57] – a compelling reason to make greater use of algae's carbon removal potential.

Algae are nature's hidden champions, especially when it comes to carbon removal and marine ecosystems in general. Their importance for marine ecosystems, their unique characteristics, and their versatile applications are often overlooked.[58] One of the greatest strengths of algae lies in their rapid growth.

There is already a seaweed farming industry with a global algae production of approximately 35 million tons per year, which is dominated by Asian countries such as China, Indonesia, the Philippines, North and South Korea, Japan, and Malaysia with a market share of 98 percent; however, there is no focus on carbon removal.[59]

The diversity of algae

Algae are an extremely diverse group of organisms found in fresh and salt water. They are divided into different groups, including brown, green, and red algae, and vary greatly in size, shape, biological characteristics, and habitat. Algae can be sessile or free-floating and can be roughly divided into three categories: free-floating single-celled planktonic algae (phytoplankton), seaweed growing attached, and free-floating macroalgae.

- Plankton algae (phytoplankton) are microscopic single-celled organisms that float freely in the water and play a central role in the marine ecosystem as a food source for many marine organisms.
- Seaweed species growing attached to hard substrates, such as giant kelp, sugar kelp, bladderwrack, and other types of seaweed, anchor themselves to the seabed or other surfaces near the coast and form dense underwater forests.

[57] Field et al. 1998 and Falkowski et al. 1998

[58] See Brooks et al. 2024, Duarte et al. 2017, D'Abramo & Slater 2019, Röschel et al. 2022, Hanley 2025a, Slater 2024 and the documentation Patagonia Films 2023

[59] Kainz 2023

- Free-floating seaweed drift freely in the water and can therefore also live in the open ocean. A well-known example is the brown seaweed Sargassum, which forms huge floating carpets in the Sargasso Sea.

Sargassum – the floating wonder

Sargassum is a genus of seaweed best known for its two free-floating species, *Sargassum natans* and *Sargassum fluitans*. These two species form extensive floating mats on the ocean surface, after which the Sargasso Sea in the north-western Atlantic is named - often referred to as the 'golden rainforest of the Atlantic' because of its exceptionally high biodiversity and protection for many marine organisms (see Figure 7). Unlike many other seaweed species, they complete their entire life cycle free-floating in the water column without being attached on the sea floor or on solid surfaces. For the sake of clarity, the term "Sargassum" will be used throughout this paper to refer to both species.

Sargassum has enormous growth rates, doubling in biomass within about 10 days or less and developing a layer two to three meters thick near the surface, under which plankton and, subsequently, the rest of the marine food chain can settle.[60] Sargassum has a high ratio of carbon to the nutrients nitrate and phosphate and can bind up to eight times more carbon than microalgae with the same amount of nutrients.[61] When dried, Sargassum consists of an average of 30 percent carbon.[62] These beneficial properties could be further optimized through seaweed cultivation programs, just as humanity has bred land plants with beneficial properties since the beginning of agriculture. Another major advantage of Sargassum is that it reproduces by fragmentation and does not require complex hatcheries after reproduction, as is the case with many other seaweed species.

[60] See Prosek 2019, Lapointe 1986, Lapointe et al. 2014, Xiao et al. 2019, Magaña-Gallegos et al. 2023
[61] See Lapointe et al. 2021
[62] See Desroches et al. 2020

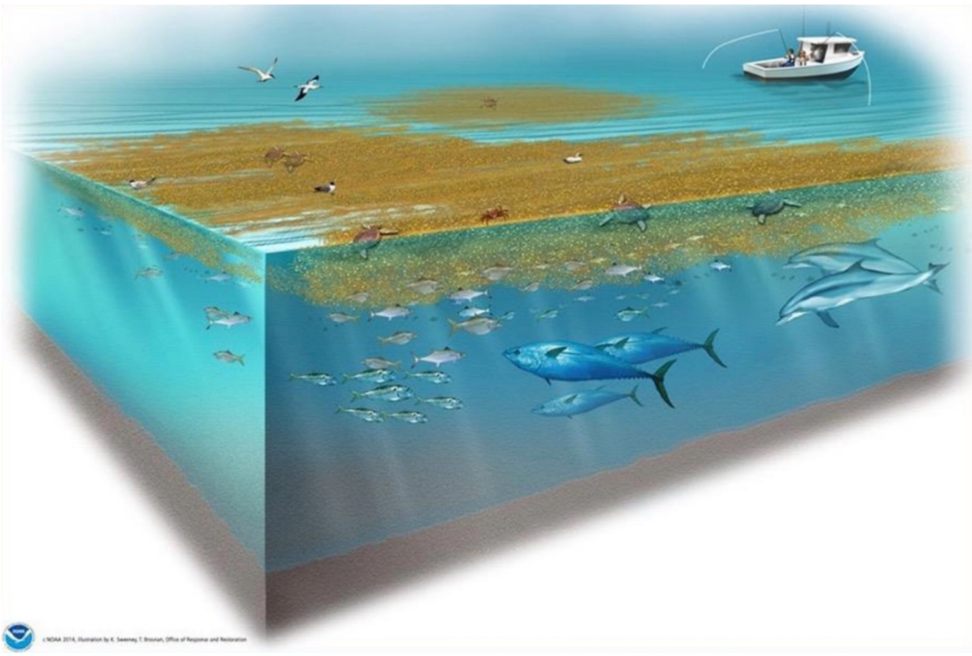

Figure 7: Illustration of the brown seaweed Sargassum, which forms a unique and extremely productive floating ecosystem on the surface of the open ocean, connected to marine fauna including fish, sea turtles, birds, and marine mammals.[63]

As the Sargasso Sea shows, free-floating Sargassum mats provide valuable habitat for many marine organisms. Similarly, large-scale seaweed farms in the open ocean could create new ecological hotspots and promote marine life in previously nutrient-poor regions. Some of the nutrients from the deep water would also stimulate the growth of plankton – the basis of many marine food chains. In addition, the seaweed release organic substances into the water that serve as food for microorganisms and small animals. This could lead to the development of diverse animal communities around the farms – from schooling fish to predatory fish. These would not only contribute to biodiversity, but also create new, sustainable fishing grounds. In addition, edible seaweed species and marine animals could be cultivated on the farms. Seaweed-based animal feed also has potential: it could replace soy and thus help to reduce deforestation in tropical forests.

The Sargassum mats also provide an important habitat and shelter for numerous marine organisms. At least ten endemic species live in the Sargasso Sea that are found exclusively in floating Sargassum. These highly specialized organisms - including the Sargasso fish—have adapted perfectly to the appearance of Sargassum and are virtually invisible among the seaweed thanks to this camouflage - proof that Sargassum itself is hardly ever eaten. Many fish species use Sargassum to lay their eggs, hide from predators, or hunt, including species such

[63] Image: NOAA 2014, illustration by K. Sweeney, T. Brosnan, Office of Response and Restoration

as tuna, dolphins, and swordfish. These mats are particularly important for various species of sea turtles, which find shelter and food in the drifting seaweed mats when they are young. A special phenomenon is the migration of the European eel. This species uses the seaweed mats in the Sargasso Sea for reproducetion, traveling thousands of kilometers from European inland waters to reach them.

Sargassum sometimes forms huge carpets, some as large as soccer fields, which are visible from satellites in space.[64] The Sargassum carpets are not only a habitat for numerous marine organisms, as described above, but also important carbon sinks. By installing infrastructure to promote nutrient-rich deep water – similar to irrigation canals on land – these algae could be cultivated and used specifically for carbon removal. We therefore speak of the potential of "Ocean Carbon Systems".

Ocean Carbon Systems, the marine ocean industry with carbon removal potential

Unlike blue carbon systems, ocean carbon systems involve the industrial cultivation and harvesting of fast-growing large algae in the open ocean with the aim of removing carbon and opening up new value chains (see Figure 8). This allows climate-damaging greenhouse gases to be removed from the atmosphere. Ocean Carbon Systems are therefore also being discussed and researched as carbon sinks and developed by start-ups as marketable services.[65]

This approach has significantly greater potential for carbon sequestration than the approaches used in the IPCC overview[66] to assess the potential of seaweed for carbon sequestration. Ocean Carbon Systems

- use free-floating seaweed in the open ocean, which offer significantly larger areas and considerably fewer conflicts of use, rather than limiting themselves to seaweed species that grow attached to hard surfaces near the coast.
- are taking the step from supporting natural seaweed growth to systematic "farming" with increased yields.
- enable access to nutrient-rich deep water to significantly increase seaweed growth in nutrient-poor ocean regions.

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[64] Ody et al. 2019

[65] See, among others, Carbonwave 2025, Climate Foundation 2025, GreenWave 2025, Kelp Blue 2025, MacroCarbon 2025, North Sea Farmers 2025, Ocean Rainforest 2025, Origin by Ocean 2025, Pull to Refresh 2025, Sea6 Energy 2025, Seafields 2025, Seaweed Generation 2025

[66] p. 1275/1276ff, column "Mitigation Potential", IPCC 2023 Full Report

- aim to permanently sequester the carbon removed from the atmosphere in long-lived materials or by depositing pre-treated seaweed biomass in the deep sea – instead of allowing the carbon bound in the seaweed biomass to be mostly converted back into CO_2 after it dies, with only a small fraction sinking and turning into sediment.

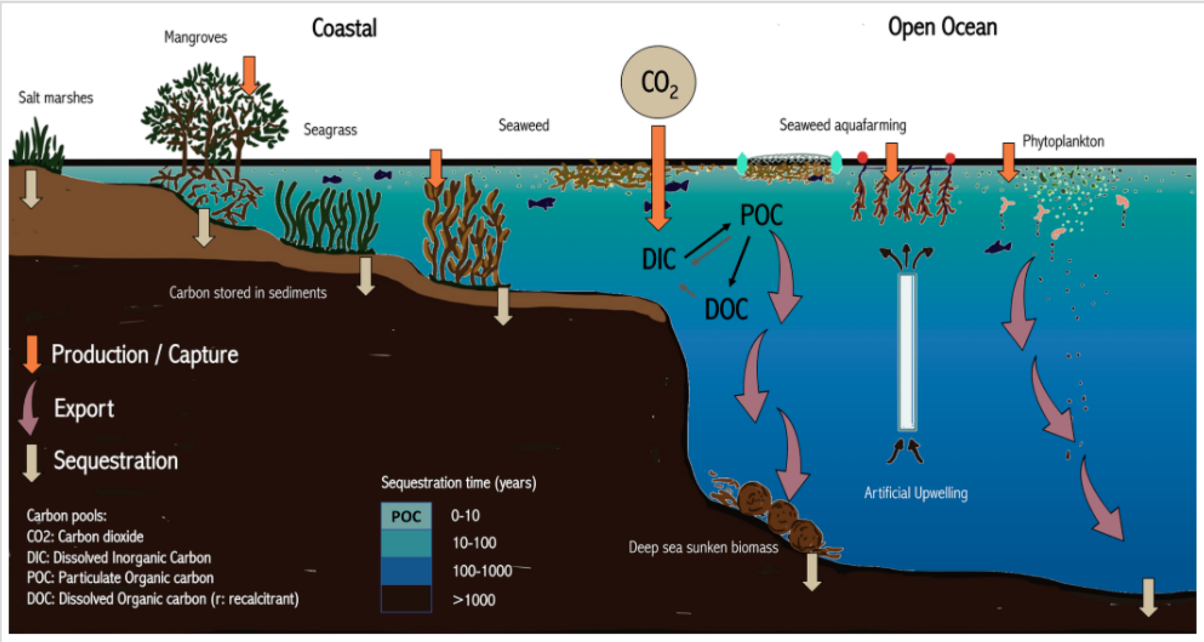

Figure 8: Blue carbon systems near the coast and ocean carbon systems on the open ocean.[67]

A real ocean aquafarming economy of free-floating seaweed could be used to cultivate the virtually lifeless marine deserts – while simultaneously removing CO_2. This is because some of the nutrients are also absorbed by planktonic algae, which in turn serve as food for zooplankton and fish, creating new food chains and increasing biodiversity. The seaweed biomass cultivated in this way can be harvested at regular intervals. It is then processed on site in production ships or in coastal facilities.

The expected harvest time of only two to three weeks enables efficient and continuous production. Many of the basic technologies required for this have long been established: offshore wind farms, deep-sea drilling rigs, floating platforms, seawater heat pumps, geothermal energy, and suction dredgers show that adapting the technology for large-scale series production is not rocket science - it is more a question of focus, financing, and market entry support.

The establishment of such natural, modular, energy-autonomous, and largely self-sufficient large-scale seaweed farms can contribute to food security and a virtually inexhaustible supply of raw materials for construction purposes on land

[67] Figure Mengis et al. 2023

through adjacent aquaculture, while also binding CO_2. The establishment of large-scale seaweed farms in the open ocean will take pressure off overused coastal ecosystems while creating income and jobs in the Global South.

If Sargassum aquafarms can be developed on an industrial scale in areas of the vast oceans, this could lead to multiple win-win solutions – carbon removal, increased marine biodiversity, the protection of currently heavily exploited coastal ecosystems, and the development of new sources of income for developing and emerging countries.

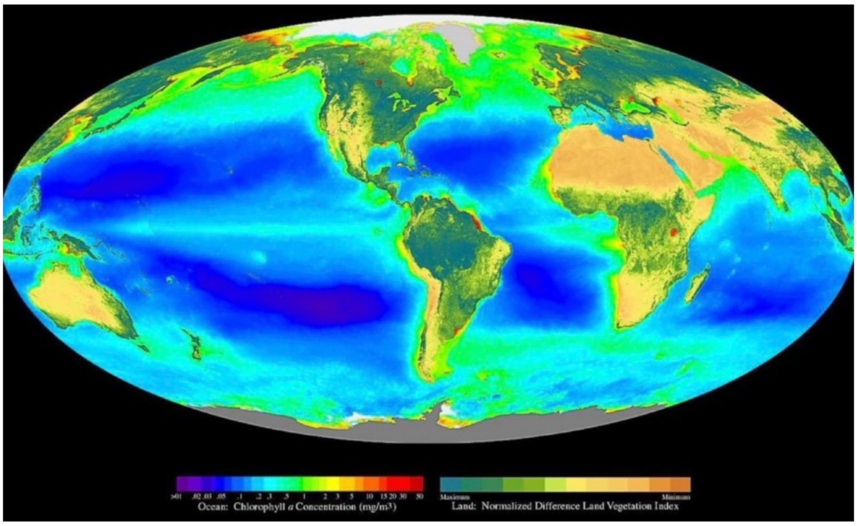

Figure 9: Visualization of global vegetation on land and in the oceans. The representation of the long-term average chlorophyll concentration in the oceans clearly shows that the five subtropical gyres (the dark blue to purple areas), which cover 50 percent of the Earth's surface, are oceanic deserts with a very low concentration of algae.[68]

Ocean carbon systems in subtropical gyres, the "deserts of the oceans"

The subtropical gyres, where a lack of deep currents near the surface provides too few nutrients for plankton and the marine food chain, are particularly suitable for this (see Figure 9). The five subtropical gyres cover almost half of the Earth's surface and are located in the Atlantic, Pacific, and Indian Oceans. They are high-pressure areas with mild weather and rare storms; [69] These "deserts of the ocean" consist of thick rotating layers of warm water with a nutrient-poor surface water of some 200 meters depth and nutrient-rich deep-water at depths of 400 to 1,000 meters. There is hardly any fishing activities due to the lack of fish stocks. What is missing is vertical mixing.

The deep water is rich in nutrients, while the surface water in the subtropical gyres is depleted. If plankton and algae are not consumed, they sink to the sea floor after they die, together with the nutrients and CO_2 they contain, where they

[68] Image: SeaWiFS Project 2000
[69] See Figure 1 in Mendelsohn et al. 2012 & NASA Earth Observatory 2006

become part of the sediment. This leads to the "depletion" of the surface, while almost unlimited amounts of nutrients are available in the deep ocean.

Seaweeds as a nuisance

Outside the subtropical gyres, Sargassum mats become a problem when they wash up on beaches and significantly impact the local economy and tourism.[70] Seaweeds are therefore a serious nuisance on some coasts. A significant growth of Sargassum mats outside the Sargasso Sea first occurred in 2011, probably facilitated by increased nutrient input in the Amazon estuary. The resulting "Great Atlantic Sargassum Belt" stretches from the West African coast to the Caribbean, where it causes significant problems, including a decline in tourism and health hazards from the release of foul-smelling gases. These gases form when large masses of seaweed rot on beaches. Such landfalls have only occurred since 2011, after Sargassum mats also appeared outside the North Atlantic subtropical gyre, where they found elevated nutrient concentrations.[71]

Quite unintentionally, the seaweed plague in the Chinese Sea clearly demonstrates that large free-floating seaweed react to the supply of nutrients with increased growth. In a short period of time, a large amount of biomass can build up and then be easily harvested.

The seaweed blooms in the Yellow Sea—between China, South Korea, and Japan—are a new phenomenon that is clearly linked to eutrophication, i.e., the increased nutrient input from rivers due to intensive agriculture. Pieces of seaweed species that normally grow attached to hard surfaces carried into the Yellow Sea by currents when aquaculture facilities are cleaned along the coast. There, they can continue to grow and build up significant biomass that later ends up on the beaches with undesirable consequences. To limit the damage to beaches and widespread aquaculture along the coast, several fishing vessels were deployed in 2022, for example, to collect 450,000 tons of green seaweed biomass with nets – a kind of "proof of concept" for a marine carbon removal industry that grows algae and then harvests it.

In their assessment published in Nature Communications, Smetacek et al. show that the seaweed blooms of a Pacific Sargassum species and the green seaweed Ulva in the Yellow Sea are suitable natural analogs for future cultivation of seaweed in the open ocean.[72]

In fact, the Sargassum plagues outside the subtropical gyres have already led to the first technology and service clusters developing marketable processes to

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[70] Smetacek 2024
[71] Baier 2024 and Jolley 2021
[72] Wang et al. 2023 & Smetacek et al. 2024

eliminate these problems. The next logical step would therefore be to develop the coastal problem-solving start-ups into an open-ocean cluster and a and a seaweed aquafarming and processing industry.

The current expansion and the potential of oceanic aquafarms, highlight the need for a large-scale strategy for the controlled containment and harvesting of these seaweeds and for systematic aquafarming development. This will enable existing problems to be eliminated, new economic potential to be created for developing and emerging countries, and a variety of technological processes to be further developed and tested near the coast in order to unlock the carbon removal potential on an industrial scale in subtropical gyres – while at the same time restoring biodiversity in coastal waters that have been partially overfished.

Scaling up seaweed aquafarming in ocean carbon systems

In addition to storage in long-lasting products, seaweed biomass can be used for markets such as biofuels, animal feed, bioplastics[73], or CO_2-binding building materials to combine economic efficiency with climate protection and substituting fossil petrochemicals. This approach can and should also be used to clean up marine areas currently affected by heavy seaweed growth (e.g., the Chinese Sea, parts of the Caribbean).

To sum it up: Seaweeds are key to carbon removal and to solving numerous environmental and economic problems. Their rapid growth quickly binds CO_2, and their versatile uses and cultivation on unused ocean areas offer new opportunities for climate protection and sustainable marine development.

The innovative task that needs to be addressed politically is scaling this marine seaweed aquafarm vision with its high growth rates to industrial levels - as a nature-based climate protection and carbon removal potential.

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[73] Abromeit & Klimpel Akahoshi 2025

5. The industrial, nature-based vision of ocean seaweeds farms

The vast expanses of the oceans invite carbon removal through industrial open-ocean seaweed farming in the form of Ocean Carbon Systems. The oceans already play a crucial role in carbon sequestration through natural processes, since they store about 40 times more carbon than the atmosphere and have already absorbed around 25 percent of CO_2 emissions caused by human activities.[74] In recent years, seaweeds have established themselves as a versatile raw material for various applications. Their versatility and rapid growth make them an attractive option for both material and energy value chains. They may even make a decisive contribution to replacing petrochemicals and fossil fuels.[75]

Below, we present how a nature-based technology – open ocean seaweed aqua-farms combined with vertical circulation using a double pipe system - can be used to direct nutrient-rich deep water to seaweed at the sea surface. The sea-weeds capture carbon while they grow, which can then be permanently stored or utilized.

Seaweed growth using the tree principle – nutrients from deep below

Seaweeds need nutrient-rich water to grow well: in the aquafarm concept this is brought to the surface from deeper layers of water using vertical pipes. The technique uses the Stommel principle, named after the American oceanographer Henry Stommel: two layers of water with different temperatures and salinity are connected by pipes, with the natural difference in density serving as the driving force.

A double pipe system improves this effect: cold, nutrient-rich deep water rises in the inner pipe, while warm surface water flows down in the outer pipe. This warms the deep-water as it rises, preventing it from sinking back down again. At the same time, oxygen-rich water flows downwards, preventing oxygen deprivation underneath the seaweed farms. Once the circulation has been started, it continues without additional energy.

The system is similar to a tree: the "trunks" bring nutrients to the "leaves" – the seaweeds – and transport oxygen down to the "roots." The technology follows natural principles and transforms nutrient-poor marine regions into productive areas. Its future development offers scope for innovation – initial pilot projects

[74] Friedlingstein et al. 2025

[75] Brooks et al. 2024, Traufetter 2004, Vincent et al. 2020, Lloyd's Register Foundation & UN Global Compact 2020, Smetacek 2024

are already planned. For the time being, solar-powered pumps can also be used, as the energy required for water transport within the water column is sufficiently low.[76]

Net carbon removal with seaweed farms

Open-ocean seaweed aquafarms farms are considered a promising method of carbon removal – but only if the harvested carbon is permanently stored or incorporated into long-lasting products, thus ensuring a positive carbon balance.

Concerns have been raised that bringing deeper water to the surface to promote seaweed growth may release more CO_2 to the atmosphere. Nutrient-rich deep water contains dissolved carbon from the decomposition of organic material. When this water reaches the surface, some of the carbon it contains can escape back into the atmosphere as CO_2. Initial estimates show that far more CO_2 is bound with seaweed growth than is released into the atmosphere by bringing deep water to the surface.[77]

The ratio of carbon to nitrogen in the seaweed can be improved through targeted breeding, and some of the nutrients can be recovered during the processing of the seaweed biomass. Despite certain opposing effects, seaweed farms therefore remain one of the most net effective options for carbon removal.

Sufficient deep water as natural fertilizer and space for growth

To achieve the ambitious goal of binding 450 gigatons of carbon, millions of cubic kilometers of deep-water would have to be used over large areas. That sounds like a lot, but it is only a fraction of the total volume of water in the world's oceans, which is 1.3 billion cubic kilometers. Since subtropical gyres make up around 50 percent of the Earth's surface, there would also be enough space to accomplish this task.[78] In other words, the subtropical gyres provide a realistic option for the large-scale use of seaweed as a carbon sink.

Sinking harvested seaweeds in the deep sea

According to studies, the long-term storage of bound carbon by sinking seaweed to the cold and pressure-intensive seabed could lead to the decomposition of the seaweed biomass, causing acidification, oxygen depletion, and ecological damage, even resulting in biological "dead zones" in the depths.[79]

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[76] Smetacek 2024
[77] Unpublished plausibility calculations Energy Watch Group
[78] Smetacek 2024
[79] Chopin et al. 2024

This can be counteracted by compressing the seaweed biomass under high pressure into larger bales. Aerobic digestion then takes place on the outer surface but progresses extremely slowly into the dense material. However, these relationships have not yet been thoroughly researched and validated. They must be assessed with a responsible attitude toward the ecological risks that these effects pose in comparison to the global effects of permanent overheating.

How seaweeds can change the world as a raw material

Large algae have the potential to be a cheaper and more effective method of carbon removal than other options. They grow quickly, are a nature-based method, require little energy, produce little waste, require manageable smart infrastructure, and the nutrient-rich deep water is available free of charge. Although the exact cost per ton of biomass cannot yet be quantified, the conditions for low-cost production are good.

The income from the new production chains created using seaweed biomass could at least partially refinance the costs of carbon removal with open-ocean seaweed aquafarms, a clear economic advantage over direct air capture and some of the biological options on land and in coastal waters.

The use of seaweed biomass as a material in durable products opens up a wide range of possibilities:

- Construction industry: Innovative approaches integrate seaweed biomass as in building materials. This could lead to more sustainable construction practices. According to the OECD, the demand for building materials will be approximately 135 Gt per year in 2060. If only 10 percent of these building materials is made of seaweeds, they would absorb the complete required carbon removal.[80]
- Seaweeds as a raw material for plastics chemistry, e.g., as bio naphtha. This can be used to produce bioplastics, paints, varnishes, and adhesives – annually replacing some 0.6 Gt of fossil raw materials used globally in the plastics industry. [81]
- Steel substitute: Researchers are investigating the possibility of using seaweed biomass in combination with carbon fibers as an environmentally friendly, partial substitute for steel; this could significantly improve the carbon footprint of the industry sector.[82] According to the OECD, the demand for iron and steel will be approx. 18 Gt per year in 2060. [83]

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[80] p. 139, OECD 2019
[81] p. 1, Levi & Cullen 2018
[82] See Lederle 2018, SGL Carbon 2019, and Technical University of Munich 2019
[83] p. 126, OECD 2019

This means that material use offers the potential to recycle the entire amount that would be needed to remove 450 Gt of carbon. If the cost of carbon removal by seaweed were in the mid-range of other biological options, at around USD 100 to 200 per ton of CO_2, it is quite conceivable that these costs could be largely refinanced through material use.

Another source of financing for seaweed farms could lie in producing additional quantities of seaweed biomass for energy use that don't permanently bind carbon but whose sale generates additional income, in addition to seaweeds that are permanently bound:

- Biofuels: Seaweeds can be used to produce "biofuel" for combustion engines.
- Ship propulsion: The marine industry is researching seaweed biomass as a potential fuel source for more climate friendly ship propulsion systems.
- Aircraft propulsion: Similar to shipping, research is also being conducted in aviation into seaweed-based fuels to reduce CO_2 emissions to net zero.

Also, fertilizer can be produced from seaweeds for additional income; their high nutrient content makes them a valuable resource for agriculture.

Further challenges surrounding growth policy

Depending on the application, scaling seaweed production will involve a variety productions model: from smaller, decentralized plants, probably located near the coast, to larger plants located far from the coast and shipping lanes.

Despite its potential, increased carbon removal from the oceans also has technical and economic hurdles as well as ecological risks. These include upfront investments in research and development, scaling paths from small-scale plants to efficient large-scale production and logistics, and the simultaneous development of supplier, customer, and technology markets. Standards are also needed to integrate the harvested biomass into existing industrial value chains, logistics processes, and infrastructure.

Despite many unanswered questions and challenges, it is worthwhile to explore and promote the potential of marine CO_2 removal responsibly and in well planned steps - not least because inaction also carries dramatic ecological and thus economic and social risks.

6. Cooling our planet with algae: historically proven

Using algae to rapidly reduce CO_2 levels in the atmosphere – that sounds unaccustomed at first. In fact, there was an event in earth history, the Azolla event[84] , which supports the basics feasibility of this approach. The Azolla event was a special phase in the history of our planet.[85] It was key to cooling our planet down to the temperature ranges that prevail today, which ultimately made human existence possible.

The Azolla event took place 49 million years ago during the Eocene epoch and impressively demonstrated the ability of marine plants floating on the surface to bind huge amounts of CO_2 and influence the global climate. Over a period of several hundred thousand years, the Azolla species, which belongs to the family of aquatic fern plants, proliferated in the then warm, partially isolated Arctic Ocean in a surface layer stabilized by fresh water.[86] Mass reproduction took place with a doubling time of two to three days. The Azolla plants absorbed large amounts of CO_2 from the atmosphere and stored it in the seabed as they died and sank. This process led to a significant cooling of the climate in what was, from a geological perspective, a short period of time by significantly reducing atmospheric CO_2 concentrations. According to calculations, the growth of Azolla reduced the CO_2 content in the atmosphere by 900 to 3,500 Gt of carbon.[87]

This demonstrates the enormous potential of fast-growing, free-floating marine plants for carbon removal. The resulting cooling contributed significantly to the transformation of the global climate system, which ultimately led to the cooler climate we experience today.

The Azolla event, which lasted for thousands of years, also had environmental impacts from which we can learn. These must be weighed responsibly against the risks of inaction in the face of persistently high temperatures. Without the removal of 450 Gt carbon, large parts of today's civilization are at risk of extinction. The predicted 3°C temperature increase by 2100 includes the risk of unstoppable warming far beyond 4°C due to the tipping points triggered by then. The choice is clear: targeted carbon removal or an escalating climate crisis with catastrophic consequences for human civilization as we know it.

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[84] Arctic Azolla Event 2025, Travers 2025, Mellor 2025, Whaley 2007, Hamdan & Houri 2021 and, for general understanding, also the Wikipedia article 2025a

[85] Living Technology 2024

[86] Brinkhuis et al. 2006

[87] Speelman et al. 2009

7. For a responsible marine carbon removal industry – the booster for biodiversity in the oceans

We invite you to rethink geoengineering - a term that has often been treated with skepticism or even as a taboo subject. Because the real geoengineering experiment is quite different: it is our current global CO_2 emissions experiment with a predictable, negative outcome.

Year after year, emissions are rising.[88] We are increasingly seeing the effects on all continents. Despite immense technical successes, regular international climate conferences, and increasingly strict climate legislation, the concentration of dangerous greenhouse gases is still growing - with increasingly catastrophic consequences for life on land and in the oceans.

One of many examples: The Atlantic Meridional Overturning Circulation (AMOC), as already mentioned above, is an important current system in the Atlantic that transports warm water northward and keeps the climate in Europe "warm." Recent studies show that the AMOC is weaker than it has been at any time in the last 1,000 years and may be approaching a tipping point. A collapse could result in drastic temperature changes, particularly cooling in Northern Europe. According to current forecasts, this could happen in this century, and perhaps as early as 2025.[89]

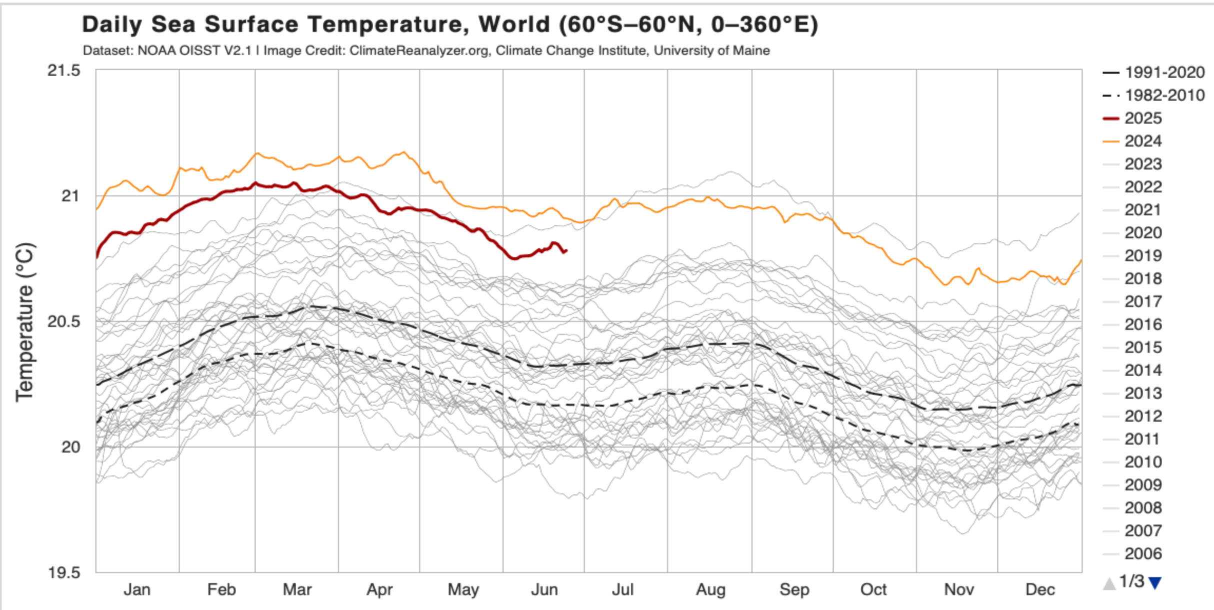

Figure 10: Visualization of the daily average sea surface temperature of all oceans between 60° south and 60° north, showing a clear increase in temperature in recent years above the long-term average values.[90]

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88 Lan et al. 2025

89 NOAA 2025, Boers 202, Ditlevsen & Ditlevsen 2023

90 Daily updated illustration at https://climatereanalyzer.org/clim/sst_daily/?dm_id=world2

Another example: Marine heatwaves (see Figure 10) pose a massive threat to ocean flora and fauna. And last not least, due to global warming, oceans have absorbed 18 times as much heat as was generated with fossil fuel combustion since 1950. This creates an enormous energy reservoir that discharges in extreme storms and torrential rainfalls. And it leads to rising water temperatures (see Figure 11) that are causing coral reefs, which are home to a quarter of all marine species, to die.[91] Their loss destabilizes the marine food chain, threatens fish stocks and the food security of billions of people, and reduces the oceans' ability to store CO_2.[92] Heat waves do not only occur directly at the surface, but extend into deeper layers. At depths of between 50 and 200 meters, they are even stronger than at the surface and sometimes last twice as long.[93]

The effects of these heat waves are devastating for the future of the oceans, their role in the food chain, and the industries and livelihoods that depend on them:

1. Coral reefs: A large proportion of the world's coral reefs are already affected by coral bleaching. When water temperatures remain above 29 °C for prolonged periods, corals suffer heat stress and lose their vital symbiotic algae.[94]
2. Biodiversity: Biodiversity is severely threatened in almost a quarter (22 percent) of the ocean's surface.[95]
3. Seabirds: Marine heat waves lead to the death of hundreds of thousands to millions of seabirds within one to six months of the temperature rise.[96]
4. Fish stocks: Many fish species, such as Baltic Sea herring and North Sea cod, are suffering from increased temperatures and migrating to cooler regions.[97]

This poses a serious threat to marine biodiversity and ecosystem stability, with potentially far-reaching consequences for global food supplies and the climate.

[91] World Ocean Review 2021 and World Ocean Review 2025
[92] Nabu 2024
[93] Fragkopoulou et al. 2023 and related reports: Rabe 2023 & Science Media Center Germany 2023
[94] World Ocean Review 202 and WWF 2025
[95] Krumenacker 2023
[96] Krumenacker 2023
[97] Nabu 2024

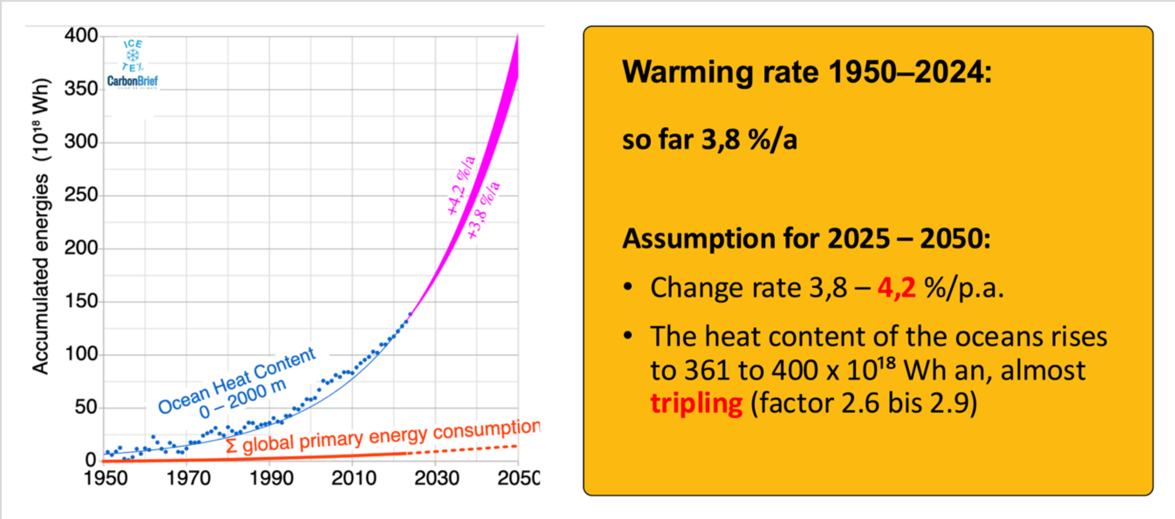

Figure 11: Tripling of ocean heat content by 2050 if the current annual warming rate of 3.8 percent continues.[98]

These examples show that unintended geoengineering has long been taking place on an enormous scale: our CO_2 emissions are the largest uncontrolled geoengineering project in human history. At 425 ppm[99], we have now clearly exceeded the safe limit of 350 ppm of carbon dioxide in the atmosphere.[100] The fact that global warming has already exceeded 1.5 °C makes it clear that we have left a stable climate system behind us - our global experiment is getting out of hand. This makes the political uproar over comparatively small ocean fertilization experiments all the more astonishing.

Accelerating carbon removal with algae fertilization – a digression into the 2000s:

The cultivation of planktonic algae for food production was already being researched in the 1950s. Scientists recognized its enormous potential for CO_2 uptake and biomass formation. However, algae need iron for their growth and thus for CO_2 uptake. It is the seventh most frequent element in living organisms, but only small amounts are needed as a catalyst. Iron is abundant in the earth's crust, but extremely scarce in the open ocean (less than 1 nanogram per liter) because iron oxide is poorly soluble, binds to particles, and sinks. To achieve maximum seaweed growth, small amounts of iron would have to be added to the rising deep-sea water. Iron sulfate is suitable for this purpose: it is an easily available by-product of many industries and is used, among other things, for phosphate precipitation in sewage treatment plants, but also as a lawn fertilizer.

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[98] Graph based on CarbonBrief 2024 by Jörn Schwarz, ASPO Germany

[99] Hanley 2025b; we have not consistently included the latest increase to 430 ppm in our calculations, but have instead used the value of 425 ppm

[100] UC San Diego 2024

In the 2000s, large-scale experiments were conducted, including ocean fertilization with iron, to stimulate the growth of planktonic algae. Political resistance, environmental concerns, and a lack of economic incentives halted many projects.[101] It is only with the climate crisis that interest is growing again - today, research and start-ups are pushing ahead with new concepts, including for free-floating seaweeds in the open ocean far from the coast.

The real geoengineering is the global CO_2 emissions experiment

As described above, geoengineering has long been taking place on a gigantic scale in the ocean – uncontrolled and with now sufficiently known catastrophic effects. Nevertheless, targeted research initiatives and controlled interventions with conscious risk assessment are rejected as "geoengineering." It is paradox: consciously and responsibly controlled measures are branded as risky experiments, while unchecked emissions with much greater, known dangers are only inadequately combatted.

Understanding and accepting the planetary limit of 350 ppm CO_2 also means recognizing our global emissions behavior as an uncontrolled geoengineering experiment on a gigantic scale. While targeted carbon removal projects must and should be accompanied by caution, risk analyses, and protective measures, they put the problem in the right context: they are a necessary response to an experiment with our planet that has long since spiraled out of control and can be stopped at any time

Rethinking the marine carbon removal industry responsibly

We invite you to discuss a marine carbon removal industry with the necessary respect for and responsible handling of foreseeable and possible new consequences. Small-scale, promising prototypes for carbon removal should be tested with the necessary caution, sound risk assessment, and suitable measures to monitor and control these risks. If successful, this will open up realistic opportunities for scalable solutions for targeted climate cooling.

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101 See Spiegel 2007, Spiegel 2008, Spiegel 2009, and Lublinski 2009

8. For a carbon removal mission #BioOcean2040

"We choose to go to the moon in this decade …
not because it is easy, but because it is hard.
Because that goal will serve to organize and
measure the best of our energies and skills,
because that challenge is one that we are willing to accept,
one we are unwilling to postpone,
and one which we intend to win …"

With these words, John F. Kennedy fired up the US moon landing program on September 12, 1962 – for the sole reason of not falling behind the USSR in the technological arms race. The gigantic sum of USD 257 billion (in today's value) was spent and 400,000 people were employed just to send three people to the moon.[102]

Figure 12: The Earth as seen from the moon.[103]

We firmly believe that carbon removal is a much more important task for the survival of our civilization on our home planet. While the moon landing was a prestige project, carbon removal is an existential necessity. Nevertheless, it is often met with skepticism and rejection - for example, with the following line of

[102] Kennedy 1962, Dreier 2022 & The Planetary Society 2022, Wikipedia 2025b
[103] Image NASA https://unsplash.com/de/fotos/erde-uber-der-mondoberflache-xFO2Xt33xgI

argument: This debate serves solely as an excuse for the lack of climate protection ambitions on the part of major climate polluters. Geoengineering only pretends to serve the climate.[104]

This attitude ignores the scientific and mathematical evidence. Even with zero emissions, too much CO_2 remains in the atmosphere. Responsible climate policy must therefore combine zero emissions, climate adaptation, and carbon removal. Initial research is looking at the policy approaches needed to scale up carbon removal on an industrial level.[105]

Instead of blocking the debate, we must conduct it responsibly - because the future of our and future generations depends on it. Industrial seaweed aquafarming in the open ocean has the potential to play a key role in combating climate change by removing CO_2 from the atmosphere at scale. The development of this marine technology naturally involves risks, both ecological and regulatory, but these are significantly lower than the well-known risks of unchecked global warming and the global warming that has already occurred and continues.

To illustrate the cognitive dissonance once again: on land, we allow agriculture that poisons the environment, destroys biodiversity, and ruins the soil in the long term. In the oceans, we have not even allowed ourselves to evaluate the possible, but very likely much lower, risks.

Recognizing and weighing ecological and technical risks

The potential of large-scale open-ocean seaweed aquafarming must be weighed against ecological risks. On the one hand, large-scale cultivation could threaten the balance of marine ecosystems by displacing native species and impairing biodiversity. However, the subtropical gyres and the seafloor below them constitute the largest interconnected ecosystems on Earth. The seaweed farms would be like oases that would have little impact on the vast - 50 percent of the Earth's surface - surrounding “deserts” in these gyres. In addition, relieving the pressure on coastal regions would be a significant gain for global biodiversity.

The argument of nutrient competition was put forward against the removal of nutrients in the Southern Ocean through iron fertilization. It is claimed that this could cause the deep water sinking at the edge of the Southern Ocean to carry fewer nutrients with it. "Tapping" the deep water beneath the gyres would not have this effect. And finally, the impact on the seafloor at great depths must also be considered. As already mentioned, this is the largest contiguous ecosystem

[104] See also White 2025 and King 2025
[105] See Sovacool et al. 2022

on Earth. Using small parts of it as plantations for algae carpets would have far less impact on global biodiversity than the continuing unchecked warming of the Earth and oceans.

Technologically and operationally, the challenges of building and operating infrastructure in the open ocean also pose risks. Natural forces such as storms and waves, which are intensified by climate change, endanger the facilities. Harvesting and drying the wet raw material, transporting and processing enormous quantities of seaweed biomass are complex and have not yet been tested at scale. Added to this is the uncertainty as to when the market for seaweed products will be sufficiently developed to justify long-term investments.

Developing regulatory hurdles and international maritime policy

Investment security is a crucial factor for the success of industrial seaweed farming in the open ocean. Companies and investors need a clear legal framework to assess the risks and potential profits of a project. However, there is considerable legal uncertainty especially in international waters, since these areas are not subject to national jurisdiction.

The London Protocol[106] prohibits marine geoengineering in principle, i.e. the introduction of waste or materials into the oceans, which significantly restricts research and development on ocean farming. Annex 5 to the London Convention defines “marine geoengineering” for the purposes of the London Protocol: "Marine geoengineering means a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe”.

Only research projects ("*legitimate scientific* research") are eligible for approval. Commercial projects are therefore prohibited.[107] Pilot projects could be carried out in the territorial waters of island states located within subtropical gyres to test the technology and determine its potential environmental impact.

Calls for a revision of the protocol are growing louder in order to enable research into carbon removal strategies such as the cultivation of seaweed aquafarming. The research community is discussing the need for more flexible but risk-conscious regulation that would allow larger research projects and initial commercial scaling projects to be carried out, a market for blueCDR to be developed in a thoughtful and constructive manner via carbon credits, while ensuring the

[106] London Protocol 2018
[107] See Ginzky & Oschlies 2023 and Frost & Ginzky 2014

protection of the oceans at the same time.[108] Without research and experimentation with manageable risks, it will not be possible to make reliable statements about the ecological risks outlined above. The well-known catastrophic climatic consequences of CO_2 emissions will then inevitably occur for all of nature and mankind - including the maritime ecosystems.

Currently, the necessary two-thirds of the signatory states have not ratified the London Protocol, and not even a dozen have ratified the amendments to Article 6 of 2024. If this situation persists, Germany and the European Union will leave the field of technological innovation to the non-signatories. The law of the high seas offers no investment security and thus prevents the establishment of a marine carbon removal industry.

Within the framework of foreign policy and diplomacy, non-signatory states must be persuaded to support and ratify the London Protocol and the amendment quickly and comprehensively, but with the following additional objective:

In addition, the signatories to the London Protocol must be persuaded to

- gradually allow blue carbon systems and ocean carbon systems so as to develop carbon removal and binding at scale paired with ecological risk limitation,
- design regulatory procedures that are innovation-friendly, clarify ecological liability issues, and develop the legal framework for investment security for these industries.

If this is not achieved, non-signatories could gain massive competitive advantages, leaving the signatories empty-handed.

International maritime transport could potentially be affected on a few shipping routes by the establishment of open-ocean seaweed aquafarms, which needs to be considered in the United Nations Convention on the Law of the Sea (UNCLOS). A balance must be struck between the interest in using shipping routes without detours and the urgency of significantly reducing CO_2 concentrations in the atmosphere through technologies such as large-scale seaweed aquafarming.

To ensure long-term investment security, it is necessary to establish international standards and a clear legal framework that supports seaweed farming in international waters and minimizes conflicts between countries. This includes establishing a secure regulatory framework for research, scaling, and the increasing industrial use of these technologies in order to protect both ecological and economic interests. Only through international cooperation and clear regulations can disputes be avoided, investments secured, and necessary scaling enabled.

[108] See Mengis et al. 2023

With the #BioOcean2040 mission, we therefore want to bring a series of proposals into the political discussion to further develop the legal framework in a responsible and risk-conscious manner, promote ocean carbon system research and start-ups, and remove international maritime law barriers to investment.

To implement ocean farming at scale, we see five areas for action:

I. Quantify carbon removal and set it as a political and legal target

Given the enormous challenge of reducing CO_2 concentrations in a sustainable manner, we advocate recognizing the removal potential of 450 Gt carbon as a political goal, enshrining it in law, and pursuing it with determination.

In this paper, we have presented a quantification that can serve as a starting point for further discussion. We strongly recommend that this calculation be systematically reviewed, regularly updated, and methodologically validated by interdisciplinary expert groups in an international process. The goal should be a broadly accepted corridor that is both scientifically robust and considerate of its political dimensions.

Such a target corridor must be incorporated into international climate agreements, European strategies, and national climate plans. This requires legally binding regulations with clear responsibilities, ratified targets, and an implementation timeline with intermediate goals. Only on that basis will the necessary infrastructure be created at the national level, programs be initiated, and the adjustments to laws, standards, and regulatory frameworks be made.

II. Support Mission #BioOcean2040 for Ocean Carbon Systems

All possible carbon removal approaches – terrestrial and marine – should be rigorously evaluated for their potential, feasibility, economic viability, and priority in relation to this goal.

As there are currently no measures known that could remove 450 Gt of CO_2 from the atmosphere in a few decades, we invite you to re-evaluate the exponential growth potential of seaweeds and Ocean Carbon Systems. They may well become a key element of nature-based carbon removal strategies.
In addition, seaweeds provide valuable synergies for nutrition, biodiversity, and the replacement of fossil fuel-based raw materials.

Essentially, we are calling for a reevaluation of carbon removal and for the scaling story of Mission #BioOcean2040 to be validated and supported politically.

III. Creating responsible framework conditions for marine carbon removal

We want to tap into the open ocean as a space for sustainable CO_2 removal – with all its opportunities and risks. Natural forces, maritime safety, conflicts over waterways, and regulatory uncertainties require careful, responsible planning. We should tackle these challenges together and create clear framework conditions for safe and effective implementation.

Given the urgent time frame, we would like to invite you not to waste time on comprehensive feasibility and risk analyses before action is taken, but rather to begin with trials, start-ups, risk research, and secondary studies in parallel, and evaluate technical, ecological, and safety-related aspects in a “rapid prototyping" approach. This will enable us to conduct targeted tests, gain experience, and advance promising approaches at an early stage, while minimizing ecological and economic risks and securing investment. At the same time, we should work together to clarify legal issues: define areas of responsibility, regulate liability issues, and adapt existing laws.

We strongly recommend adapting German law and other national regulations to enable a responsible marine carbon removal industry and adapting the London Protocol to the new challenges. This would be a decisive step towards not only providing a reliable legal framework for carbon removal projects in the open ocean, but also advancing them in a coordinated manner at the international level.

Let us seize this opportunity to make climate protection in the open ocean possible – responsibly, with a view to the future, and in harmony with ecological and economic interests.

IV. Building innovative strength for ocean carbon systems, providing political support, and shaping market development

Ocean carbon systems can meaningfully combine climate protection and economic progress. The development of this promising industry not only offers us an effective strategy for carbon removal, but also opens new economic prospects. To exploit this potential, we should make key investments in research, development, and innovative startups in ocean carbon systems, and create a market for fossil-free carbon products and circular economy.

The primary focus is on finding a technical and economic solution and testing the cultivation of seaweeds with pipe systems that bring nutrient-rich water to the surface from depths of 400 to 1,000 meters. The aim is to ensure stable yields, low costs, and durable components under the demanding conditions of the open ocean, with waves, colonization by marine organisms, and growing biomass.

Clear and focused political support is needed to enable this type of open ocean farming to take effect. It is crucial to establish a market for seaweed-based products, for example in the construction industry, for biofuels or bioplastics. Government incentives, loan guarantees, depreciation models, early-stage and growth capital, start-up support, and market development programs can secure investments and accelerate the scaling of production and uptake. If demand remains too low, willingness to invest will decline. Government support can help create new markets, such as for bio naphtha or seaweed kerosene, and ensure ramp-up.

At the same time, key assumptions must be tested in real-world operations, e.g. on long-term CO_2 sequestration in deep-sea deposits, the actual net carbon balance despite possible CO_2 outgassing, and on potential ecological side effects. Only clear validation in the form of risk-conscious accompanying research can provide the basis for further responsible political decisions.

Let us work together to develop a clear research, innovation, and education agenda that connects and finances international marine research institutes, universities, and future ocean carbon industries. The focus must be on practical solutions so that we can scale these technologies efficiently and sustainably. International research collaborations are crucial to accelerate the development of new materials, energy sources, and marine production methods.

With an ocean farming economic cluster, we could build a competitive and climate-friendly marine industry. Now is the time to establish ocean carbon systems as a strategic economic sector while making an important contribution to stabilizing our climate. Now is the time to set the political course - with vision, responsibly, and with determination to seize the opportunity of carbon removal as an essential contribution to the survival of our civilization.

V. Creating an international framework for #BioOcean2040

Technologies, capital, research, and political impetus from Germany and Europe can make a decisive contribution to developing globally effective carbon removal methods such as ocean farming. We – with a particular focus on Germany and the European Union – can now build sustainable ocean carbon industries and actively involve the oceans in climate protection. This requires a clear legal framework that enables long-term investment and promotes innovation. Let us work together to remove barriers to investment in marine investment and create dedicated marine areas as sustainable economic zones.

It is our responsibility to develop international assurances for the marine economy in order to give companies a reliable basis for planning and investment. At the same time, we must designate and regulate ocean farming areas in such a way that they are compatible with international shipping routes and ensure conflict-free, environmentally compatible, and sustainable uses of marine areas.

Strategic broadening as opposed to unregulated climate change

Politicians are facing a fundamental choice: unchecked CO_2 emissions have long become uncontrolled geoengineering with catastrophic consequences. The oceans as we know them are heating up and changing dramatically with dire consequences for flora, fauna, marine food chains, and thus also for humanity.

Now is the time to change course and take targeted action to create a responsible framework for carbon removal. A strategic broadening is needed to change course: adding carbon removal to net zero emissions as a dual policy focus. That means integrating active political and legal control of sustainable removal methods in climate policy – our #BioOcean2040 mission.

This requires a clear stance: research and innovation should not be blocked but enabled by smart regulatory guidelines. The testing of new technologies on and in the ocean should be specifically permitted and scientifically monitored. At the same time, binding framework conditions must be created that enable ocean farming in previously unused areas, offer investment security, and prevent risks and conflicts. Last not least, the interests of the Global South must be taken into account: carbon removal and economic development should go hand in hand to create fair win-win solutions. Change cannot be left to tech corporations alone, but requires global partnerships.

In summary, due to the extremely strong growth rates of seaweeds, their industrial cultivation is likely the most important opportunity for carbon removal and for returning to safe CO_2 concentrations below 350 ppm

9. Courage to act – our appeal

"Anyone who wants to colonize Mars is considered a visionary. Anyone who wants to remove CO_2 is considered a fantasist – we need to change that."
Prof. emer. Victor Smetacek

With these words, Prof. emeritus Victor Smetacek[109] sums up the urgency of moving from uncontrolled geoengineering with past and ongoing CO_2 emissions to a risk-conscious marine carbon removal strategy. The industrial cultivation of seaweed in the open ocean offers a great opportunity to deprive climate change of its "fuel."

The risks of inaction, with unchecked and intensifying heat waves in the oceans, are real – as are those of action, with the danger of oxygen-depleted zones forming in the deep sea.

Figure 13: Cooling or heating – that is the question here.[110]

However, they can be identified and mitigated if we tackle them decisively and develop viable solutions. Research and innovation must not be blocked, but enabled by smart guidelines. The technology is available – we can use it or continue to discuss it and lose time that we do not have.

109 Smetacek 2024
110 Image: www.istockphoto.com/de/foto/coral-bleichen-gm629534636-112046343

We are at a turning point. The decision to act is primarily a question of political will. In the coming years, we must succeed in developing effective climate, environmental, and marine protection policies for scalable removal strategies. The industrial cultivation of seaweeds could be the only tool that works on the scale needed to reduce CO_2 concentrations to a safe level.

Imagine if we succeed: a nature-based method that helps mitigate the climate crisis, secure our livelihoods, and rewrite the history of geoengineering – turning it from a story of failure to a success story for humanity and our oceans. The opportunity lies in working together now, with vision and responsibility, to initiate something that will not only stabilize the climate but also usher in a new era of sustainable marine use.

What is stopping us from giving this opportunity a real chance?
Or putting it another way: Cooling down or heating up – that is the question.

10. Appendix

a. The authors

About the Energy Watch Group

The **Energy Watch Group** is a non-profit think tank. We contribute to reducing CO_2 emissions and cooling the Earth's atmosphere at the global, national, and local levels. With our network, we develop appropriate targets, effective solutions, and pragmatic policy recommendations. With these, engage with decision-makers and the media.

Hans-Josef Fell is one of the most prominent thought leaders of the global energy transition. A long-standing member of the German Bundestag (1998–2013) for the Alliance 90/The Greens parliamentary group, he played a key role in drafting the Renewable Energy Sources Act (EEG), which is regarded worldwide as a model for the expansion of renewable energies. Fell studied physics and sports. He worked as a high school teacher before specializing in climate, environmental, energy, and research policy. Since 2006, he has been internationally active as president of the Energy Watch Group (EWG), an independent network of scientists and parliamentarians that develops science-based strategies for 100% renewable energy and other climate protection issues. Fell has received numerous international awards, including the LUI Che Woo Prize, the Federal Cross of Merit, and the Global Solar Leaders Award, and is one of the more influential voices for a fossil-free future. His expertise combines scientific understanding, political experience, and visionary thinking for a sustainable world.

Franziska Pausch has a master's degree in marine biology and works as a freelance science communicator. In addition to her freelance work, she is doing her doctoral thesis at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research in Bremerhaven on the effects of climate change on microalgae in the Southern Ocean and has participated in two interdisciplinary research expeditions in the Atlantic and Southern Oceans. She is also co-founder of AWIs4Future, a regional group of Scientists for Future that was founded in 2019. Within AWIs4Future, she is actively involved in organizing and moderating the YouTube channel "Wissenschaft fürs Wohnzimmer" (“Science for the living room), which presents scientific topics, especially those related to climate change, to a broad audience. As part of the AWIs4Future core team, she won the AWI Prize for Science Communication in 2020.

Frank Schweikert is a journalist, biologist, entrepreneur, diver, and sailor. The protection of the oceans and our natural resources is particularly close to his heart. His friendship with Elisabeth Mann Borgese, maritime law expert, ecologist, and publicist, and youngest daughter of Thomas Mann, made him an activist for a healthy ocean as "the common heritage of mankind." Early on, Prof. Dr. Hartmut Graßl, Nobel Peace Prize laureate for the IPCC, encouraged him to take action against climate change. He got to know ocean legends Hans Haas and Jacques-Yves Cousteau personally. Since 1992, he has been operating Europe's only research and media ship under sail with an exemplary low ecological footprint as a communication bridge between the ocean and society. Schweikert founded the German Ocean Foundation and is a board member of the Federal Association for Marine Litter, deputy board member of the German Society for Marine Research, and, since April 2024, a member of the EU Mission Board for our oceans and waters.

Prof. emer. Victor Smetacek is one of the internationally most renowned oceanographers and marine biologists. From 1986 to 2011, he was Professor of Bio-Oceanography at the University of Bremen and Head of the Pelagic Biology Section at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research in Bremerhaven. He has led eight interdisciplinary, international research expeditions aboard the FS Polarstern, including three successful iron fertilization experiments to determine the role of the Southern Ocean in regulating atmospheric CO_2 levels during past climate cycles. His numerous publications in leading scientific journals have fundamentally changed our understanding of the marine biosphere in the climate system. He has been on many international scientific committees and has received several awards for his achievements. He remains active in research and teaching.

Heinrich Strößenreuther is one of Germany's best-known climate and transportation policy initiators. For over 30 years, he has been working at the interface of environmental policy, communication, and social change. As co-founder of NGOs such as Changing Cities, GermanZero, KlimaUnion, and BaumEntscheid -of which he is a board member - and as the initiator of the successful referendums on bicycles and trees in Berlin, he has provided significant impetus for sustainable urban and climate policy. His initiatives have inspired over 50 bicycle referendums and over 80 climate referendums nationwide. Strößenreuther was previously chairman of the Association for Ecological Economic Research and has worked for Greenpeace, Deutsche Bahn, and the German Bundestag. As senior advisor and managing director of the Agency for Smart Cities, he now advises local authorities, associations, and politicians on climate, mobility, and energy issues. He is considered an experienced strategist, campaigner, and narrative expert with a keen eye for social levers beyond party lines.

b. Disclaimer

The vision and conceptual basis for large-scale aquafarming of free-floating seaweeds in the open ocean presented in this document is based on the ideas and research of Prof. emeritus Victor Smetacek. *Seafields Solutions Ltd.* was founded based on this idea and is working on the practical implementation of corresponding approaches to marine carbon removal. Prof. emeritus Victor Smetacek and Franziska Pausch act in an advisory capacity for Seafields and are on its Advisory Board. The company did not commission or financially support the creation of this paper. This information is provided for the sake of transparency and is to be understood as part of this document.

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Figure 01: The scale of the CO_2 removal task compared to current emissions and the volume of the carbon market; own representation based on https://cleantechnica.com/2024/06/30/ccus-is-mostly-an-oil-gas-shell-game-sfu-seminar-slides-notes/

Figure 02: Development of global CO_2 concentrations, which at 425 ppm are now well above the safe planetary limit of 350 ppm; original image by Mark Maslin, John Lang, and Fiona Harvey, CC-BY 4.0, edited by Ivan Villanueva on holoceneproject.org (as of May 13, 2025, 4:11 p.m.) and further edited by Heinrich Strößenreuther; https://www.solarify.eu/2024/07/09/692-das-holozaen-projekt/

Figure 03: 93% of the additional heat stored by human greenhouse gas emissions is absorbed by the oceans: own representation

Figure 04: Schematic representation of the derivation of the removal quantities of 450 gigatons of carbon in order to return to a safe climate level: own representation based on data from https://essd.copernicus.org/articles/15/5301/2023/

Figure 05: Representation of CO_2 reduction pathways and CO_2 removal pathways as well as the removal gap; unpublished graphic by Karina Demeisi and Dr. Bernd Faber, EduClimate gUG based on Sovacool et al. 2022, schematically corrected to reflect actual quantities

Figure 06: Overview of possible technologies and processes for removing CO_2 already emitted from the atmosphere; own representation

Figure 07: Illustration of the brown algae Sargassum, which forms a unique and extremely productive floating ecosystem on the surface of the open ocean, and the associated marine fauna, including fish, sea turtles, birds, and marine mammals: https://oceanservice.noaa.gov/facts/sargassosea.html

Figure 08: Blue carbon systems near the coast and ocean carbon systems in the open ocean: graphic CC from https://journals.plos.org/climate/article?id=10.1371/journal.pclm.0000148

Figure 09: Visualization of global vegetation on land and in the oceans. The representation of the long-term average microalgae concentration in the oceans clearly shows that the five subtropical gyres (the dark blue to purple areas), which cover 50 percent of the Earth's surface, are oceanic deserts with very little algae: Graphic from https://earthobservatory.nasa.gov/images/838/the-third-anniversary-of-seawifs

Figure 10: Visualization of the daily average sea surface temperature of all oceans between 60° south and 60° north, showing a clear increase in temperature in recent years above the long-term averages; graphic from https://climatereanalyzer.org/clim/sst_daily/?dm_id=world2

Figure 11: Tripling of ocean heat content by 2050 if the current annual warming rate of 3.8 percent continues; data and image based on CarbonBrief 2024; graphic by Jörn Schwarz, ASPO Germany http://www.aspo-deutschland.org/p/aspo-deutschland-ev.html

Figure 12: Earth seen from the moon; image NASA https://unsplash.com/de/fotos/erde-uber-der-mondoberflache-xFO2Xt33xgI

Figure 13: Cooling down or heating up – that is the question here; image istockphoto https://www.istockphoto.com/de/foto/coral-bleichen-gm629534636-112046343

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