MARINE GEOENGINEERING – QUARTERLY REVIEW III (PART 2)

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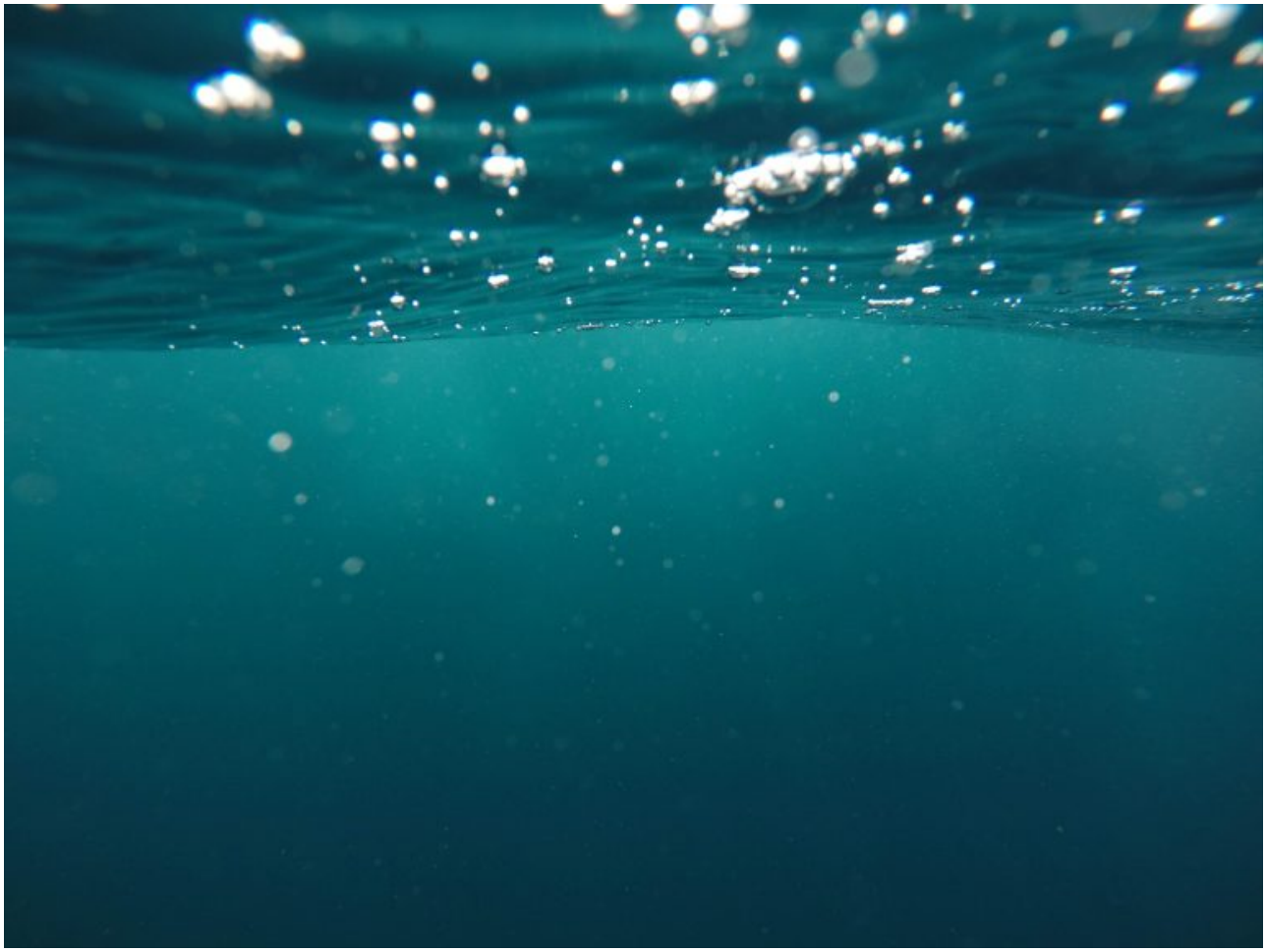

Photo Credit: Jeremy Bishop

By Anja Chalmin

The second part of the third quarterly review of 2022 looks at geoengineering developments on water and on land with a focus on marine projects. Many of the approaches to marine geoengineering involve technologies to remove CO_2 from the atmosphere, including ocean fertilisation, enhanced weathering, artificial upwelling and the proposal to dump biomass on the seabed. But there are other approaches as well: An increasing number of projects seek to capture CO_2 using algae. The Artic Ice Project aims to cover large areas of sea and land ice with a reflective substance. The approaches have in common, that they are associated with numerous and sometimes unpredictable risks to the marine environment, e.g., threats to the marine food web, oxygen depletion, increased release of methane, potential effects on marine biochemical processes, harmful toxin-producing algal blooms as well as potential transboundary effects on fisheries, coastal communities and

weather patterns. None of the proposed marine geoengineering technologies have proven successful so far – although some of them have been researched for decades. The potential risks alone speak against their use as well as further research.

UPDATES ON MARINE GEOENGINEERING PROPOSALS, PROJECTS AND INITIATIVES

The **Sabin Center** and Ocean Visions, an organisation that aims to develop, test and deploy marine geoengineering proposals at scale, will jointly host a series of stakeholder workshops where members of the scientific community, government agency representatives and other interested parties can provide their input to support the development of model legislation for ocean-based carbon dioxide removal.

Exploring Ocean Iron Solutions (ExOIS) conducted the forum "*What's Next? R&D Planning for Ocean Iron Fertilization*" in September 2022. ExOIS describes itself as "*an umbrella organization that strives to foster partnerships for scientific research as well as with public and private partners for funding and to establish best practices and governance of study of ocean iron fertilization as one of many steps that will be needed to remove atmospheric CO_2 over the coming decades. The goal of ExOIS is to stimulate and coordinate activity around OIF research based upon recommendations from the recent NASEM and Aspen reports, and to catalyze individual enabling studies and help organize large international proof of concept field and modeling studies*." Among the members are the Centre for Climate Repair at Cambridge (CCRC), Geomar and Ocean Visions.

The **Arctic Ice Project** suggests covering Arctic sea ice or land ice with a layer of floating reflective material to slow down the melting of the ice and/or to restore the ice. The proposed cover material is a reflective silica glass and consists mostly of silicon dioxide. The silica glass has the form of tiny hollow glass spheres. Since ~2010, the project carried out trials at various test sites. In March 2021, the Arctic Ice Project announced plans to conduct tests on sea ice in Svalbard, Norway, e.g., to further quantify the albedo-effects of the proposed cover material. The tests are carried out in cooperation with Norwegian research institutions, primarily SINTEF. The Arctic Ice Project commented on the status of trial design saying, "*SINTEF scientists have already identified field test locations in Svalbard, north of the Arctic Circle […]. We still need to secure permits and additional funding*". In addition, SINTEF's Ocean Lab is evaluating the impact the reflective material might have on the Arctic ecosystem and

what will likely happen to the glass spheres if deployed in the Arctic Ocean.

Since ~2020, the Arctic Ice Project has been conducting simulations on the use of their reflective material in the **Beaufort Gyre**, currently in collaboration with Climformatic, University of Bergen and the Bjerkens Centre for Climate Research in Norway. Last year, the Arctic Ice Project conducted climate modeling on the **Fram Strait**. The Arctic Ice Project is actively and intensively seeking sponsors for the planned open-air tests and has acquired the Mumbai-based Spectrum Impact as a new sponsor. Spectrum Impact is part of Aarti Industries Ltd, a larger Indian chemical/pharmaceutical company.

The newly founded **Bright Ice Initiative** continues to look for backers to fund outdoor tests with a reflective substance in the Himalayas – with the technology developed and tested by the Arctic Ice Project.

The San Francisco-based '**Vesta**' seeks to test and scale enhanced weathering with olivine – a soft, green volcanic stone – on beaches. Vesta plans to mine olivine, grind it into small grains and spread them on beaches where wave action is expected to support the weathering process. In July 2022, Vesta spread 650 tonnes of olivine on a 130 metres stretch of North Sea Beach, a beach north of Southampton on Long Island in eastern New York. The open-air experiment is expected to last two years, and upon completion Vesta plans to quantify the amount of CO_2 absorbed. The testing is conducted in cooperation with Stony Brook and Cornell University. Along with other critics, a regional newspaper has strongly questioned the project's carbon footprint, partly because the crushed olivine comes from Norway. In 2020, the project announced another outdoor experiments in two bays in the Dominican Republic. The two bays are about a quarter of a mile apart: a test cove (for enhanced weathering trials), and a nearby control cove. Vesta says it has received approval from the Dominican Ministry of the Environment for the first phase of the pilot, which includes baseline research and outdoor experiments in so-called mesocosms (large test tubes in the sea). The start of the trial is currently announced for 2022, but has been postponed several times since 2020. Details of how much crushed rock is to be spread during the trial and where the rock was sourced are not publicly available.

Zhejiang University has studied artificial upwelling for several decades. The University developed an air-lift pumping system in 2010 and undertook various outdoor trials. Since November 2018 the university's aeration system has been running at a coastal kelp farm in Aoshan Bay, Shandong Province. Further trials are carried out in a water tank at

Zheijang University, e.g., to further improve the air-lift upwelling device, or to measure the correlation of chlorophyll concentration and water properties such as salinity, temperature and pH. Based on the ongoing artificial upwelling trial in Aoshan Bay, kelp farming combined with artificial upwelling is modelled for three bays in Shandong Province (Aoshan Bay, Jiaozhou Bay, and Sanggou Bay). At the trial site in **Aoshan Bay**, Shandong Province, deep ocean water is upwelled during the kelp growing season, covering an area of ~0.8 hectare. Compressed air is pumped down to the seabed from a floating platform, 24 metres in diameter. The process is powered with wind, solar and tidal energy. The rising air bubbles transport colder and more nutrient-rich deep ocean water and mix it with the warmer and less nutrient-rich surface layers in Aoshan Bay. The project is led by Zhejiang University and carried out in collaboration with Xiamen University, Hangzhou Dianzi University and Shandong University.

Ocean GeoLoop was founded in 2020 and is situated in Verdal, Trondheim Fjord, Norway. The company claims that its technology can capture close to 100% CO_2 from flue gas, that the capture process is based solely on an electrical process and that no chemicals are used. A prototype was installed in 2021 in the Trondheim Fjord. In summer 2022, the company commissioned its first carbon capture pilot plant at the Norske Skog Skogn facility, a pulp and paper mill in Norway, about 20 km southwest of Ocean GeoLoop's site. The captured CO_2 is not to be stored in gaseous form but dissolved in seawater *„as ultrasmall, inert and buoyancy-neutral gas nanocavities"*. The nanocavities are to be stored in abandoned oil and gas reservoirs or in the deep sea (seabed), at depths of more than 2,000 metres. The captured CO_2 can also be used to produce ethanol or methanol.

The pan-European research **project OceanNETs** (Ocean-based Negative Emission Technologies) is coordinated by the GEOMAR Helmholtz Centre for Ocean Research Kiel and conducted in cooperation with 13 partner organizations: universities and research institutions from Norway, Germany, UK, Finland, Spain and Australia. OceanNETs aims to investigate the feasibility and impacts of ocean-based approaches to remove CO_2 from the atmosphere. The project conducts experiments in the GEOMAR laboratories in northern Germany as well as offshore experiments off Gran Canaria (Spain) and off Bergen (Norway). In Norway, the offshore experiments were carried out in the Raunefjord (south of Bergen) from May to July 2022, in ten mesocosms – large plastic tubes with a diameter of two metres and a depth of 20 metres that hang in the fjord like giant test tubes. Alkaline minerals were dissolved in them to observe the effects of enhanced marine weathering, including the effects on herring larvae and carbon.

The project "**Enhanced Silicate Weathering**" (ESW) is conducted by Antwerp University, in Wilrijk, Belgium and undertakes studies to analyse enhanced weathering in terrestrial, aquatic and coastal environments. The project aims to enhance the weathering rate and CO_2 uptake of rock (silicate) minerals such as olivine, by grinding mined silicate rocks into small grain sizes. The research is accompanied by experiments in containers (vessels filled with ~600 l of seawater/sediment), to investigate the rates of ESW as well as CO_2 uptake in seawater. The project also looks at economic and environmental feasibility of ESW. Since 12/2021, the researchers have also been studying natural silicate weathering in the **DEHEAT project** (this project involves creating natural analogues and system-scale modeling of marine enhanced silicate weathering).

The project **Solid Carbon: A Climate Mitigation Partnership Advancing Stable Negative Emissions** is a four-year research partnership, led by the Ocean Networks Canada (ONC). ONC is an initiative founded by the University of Victoria, British Colombia (B.C.). The following partners from Northern America and Europe participate in the project: University of Victoria (ONC), University of B.C., University of Calgary, University of California, Columbia University, University of Washington, GEOMAR Helmholtz Centre for Ocean Research in Germany, K&M Technology Group (Texas, USA), and Carbon Engineering (B.C.). The project aims to develop and design a demonstration plan for a floating platform able to capture CO_2 from ambient air and inject it beneath the seafloor for carbon mineralisation. A demonstration trial is anticipated for 2025, in the Cascadia Basin off the shore of Vancouver Island (B.C.). The production and deployment of a large-scale global fleet is anticipated for 2050. CO_2 will be captured with Carbon Engineering's direct air capture technology. Once injected into deep-sea ocean basalt the CO_2 is expected to turn into rock and to remain in the basaltic rock permanently. So far there are no long-term investigations to assess and prove this assumption. The project plans to power the processes on the platform with renewable energy, e.g., wind power. The design involves oil and gas drilling expertise (K&M Technology Group) to reach ocean basalt layers in the deep ocean. The project also aims to examine the acceptance for this project from a social, regulatory, and investment point of view.

California-based **Ebb Carbon** was founded by Matthew Eisaman and Ben Tarbell in 2021 and emerged from the research project SEA MATE (Safe Elevation of Alkalinity for the Mitigation of Acidification Through Electrochemistry). The company seeks to commercialise an electrochemical process for removing acid from seawater, with the goal of fixing more CO_2 in the form of bicarbonate in the oceans and reducing ocean acidification. According to Ebb Carbon, this electrochemical process

uses electricity and a membrane to separate an acid (hydrochloric acid, HCl) from seawater. The seawater is then returned to the ocean to increase the ocean's ability to store atmospheric CO_2 in the form of bicarbonate. The acid is to be sold as an industrial product, such as for use in mines or the chemical industry. According to Ebb Carbon, the membrane used has a shelf life of several years. No information has yet been found on the electricity consumption of the process. Ebb Carbon plans to install the system in facilities that already treat seawater – including desalination plants, aquaculture facilities and wastewater treatment plants. This is to save costs, such as the cost of pumps and pipes. The first Ebb Carbon system is scheduled to go into operation in 2022. The planned CO_2 offsets are to be sold to Stripe. In ~2027, the company plans to operate at megaton scale.

The research project **SEA MATE** is a collaboration of researchers led by Matthew Eisaman at the College of Engineering and Applied Sciences at Stony Brook University. Further project partners are the University of Washington, the National Oceanic and Atmospheric Administration (NOAA) and the company Ocean Visions. Besides exploring an electrochemical process for removing acid from seawater, SEA MATE also looks at issues such as the relationship between the amount of HCl removed and the amount of CO_2 captured in the form of bicarbonate, as well as the duration of the process, the biological effects of acid removal and the generation of valuable by-products from the HCl removed. The SEA MATE technology is being tested in laboratory tanks at Stony Brook University. The research team is also designing and building a test unit for field testing, which will be housed in a shipping container. The location of the planned tests is not yet disclosed.

The company **Ocean-Based Climate Solutions** developed the Oxygenator, an artificial upwelling device. The company had announced a demonstration-scale test in the waters of the Canary Islands for July 2022. So far, there is no evidence that the announced test was carried out.

The US-based company **CLIMOS Inc.** was started by Dan Whaley in 2006. The company proposed a large-scale ocean fertilization trial for 2009/2010, aiming to cover an area of four million hectares and considering sites in the Atlantic and the Pacific Ocean. In 2008, CLIMOS raised US$ 3.5 million for the implementation of the trials, e.g., from Tesla founder Elon Musk. However, the planned experiment was not conducted and the company stated that the available funds were not sufficient to cover the costs. In ~2011, the CLIMOS website stopped working for a few years. Since ~2020, the website is back online and again advocating for large-scale iron fertilisation experiments in the ocean.

OPR Alaska, founded by Russ George in 2020, moved its office from Kenai, Alaska to Kodiak, Alaska and thus closer to the site of its planned **ocean fertilization project** in the Gulf of Alaska, south of Kodiak. Russ George has been trying to dump iron fertilizer into the ocean for two decades and has renamed his company in the wake of these failures.

The company **SeaChange** is based on research conducted at the University of California and was founded by Gaurav N. Sant to commercialise the findings. SeaChange aims to further develop and test an electrochemical process to capture carbon in seawater. The process extracts CO_2 from seawater and converts it into carbonates. The company aims to pilot the technology in Los Angeles and in Singapore in 2022. The pilot trials are expected to capture between ~35 to ~350 tonnes of CO_2 from the ocean each year. The exact schedule and location for the trials is not yet publicly known.

The US-based-**The Climate Foundation** (TCF) was founded in 2007 by Brian von Herzen with the goal of capturing CO_2 by employing artificial upwelling at a larger scale. TCF developed a floating platform with wave-driven pumps to transport deep ocean water to sunlit ocean surface layers. At its project site on the Philippines, TCF announced the deployment of an additional platform (1,000 m^2) in 2022.

CQuestr8's enhanced weathering technology mineralises CO_2 and forms bicarbonate. Detailed information on the technological approach is not yet available. The company states that the technology requires access to the sea and that its technology can be integrated at point sources, e.g. in cement, steel, lime or other large emitters. The company partners with the University of Nottingham and the University of Malaysia.

Out of the blue was founded in 2019 by Lennart Joos to commercialise a process he developed to remove CO_2 directly from seawater. The company plans to store captured CO_2 underground and is currently looking for partners to test and scale the developed concept.

The marine geoengineering approaches that are to be further developed in research projects and marketed by companies are primarily ocean fertilisation, enhanced weathering, artificial upwelling and surface albedo modification. Further information on these marine geoengineering technologies, especially on the associated risks, can be found here: https://www.geoengineeringmonitor.org/

GEOENGINEERING PROJECTS WITH ALGAE

There are more and more projects that rely on marine algae, both microalgae and macroalgae, to capture CO_2. The approaches to exploiting the algae vary widely. Some of the projects and research efforts are presented below. In the end of the chapter, study results show that algae cultures have a large land consumption, require a lot of infrastructure and are not considered very effective in terms of carbon removal, e.g., large-scale algae cultivation can even be a potential net source of CO_2.

Running Tide Technologies Inc. is based in Portland, Maine. Marty Odlin, the founder of Running Tide, aims to grow seaweed such as kelp in large quantities in the open ocean and then sink it to a depth of 1,000 m on the ocean floor to capture and store carbon. Since 2018, Running Tide has launched initial pilot projects in Portland, Maine and neighbouring communities. Ropes wrapped with kelp seeds were released into the water, where they grew for about seven months. The kelp plants are attached to biodegradable buoys. After three to seven months, the kelp plants are supposed to become too heavy and sink. In 2021, Running Tide wanted to demonstrate the concept with 1,600 buoys, but this plan was postponed and the approach was further explored in collaboration with Ocean Visions Inc. In July 2022, the Icelandic government granted the company a four-year permit to release buoys: up to 50,000 tonnes off the Icelandic coast, and up to 450,000 more tonnes in international waters. There are increasing reports of technical difficulties in implementing kelp cultivation, as well as doubts about the scientific credibility of Running Tide, partly because the proposed rate of expansion is not considered realistic.

Brilliant Planet is headquartered in London, UK, and was founded in 2013. After years of research and development and pilot testing, a first commercial installation is currently being prepared in the Moroccan coastal desert. Pilot tests have been conducted in South Africa (3 m^2 experiment on the coast of St Helena), Morocco (3 ha) and Oman. A funding round in 2022, amounting to US$12 million, will be used to finance the construction of the 30 hectare commercial demonstration plant on the Moroccan coast in the Sahara Desert. Algae production will be realised close to the coast, as seawater will be pumped into the plant. The seawater serves as a nutrient and CO_2 supplier for the algae. After about 20-30 days, the algae is harvested and the water is returned to the sea. Afterwards, the harvested algae is to be dried and then buried under Sahara sand, 1-3 m below the surface, to store the absorbed carbon. The company’s marketing concept is carbon credits to be sold to

emitting companies.

The California-based company **Pull to Refresh** was founded by Arin Crumley and aims to increase the growth of seaweed (macroalgae) and sink the seaweed into the ocean to remove CO_2 from the atmosphere. Using semi-autonomous, solar-powered ships, algae is to be captured from seawater in a bottomless cage and lowered into the ocean until the uplift of the algae is cancelled out by the water pressure and the algae sinks to the seabed on their own. This way, the carbon is to be trapped, and carbon certificates are to be sold on this basis. The company promises that the carbon will be trapped for more than 100 years – on what basis this promise is made is unclear. The company's first project is to sink Sargassum macroalgae in the Caribbean.

Kelp Blue is headquartered in the Netherlands and was founded by Daniel Hooft and Caroline Slootweg. The company wants to establish large-scale kelp plantations in a coastal area in Namibia. In 2021, the Namibian government granted permission to establish a pilot operation in Luderitz in southwestern Namibia. By 2029, Kelp Blue plans to cultivate 70,000 hectares of kelp with an annual harvest of 120 tonnes. Kelp Blue's biotech division is responsible for processing and marketing. The company's goal is to manufacture kelp-based products for crop production, replacement of plastics, animal feed supplement, fibres for textiles, pharmaceutical, nutraceutical and cosmetic applications. This means that it is only a very short-term storage of CO_2.

The Washington D.C.-based **Fearless Fund** received funding from the US-DOE to research macroalgae farming in the open ocean for energy production. Los Alamos National Lab (LANL) and Pacific Northwest National Lab (PNNL) joined the research team. In collaboration with NOAA's Atlantic Oceanographic and Meteorological Lab (AOML), the Fearless Fund also focused on removing CO_2 from the oceans through the growth and harvesting of algal biomass known as Sargassum.

Seaweed Carbon Solutions is a three-year joint industry project led by Norwegian SINTEF. The aim of the pilot project is to test CO_2 capture and storage with seaweed on an industrial scale off the Norwegian coast. The project will cultivate sugar kelp on long ropes in the sea for about six months. The harvested kelp will be tested in two ways: a pyrolysis process and subsequent application as a soil conditioner on agricultural land; the harvested biomass will be sunk to depths of more than 1,000 m on the seabed. *"In case of success, DNV said commercial-scale seaweed production could start offshore in central Norway from 2025 from one or several farms. The company also stated the goal would be to capture millions of metric tons per annum (mtpa) of carbon."*

UK-based **Carbon Kapture Ltd.** was founded in 2019 by Howard Gunstock and Dave Walker-Nix. The company aims to establish kelp farms off the coast of the UK, including Wales, Ireland, England and Scotland. The kelp will be harvested and sold for further processing. The company also aims to sell carbon credits. The company reported that its first 10 hectares have been financed, the exact location is not yet disclosed.

Omega Green aims to combine algae production and CO_2 capture by injecting flue gas into the algae culture system. The company has established production systems at three sites, the largest of which is located in Morocco and covers an area of one hectare. Omega Green's R&D facility and another production site (0.25 ha) are located in Eemshaven, the Netherlands. At the site in Morocco, waste gases from the cement industry are to be fed directly into the algae facility. It is not disclosed how the algae – which may be contaminated with pollutants from the flue gases – are marketed.

Global Algae Innovations was founded in 2013 by Dr David Hazlebeck and has an algae production facility in Hawaii. In 2022, the company was an XPRIZE carbon removal milestone winner and plans to use its prize to establish a ~65 ha algae farm in Shandon, Southern California. There, algae is to capture atmospheric carbon and the harvested algae is to be used to produce biofuels and polymers, among other things.

Ontario-based company **Pond Technologies** has developed an approach to capture CO_2 and feed it into photobioreactors. Microalgae are grown in the photobioreactors and CO_2 from industrial plants is fed into the reactors. The algae are used to make products such as food supplements, animal feed and algae biomass for biofuels. Pond Technologies plans to cooperate with industrial partners, including Stelco's Lake Erie Work steel mill in Nanitoke, Ontario. Construction of the photobioreactor at Stelco's steel mill was planned for the fourth quarter of 2019, was initially postponed and is now cancelled. The construction works were to be carried out in cooperation with SNC-Lavalin Inc.

The **Chinese ENN Research and Development Co. Ltd**. started looking into microalgae research in 2006. Soon afterwards, two test sites were established: a pilot testing site for microalgae cultivation in Langfang (Hebei) and an algae demonstration facility in Dalat, Inner Mongolia. At these sites, ENN tested more than 200 different microalgae strains, aiming to develop biofuels, animal and fish feed and high-value products. The project site in Inner Mongolia was supposed to grow to a 280 hectares microalgae farm by 2013, but there is no evidence that this plan was realised.

Seambiotic Ltd. was founded in 2003 by Ami Ben Amotz. In 2006, the Israeli company began cultivating microalgae in open ponds using waste gas from the Israel Electric Company's Rutenberg power plant near Ashkelon. Seambiotic tested various microalgae species and planned to use the harvested algae as feedstock for nutraceuticals and biofuels. Further pilot plants and larger facilities were planned, e.g., in the United States, Italy and China. In 2015, Seambiotic discontinued its activities as project performance fell short of expectations.

Seaweed Generation Ltd was founded in 2021 and is a company registered in Cornwall, England. The company aims to intercept Sargassum seaweed in the mid-Atlantic and sink it to depths of 2,000 m for CO_2 removal. The first pilot tests are planned for 2023 and 2024. No information is yet known about the exact locations and scale of the pilot trials.

There are several recent studies that look at the carbon removal potential of algae in the ocean. According to these studies, deep-sea biomass dumping and large-scale algae cultivation have a much lower potential than described by the companies that seek to sell carbon credits on this basis, e.g., large-scale algae cultivation can even be a potential net source of CO_2:

- Chelsey A. Baker, et al., in a study published in May 2022 in Global Biogeochemical Cycles, investigated the residence time of organic carbon compounds in deeper ocean layers used in climate models. The authors conclude that the proportion of organic carbon compounds that remain in deeper ocean layers for at least a century or more is significantly overestimated (by at least ~40 %). Miscalculations have direct implications for the storage potential of projects that seek to sink biomass such as macroalgae into deeper ocean layers.
- Using the macroalga Sargassum as an example, Lennart T. Bach, et al. show in a study published in nature communications in May 2022 that biogeochemical processes in seawater can lead to the macroalga's CO_2 removal effectiveness being very low and that it could even represent a potential net source of CO_2.
- A study published in February 2022 in ICES Journal of Marine Science by John Barry Gallagher, et al., also concludes that algal ecosystems are a source of carbon, partly because algae harbor species that exhale large amounts of carbon.
- In March 2022, John Barry Gallagher added in The Conversation: *seaweed may emit as much as 150 tonnes of CO_2 "to the atmosphere per square kilometre every year, in contrast to previous estimates that seaweed absorbs 50 tonnes per square kilometre".*
- The National Academic Press estimated in "*A research strategy for*

> *ocean-based carbon dioxide removal and sequestration (2022)"* that the area of seaweed farms capable of sequestering 0.1 gigaton of CO_2 per year would need to cover 73,000 square kilometres, which is nearly the size of Panama or the Czech Republic. A single square farm would have an area with a side length of 270 kilometres. A 100 metres wide belt of algae farms along the coasts would require 730,000 kilometres – equivalent to 63 % of the world's coastline. The National Academic Press adds: *"The amount of ocean surface area required to sequester 0.1 gigaton of CO_2 per year demonstrates the size of the engineering and logistical tasks at hand associated with scaling seaweed-cultivation CO_2 removal solutions to climate-relevant scales."*

FURTHER CURRENT GEOENGINEERING DEVELOPMENTS

Africa & Northern America
De Beers Group is the world's largest diamond producer and trader and headquartered in London. Project Minera was launched by De Beers Group in 2015 and aimed to look into carbon mineralization/enhanced weathering in the mining sector. The project tested options to store CO_2 in kimberlite rock, a mine tailing from diamond mining and involved R&D, laboratory trials and field experiments at four mining sites: Gahcho Kué diamond mine in Canada, Venetia mine in South Africa, Jwaneng and Orapa diamond mine in Botswana. De Beers' successor project CarbonVault aims to accelerate carbon mineralisation processes by conducting R&D, laboratory testing and field testing and is conducted at the Canadian **Snap Lake** and **Gahcho Kué diamond mines**, South-African **Venetia diamond mine**, and **Orapa** and **Jwaneng diamond mines** in Botswana.

Asia
The Omani company **44.01** aims to permanently mineralize one billion tonnes of CO_2 in peridotite rocks in Oman by 2040. Peridotite reacts with CO_2 and water to form the mineral calcite. In order to accelerate this years-long process, highly carbonated water is to be injected into the rock through targeted boreholes. For CO_2 capture, 44.01 has been in talks with DAC companies and has entered into collaborations with Switzerland's Climeworks and the UK's Mission Zero Technologies. Since 2021, Climeworks and 44.01 are jointly exploring the combination of Climeworks DAC technology with geological storage of CO_2 in peridotite rock in Oman.

Australia
In July 2022, Highly Innovative Fuels Global (HIF Global) announced

plans to develop an eFuels production facility 30 km south of Burnie, in north-west Tasmania, Australia. **HIF Asia Pacific**, a subsidiary of HIF Global, filed a Notice of Intent with the Tasmanian Environment Protection Authority, seeking approval for the facility. HIF plans to start construction in 2024 and aims to produce up to 100 million litres of eFuels annually at this site.

AspiraDAC Pty Ltd. develops modular, solar-powered DAC technology. The solar power supply is directly integrated into the DAC modules. The CO_2 sorbent is based on a metal-organic framework (MOF) structure. According to AspiraDAC, the DAC approach requires little thermal energy and is cost-effective – but precise details on energy and resource consumption are not yet publicly available. The captured CO_2 is to be injected underground. With financial support from the Australian Federal government, AspiraDAC has committed to build a DAC plant that will deliver ~310 t of CO_2/year; no information is yet available on the location or timeline.

Europe

greenSand, a company founded by Eddy Wijnker in 2008, proposes to remove atmospheric carbon by enhanced weathering with olivine-rich rocks. On its website, greenSand offers the compensation of CO_2 emissions by selling CO_2 certificates. According to greenSand, for every tonne of CO_2, one tonne of olivine is scattered, e.g., in home gardens or fields. It is unclear where the olivine is mined and crushed and how much distance it has to travel before it is spread. In September 2022, the company stated that it has spread 68,000 tonnes of olivine to date.

Parallel Carbon was founded in 2021 by Ryan Anderson and Aránzazu Carmona Orbezo. The UK-based company is a developer of direct air capture (DAC) technology. The DAC approach combines an electrochemical process with passive, ambient mineral carbonation and uses wind, sunshine and the mineral $Ca(OH)_2$ (calcium hydroxide). The calcium hydroxide particles capture CO_2 through ambient carbonation and create solid calcium carbonate ($CaCO_3$). Through an aqueous acid-base reaction, the CO_2 is released from the solid calcium carbonates and the recovered $Ca(OH)_2$ can repeat the cycle. The carbonation phase runs passively and can take hours to days. The concept is currently being patented.

North America

CO_2Lock Corporation was founded as a subsidiary of FPX Nickel Corp. to commercialise CO_2 mineralisation in ultramafic rock. The company's goal is to develop CO_2 storage projects – first on a regional scale and later on a global scale. Prior to the formation of CO_2Lock Corporation, **FPX**

Nickel Corp. conductedresearch on the mineralisation of CO_2 in brucite-rich serpentinised periodite in collaboration with the University of British Columbia and Natural Resources Canada since ~2016. Under laboratory studies, CO_2 was mineralised in this ultramafic rock in the form of carbonates. FPX was funded with CAD$1.5 million in an initial round of investment in 2022. Up to CAD$ 50 million is targeted to be raised by 2026 to realise a large-scale demonstration project and plan a first commercial project. The planned carbon mineralization activities are to begin in FPX's Decar Nickel District and the preceding research work involved rocks from this mining area. In its investor presentation, CO_2Lock Corp. states that it is already acquiring tenures in areas of British Columbia with occurrences of ultramafic rock for the development of CCS projects.

In 2020, Canada Nickel Company Inc. formed **NetZero Metals Inc.** to research and develop CO_2 capture from flue gas and carbon mineralization at a processing plant in the Timmins-Cochrane region of northern Ontario. In the past, Canada Nickel has conducted initial laboratory testing of carbon mineralisation with ultramafic mine tailings at its Crawford nickel-cobalt-sulphide project, south of Timmins. A focus of the NetZero initiative will be to maximize the conversion of ultramafic tailings to carbonate minerals in the tailing's storage facility. CO_2 and SO_2 are to be captured from the flue gases in all production operations and diverted for absorption in the ultramafic mine tailings.

The **Hinton Bioenergy Carbon Capture and Sequestration (BECCS) project** is being led by Vault 44.01 in partnership with West Fraser and TorchLight Bioresources. The project aims to capture 1.3 million tonnes of CO_2 emissions per year at West Fraser's Hinton Pulp Mill. In addition, it aims to generate so-called "negative emissions" and sell them to carbon-intense sectors such as aviation, shipping, and the steel industry. The Government of Alberta is funding the project with CAD$ 2.49 million through its Emissions Reduction Alberta (ERA) program.

Heirloom Carbon Technologies aims to develop a land-based and cost-effective CO_2 capture process based on mineral carbonates (limestone) such as magnesite ($MgCO_3$). The company has a target of capturing one million tonnes of CO_2 by 2035 and is currently analysing where its technology could be installed. The process developed combines Enhanced Weathering and Direct Air Capture and, according to Heirloom, it requires the following: carbonate (limestone) and thus proximity to limestone mines, energy, land, water and access to CO_2 pipelines.

The San Francisco-based company **Living Carbon** genetically modified trees to increase their CO_2 assimilation and growth. Living Carbon claims that

its modified trees produce over 50% more biomass – but there is no peer-reviewed study to date to confirm this. By 2050, the company aims to plant 13 million hectares of land with genetically modified trees. Currently, an area with ~600 genetically modified trees is planted in Corvallis, Oregon, and is being monitored in collaboration with Oregon State University's College of Forestry. Further planting sites are located at Reidsville, Georgia (~1,130 ha) and at Zion Grove, Pennsylvania (~120 ha).