Planeteers

Carbon dioxide removal prepurchase application

Summer 2024

General Application

(The General Application applies to everyone; all applicants should complete this)

Public section

The content in this section (answers to questions 1(a) - (d)) will be made public on the Frontier GitHub repository after the conclusion of the 2024 summer purchase cycle. Include as much detail as possible but omit sensitive and proprietary information.

Company or organization name

Planeteers GmbH

Company or organization location (we welcome applicants from anywhere in the world)

Hamburg, Germany

Name(s) of primary point(s) of contact for this application

Frank Rattey, Tobias Sodoge

Brief company or organization description <20 words

The Planeteers remove carbon by transforming CO_2 and alkaline materials in reactors into bicarbonate and hydrated carbonate minerals for OAE

1. Public summary of proposed project[1] to Frontier

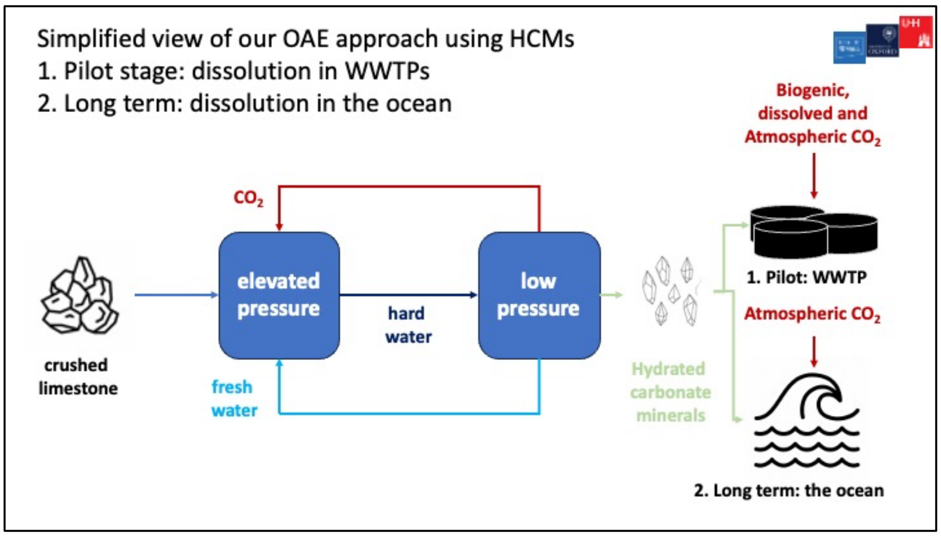
a. **Description of the CDR approach:** Describe how the proposed technology removes CO_2 from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If your project addresses any of the priority innovation areas identified in the RFP, tell us how. Please include figures and system schematics and be specific, but concise. 1000-1500 words

[1] We use "project" throughout this template, but the term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

Context, summary and differentiation

Ocean alkalinity enhancement (OAE) is a carbon dioxide removal (CDR) approach, which aims to durably store atmospheric carbon dioxide (CO_2) as dissolved bicarbonate (HCO_3^-) and, to a much lesser extent, carbonate (CO_3^{2-}) ions. This is achieved by adding alkalinity to the oceans, which enhances the ocean's ability for additional CO_2 uptake from the atmosphere through air-sea gas exchange (Oschlies et. al, 2023). The oceans contain ~ 38,000 Gt of carbon, while dissolved inorganic carbon (DIC) has a residence time of >10,000 (Middelburg et al., 2020; Renforth and Henderson, 2017). A co-benefit of this approach is (locally) counteracting ocean acidification. Our OAE approach is based on the production and dissolution of hydrated carbonate minerals (HCMs), e.g., ikaite or amorphous calcium carbonate (ACC). The deployment of our solution will be twofold:

1. Pilot stage: we will produce and dissolve HCMs within existing wastewater treatment plants (WWTPs), bearing in mind regulatory, ecosystem, and measurement, reporting, and verification (MRV) uncertainties.
2. Long term: we will distribute HCMs, either pre-equilibrated or directly in the ocean, depending on the results of our pilot stage and related scientific, social, and regulatory developments.



Our approach has the potential to become best in class and **strategically differentiated** from other OAE approaches for **5 main reasons**.

First, it is energy and carbon removal efficient, due to lower losses in the production process, e.g., compared to approaches involving calcination, which potentially could release heat to the ocean (when quicklime is used) and CO_2 to the atmosphere, since calcination is notorious for its energy and carbon footprint (Renforth et al., 2022).

Second, it is cost efficient, e.g., by using waste fines from limestone production and a pressure swing approach that minimizes losses of process water and CO_2, and not relying upon complex and costly equipment, e.g., membranes used in electrochemical approaches (Renforth et al., 2022).

Third, the approach is scalable, since alkaline feedstocks are abundantly available with a global industry for quarrying, grinding, and transport already in place. No additional infrastructure for the CO_2 transport and storage needs to be built. The technology for production does not rely heavily on scarce resources, such as biogenic CO_2, or other scarce materials and does not generate by-products, such as hydrochloric acid (HCl) in the case of electrochemical approaches.

Fourth, measurement based MRV systems become feasible, and losses of dissolved inorganic carbon can be limited, by controlled release of CO_2-equilibrated solutions and the relatively fast dissolution of HCMs. This is a key challenge for ocean liming using less reactive materials (Hartmann et al., 2023, Suitner et al., 2023).

Fifth, impacts on the (marine) ecosystems can be minimized, by adding HCMs which release both magnesium and calcium and by mixing with sufficient amounts of untreated water. After release, the addition of HCMs results in pH values below 8.7 and is thus within the limits of natural variability in the oceans. The high pH and particles sinking into sediments are key issues which other OAE approaches, e.g., hydroxide or olivine addition are facing (Renforth et al., 2013)

Combining all these reasons make our approach a perfect candidate for reaching scale, cost, and social and environmental requirements for gigaton (Gt) scale CDR.

Scientific Background

The ocean basins are supersaturated with respect to most non-hydrated, naturally occurring, carbonate minerals, and thus these barely dissolve in seawater. However, ocean basins are not saturated with respect to HCMs, which, therefore, spontaneously dissolve in seawater (see figure 1 below).

Ikaite, monohydrocalcite (MHC), hydromagnesite, nesquehonite, and amorphous calcium carbonate (ACC) are all naturally occurring, metastable HCMs, making them candidate materials for our OAE approach (for details see Table 1 in Eisaman, Geilert, Renforth et al., 2023). Depending on the candidate material, dissolution rates vary, e.g., ACC dissolves within hours, while ikaite dissolves within days (but maybe pre-dissolved before release of the alkaline solution into the ocean). Stability of HCMs depends on storage conditions. Bastiani et al. are preparing a paper on dissolution kinetics and stability of HCMS under varying conditions, e.g., temperature. Preliminary results were shown at the International Conference on Negative CO_2 Emissions 2024 in Oxford this June and are in support of our system, since HCMs dissolution results in increased alkalinity.

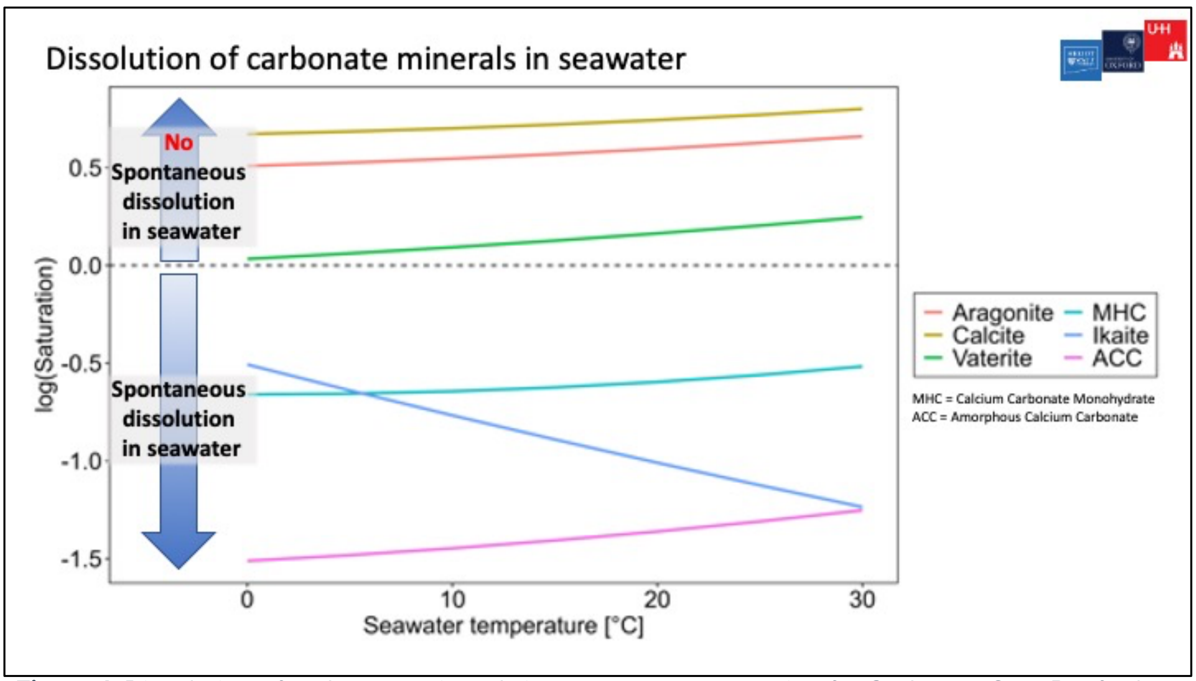


Figure 1: *Dissolution of carbonate minerals in seawater, presentation for Carbon to Sea, Renforth et al. 2024.*

Total alkalinity (TA) increase, and TA efficiency depend on material and environment specific parameters, e.g., seawater temperature, particle size, and hydrodynamics. Figure 2 below shows that under optimized conditions, nearly 100% of the alkalinity potential can be released (Renforth et al., 2022). However, employment must take into account environmental conditions, particularly temperature. Additionally, pre-dissolving HCMs, before releasing them, into seawater should be considered as a means to optimize MRV.

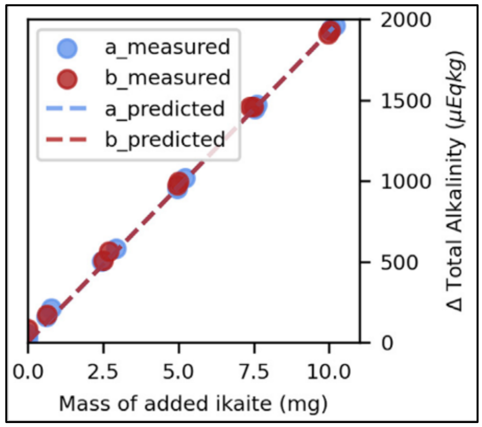


Figure 2: *Alkalinity potential of Ikaite, Renforth et at., 2022*

A runaway calcium carbonate ($CaCO_3$) formation process, potentially expected at higher alkalinity additions, can be avoided via pretreatment and by diluting with untreated seawater in time (Moras et al., 2023, Suitner et al., 2023).

Technology overview:

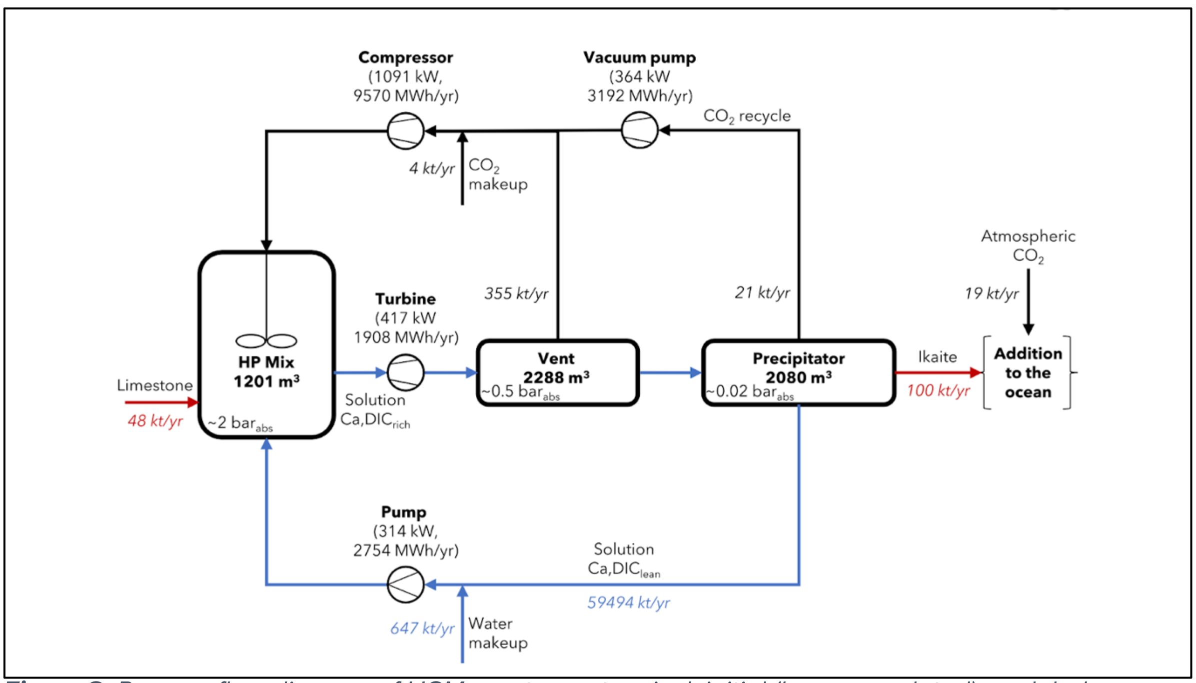


Figure 3: *Process flow diagram of HCM reactor system incl. initial (by now updated) modeled mass flow analysis, Renforth et al. 2022*

1. Dissolution/HP Mix

Through our intake system, relatively pure CO_2 gas is mixed with water forming an acidic solution rich in DIC. Our flexible system can be fed from a variety of sources, e.g. biogas, or sludge incineration at a WWTP, or the calcination of limestone. Separately, alkaline materials, e.g., (waste) products from limestone manufacturers containing mainly calcite, aragonite, dolomite are mixed with water, resulting in an alkaline solution. CO_2 enriched water and alkaline materials are then mixed under pressure (2-4 bar), resulting in the enhanced dissolution of the alkaline materials and thus the transformation of the influx CO_2 into a (bi)carbonate-rich solution.

2. Precipitation
The bicarbonate rich solution is passed through an intermediate venting reactor (0.5 bar) to a low pressure (0.05-0.01 bar) reactor. In these reactors, conditions are created which favor HCMs formation and inhibit precipitation of other minerals, e.g., vacuum stripping of CO_2 and use of inhibitors/catalysts. The degassed pure CO_2 and the remaining solution can be reused in the dissolution system. Precipitated HCMs are then harvested from the reactor.

3.Storage
The produced HCMs will be- if required - stored under conditions ensuring sufficient stability for later distribution, e.g., cold and humid.

4.Distribution
The distribution into the ocean can be done in a variety of ways. Initially we will deploy our technology at WWTPs to ensure compliance with regulations and ecosystem safety. Here, we will release the HCMs before the last monitoring point of a selected WWTP. Once regulations are clearer, e.g., for test sites, HCMs can be dispersed through (existing) pipe systems from land or offshore structures. The equilibration with CO_2 from the atmosphere can take place before or after release to seawater. In the long run, once MRV systems have matured, distribution could also be facilitated via ships. If dispersion is done via ships and/or offshore structures, existing infrastructures such as ports and (container and bulk) vessels, offshore wind farms, oil rigs, and supply ships could be used. If dispersion is done via pipes, site selection in proximity to renewable energy, alkaline feedstocks, and favorable hydrodynamics should minimize transport and dispersion costs. Here it is important that pipe systems are releasing the alkalinity in surface ocean waters.

5. MRV
The basic concept of our MRV system consists of a combination of complex computer models, as well as continuous and point-by-point measurements and comparison with historical and on-site monitoring data.

Based on our reactor technology, we need to distinguish two steps of the MRV: (a) the reactor itself and (b) the reactions that happen when releasing the created alkalinity into the target water.

Reactor: We continuously measure and compare both inflow and outflow with pH, CO_2, and conductivity sensors within our reactor. This allows us to describe system performance for HCMs production very accurately.

HCMs Distribution: Consequently, we can release controlled amounts of HCMs below critical pH/carbonate saturation values, the excess of which would lead to a reduction in the efficiency of our approach. These values are established through leading scientists in our wider project team and/or collaboration projects (e.g. Suitner et al., 2023, https://doi.org/10.5194/egusphere-2023-2611 and within the CDR-mare-RETAKE II consortium for the Elbe-estuary). This approach allows us to create an alkaline solution that is already equilibrated with respect to the target water and the water-atmosphere conditions. Site-specific, hydrodynamic computer models are used to assess water movements and mixing conditions with downstream water. Additionally, selective measurements are performed to derive maximum values for appropriate alkalinity intake from the calculated and measured data points. Based on this “calibration”, our systems are continuously further developed, e.g., optimizations are made to the reactor and MRV concept and the monitoring concept will be adapted.

Both the reactor and MRV systems will follow the five guiding principles that represent the scientific standard for land- and ocean-based CDR (Buessler et.al. 2022).

Priority areas addressed:

Industrial integration:
Our project (described in more detail in the "Project objectives") will integrate our HCM reactor systems, dissolution, and MRV into the WWTP of Hetlingen, Northern Germany (AZV Suedholstein), located at the Elbe estuary. We are partnering with a subsidiary of Omya, located approximately 40 km away, for limestone acquisition. Additionally, we are collaborating with Fels-Werke, about 250 km away, to utilize their (waste) products as feedstocks. This approach is scalable to other WWTPs and limestone production facilities. Additionally, EU regulation leads to further growth in sludge incineration and usage as heating feedstock for limestone producers, enabling circular models between WWTPs, the Planeteers, and limestone production.

Redundancy across know promising approaches
As pointed out above, inputs for our reactor could come from waste materials from lime and cement manufacturing. Using these to produce HCMS, dissolving it in WWTPs could help bind biogenic CO_2 unused in the water, unused until now. Additionally, by using biogenic CO_2 from sludge incineration in our system, we create an additional purpose for previously emitted CO_2.

Additional revenue sources:
By using waste products from limestone production our synthetic HCMs can potentially be used as a carbon negative substitute for other liming materials such as quicklime (CaO) or hydrated lime ($Ca(OH)_2$) by WWTPs (e.g., for pH management based and removal of phosphorus and other contaminants).

Environmental/ economic co-benefits
Our project also counteracts local ocean/water acidification, again, based on the delivered alkalinity of HCMs. Our MRV system can be used to gather environmental data on ocean and river waters and thus helps to identify measures to improve riverine health. WWTPs are widely accepted by society for their operations. We believe that integrating with them can generate local project support. This can be achieved by transparently reporting and providing environmental data. Additionally, fostering economic participation from both WWTPs and local communities is essential. This approach can serve as a blueprint to broaden support for more ambitious climate action initiatives.

Our project meets all marine CDR (mCDR) specific criteria:
Working with WWTPs or in proximity to shores or offshore structures enables deploying our measurement-based MRV system (e.g., using moving vessels, buoy-based systems, and/or ferry boxes for measurements).
As pointed out above, limestone and cement/lime manufacturing wastes are key feedstocks, which are available both in terms of amount and infrastructure to support the much-needed Gt scale. Additionally, we plan to test other alkaline feedstocks.
Our reactor-based approach to synthesize HCMs, and their rapid dissolution, allows us to quantify the feedstock dissolution before the point of discharge and then track it by our measurement based MRV system.
By partnering with WWTPs we aim to include efficient methods for treating or remediating feedstocks with dangerous contaminants, as to unlock more feedstock sources without compromising ecosystem safety. In addition, limestone has the advantage of containing almost no potential harmful elements, in contrast to mafic silicate rocks which contain impurities such as, nickel and chromium.
Lastly, and by design, our HCM reactor and dissolution systems are a “novel technology for rapid mineral dissolution and/or pre-equilibration with atmospheric CO_2”

b. **Project objectives:** What are you trying to build? Discuss location(s) and scale. What is the current cost breakdown, and what needs to happen for your CDR solution to approach Frontier's cost and scale criteria?[2] What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. 1000-1500 words

Context and current status

Planeteers
Starting in Q4/2022, the Planeteers have successfully developed and tested an enhanced weathering / alkalinity reactor system at pilot scale (50t/y CDR) based on a bench-top lab reactor built by Dr. Jens Hartmann at the University of Hamburg. We are now starting the validation of this pilot at the WWTP in Hetlingen, Northern Germany, in the Elbe estuary. This reactor converts CO2 and limestone into bicarbonate dissolved in water. It is equivalent to the Dissolution / HP Mix module of the HCM reactor system, described in the technology overview section of 1a.

We have developed a MRV concept, built partnerships, and clarified the regulatory and environmental compliance of piloting this system at WWTPs in Germany. We are planning to further develop this "core" technology of the Planeteers and scale it to commercialization. The idea is to continuously leverage learnings from the Planteers for the HCM based OAE approach described in this application.

Project partners: University of Hamburg, Heriot Watt University/Edinburgh, University of Oxford, GEOMAR Kiel, Carbon to Sea Initiative
"Crystal ocean" is an R&D project centered on HCMs and funded by the Carbon to Sea initiative. It is a collaboration between Dr. Phil Renforth and Dr. Spyridon Foteinis of Heriot-Watt University, Dr. Jens Hartmann of the University of Hamburg, and Dr. Aidong Yang of the University of Oxford. The key results of the project are: HCMs were produced from a bench-top pressure swing process. The stability of the produced HCMs depends on how they are handled post-production, but days to months of stability appear possible. When added to seawater, HCMs dissolve within a couple of hours to days depending on the mineral precipitated, resulting in an increase in alkalinity. For details see 1a.
The team at Heriot-Watt University, lead prototype build and operation, the team in Oxford process modeling and system verification, and the team in Hamburg characterization of stability and dissolution behavior of the HCMs.
This collaboration will continue and will be completed by the Planeteers to further advance the development of the technology.
The GEOMAR in Kiel has led and completed 3 mesocosm experiments in Bergen, Gran Canaria and Helgoland to assess ecosystem impacts of CO_2-equilibrated addition of alkalinity. Mesocosm experiments with particle-based addition of alkalinity are ongoing.
It is planned to conduct mesocosm experiments with HCMs with research partners in the future.

[2] We're looking for approaches that can reach climate-relevant scale (about 0.5 Gt CDR/year at $100/ton). We will consider approaches that don't quite meet this bar if they perform well against our other criteria, can enable the removal of hundreds of millions of tons, are otherwise compelling enough to be part of the global portfolio of climate solutions.

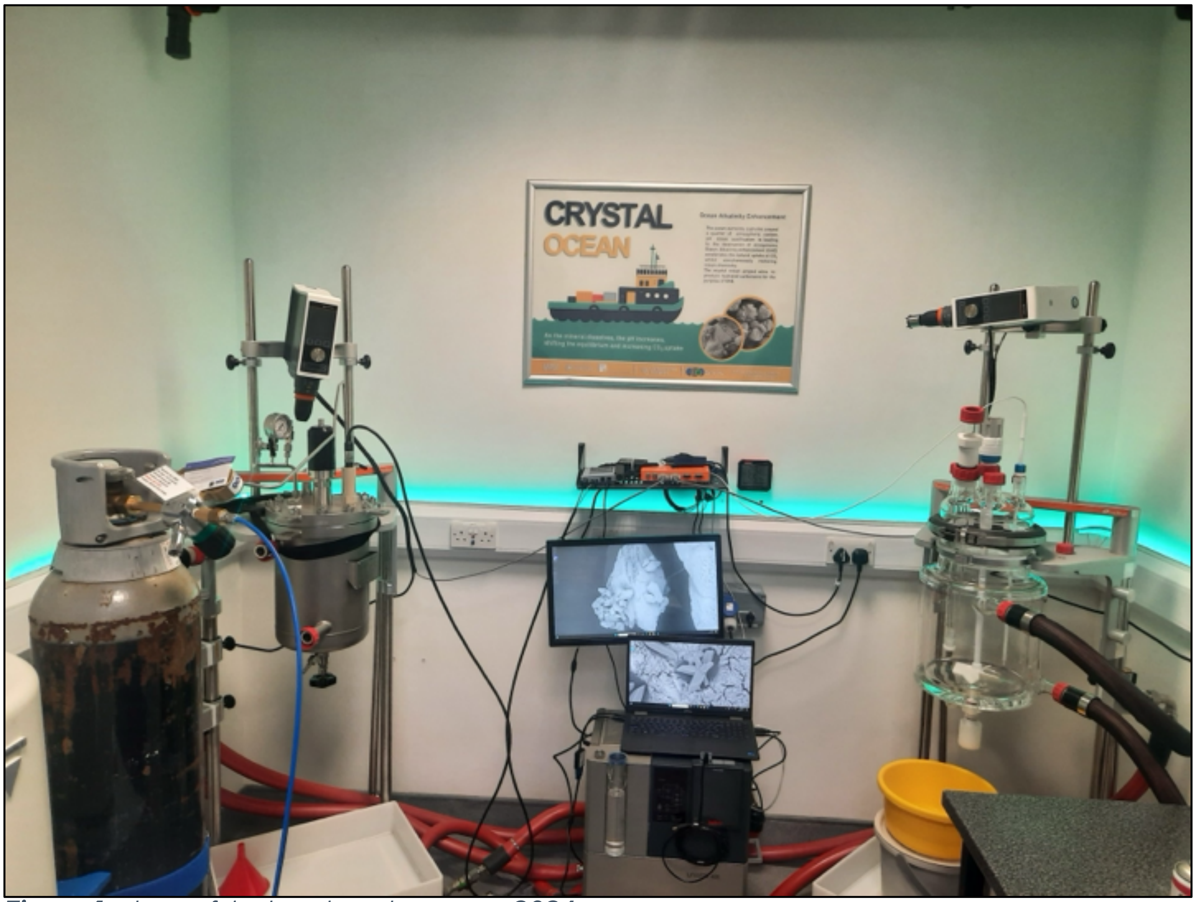


Figure 4: *photo of the bench scale reactor, 2024*

Project objectives and workstreams

Our project has **three main objectives**, all focused on enabling scalability, cost efficiency, and sustainability (environmental, social, economic, and regulatory) of our HCM OAE approach:

Objective 1: To derive our pilot reactor system (50 t CO_2/y) from our bench top system, to evolve the pilot into our first of a kind (FOAK) plant (1000 t CO_2/y) and to remove about 250 t CO_2 over the next 4 years.

Objective 2: To validate our CDR approach regarding ecosystem safety, and the effectiveness of our MRV approach through a series of micro-, mesocosm and small-scale real-world experiments.

Objective 3: To carry out all work aligned to the principles described in the Code of Conduct for Marine CDR (Aspen Institute, 2023) and in the Guide to Best Practices in Ocean Alkalinity Enhancement Research (Copernicus Publications, 2023)

To achieve these objectives, we have structured our project into three corresponding workstreams:

Workstream 1 - HCM production: R&D on reactor and technology deployment at WWTP Hetlingen at the Elbe estuary.

Sub workstream 1.1 - Pilot HCM reactor system with 50 t annual CDR capacity:

We will carry out aligned modeling and real world experiments using our bench scale (10 L dissolution and precipitation reactors) system in Edinburgh and our model reactor (digital twin) in Oxford to derive the design of the pilot reactor in quick iterations. In parallel, we will continue to test stability and dissolution of HCMs at the University of Hamburg.
We will engineer and commission our pilot HCM reactor (with a HCM capacity of up to 250 tons/y, resulting into CDR of at least 50 tons/y) in the Planeteers' facilities in Hamburg and then deploy it in the WWTP Hetlingen. We will feedback learnings from this deployment to run additional modeling and experiments to further optimize the reactor design.

Sub workstream 1.2 - FOAK HCM plant with an annual CDR capacity of 1.000 t:
Based on the results of workstream 1.1 we will develop our FOAK plant (with a HCM capacity of up to 5,000 tons/y, resulting into CDR of 1,000 tons/y) in our facilities in Hamburg, and then deploy it at the WWTP in Hetlingen.

Workstream 2 - HCM dissolution: validation of MRV approach and incorporation of environmental, social, and regulatory aspects

Sub workstream 2.1 - MRV development: Deploy, test, and refine our MRV system (described in detail in Section 5) at the WWTP Hetlingen and in the Elbe estuary in iterative loops. For the pilot stage, leverage the Planeteers MRV approach for equilibrated dissolved HCMs and then evolve this system towards the long-term application in the ocean.

Sub workstream 2.2 - Integration of studies on environmental, social, and regulatory aspects:
Through our partnerships with research organizations and our close connections into the wider scientific community we will integrate into and learn from studies, e.g., at the Carbon to Sea test site in Iceland. When deploying our technology at Hetlingen, we will proactively manage environmental, social, and regulatory aspects and stop operation immediately in case of unforeseen impacts, e.g., through gathering environmental data and making them openly available.

Workstream 3 - Project management: coordination of partners, stakeholder management, and community participation.

Given the geographical, technological, and scientific complexity of our project, and the potential environmental and social impacts, we are dedicating capacity and plan to proactively manage and coordinate all activities in workstreams 1 and 2, e.g., through regular steering meetings on operational and supervisory levels, through tailored communication to relevant stakeholders and community participation activities in Hetlingen.

Current cost breakdown and pathway to meet scale and cost criteria
Costs for the pilot are driven by more than 60% by capital expenditures (CAPEX), 30% by operating expenses (OPEX), and 10% by MRV and other costs. The high CAPEX portion is a result of lacking economies of scale and novelty of the technology. Through learning and scaling we see a pathway to reaching a cost of about 90$/t. OPEX is driven by (renewable) electricity and limestone, and personnel cost. By the rapid global scale up of renewables, in particular in proximity to oceans, by securing long term strategic partnerships with lime producers and use of waste materials, and by predictive and preventive maintenance processes in a learning system we are confident that OPEX costs will also decline in line with the reductions required to reach the ambitious cost target. Based on our close integration into the scientific community and the increase of available data and learnings from deploying our MRV system, we are also convinced that MRV cost will likely decline in the future.

As pointed out in the differentiating criteria, due to the abundantly available feedstocks, the growth in available renewable energy, no need for scarce materials, or limiting by-products, and finally the fact that the capacity of the ocean is sufficient to store Gt of CDR, we see a clear path to scale our approach.

c. **Risks:** What are the biggest risks and how will you mitigate those? Include technical, project execution, measurement, reporting and verification (MRV), ecosystem, financial, and any other risks. 500-1000 words

Social acceptability
We are aware that an innovative CDR approach like our HCM based OAE faces several important risks. The recent developments at Running Tide as well as the ones in relation to the Planetary Technology test site in Cornwall in 2023, highlight the need to ensure the social acceptability of a solution. We therefore believe that the social license to operate is fundamental to the successful delivery of a pilot demonstration and the scalability of OAE as a pathway. We have therefore made objective 3 (see section 1b) a central part of this application. Our mitigation strategy is to invest significant efforts into obtaining a social license to operate leveraging learnings from the past, e.g., by early and transparent involvement of all relevant stakeholders and communities and in general working according to the principles described in the Code of Conduct for Marine CDR (Aspen Institute 2023) including consent, reciprocity, inclusiveness, reflexivity, responsiveness, accountability, and precaution (see Section 8).

Technical risks
These are mainly linked to the early stage of the HCM approach. Current experiments exploring the creation and precipitation of synthetic HCM are promising, yet the parameters of its mass-production need to be refined. Additionally, challenges in the development, scaling, and deployment of the technology remain. We are mitigating these through early customer & partner integration, rigorous and short-looped pilot testing, a phased scaling approach and continuous R&D benefiting from our coordinated teams in Edinburgh, Oxford and Hamburg.

Project execution risks
The integration of our technology into the WWTP's operations could prove more complex than anticipated and provisioned for. In addition, logistical and supply chain risks. We have established several partnerships to WWTPs in Germany to cover a broad range of operation practices, formed strategic partnerships with local suppliers, optimized logistics planning, and leveraged existing infrastructures where possible.

Ecosystem risks
Releasing alkalinity has potential negative impacts on marine ecosystems and water chemistry. We will set up detailed environmental monitoring plans, adaptive management strategies, collaboration with marine scientists, and ensuring the alkalinity levels remain well within safe limits for marine life.

MRV risks
Our MRV approach could prove less accurate or feasible than anticipated. Therefore, field testing is essential to understand the dissolution behavior in a more scalable, realistic environment as well as the ideal conditions and processes for the HCM dissolution. These experiments are currently in the planning phase to be launched in 2025 and onwards in parallel to the deployment at a WWTP. Additionally, we rely on the implementation of robust MRV protocols, use of third-party verification agencies, and continuous data collection & reporting.

Regulatory risks:
A general uncertainty for any OAE project are national and global regulations related to the ability to add alkaline material to seawater or rivers. It is likely that these regulations will change in favor of the approach to support the climate targets of the Paris Agreement. The international community is already in discussions regarding potential regulatory frameworks for using the ocean as a permanent carbon sink, for instance, initiatives led by the IMO and the White House. (https://www.imo.org/en/MediaCentre/PressBriefings/pages/Marine-geoengineering.aspx).We are assuming to resolve these uncertainties, while we deploy our technology within existing regulatory frameworks at WWTPs allowing the deployment of the technology as of today.

Financial risks
Securing sufficient funding and managing costs effectively will be key to delivering this project. We have just closed our seed finance round with € 4.7 mil. - on-top we have secured funds through grants. A robust financial planning, phased funding strategies, securing partnerships and grants, and a

detailed cost-benefit analyses helps us to manage the financial risks.

d. **Proposed offer to Frontier:** Please list proposed CDR volume, delivery timeline and price below. If you are selected for a Frontier prepurchase, this table will form the basis of contract discussions.

Proposed CDR over the project lifetime (tons) *(should be net volume after taking into account the uncertainty discount proposed in 5c)*	255 tons
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	2028
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	$1,569
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	$1,960

[3] This does not need to exactly match the cost calculated for "This Project" in the TEA spreadsheet (e.g., it's expected to include a margin and reflect reductions from co-product revenue if applicable).