Carbon Atlantis

Carbon dioxide removal prepurchase application

Summer 2023

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 2023 summer purchase cycle. Include as much detail as possible but omit sensitive proprietary information.

Company or organization name

Carbon Atlantis GmbH

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

Munich, Germany

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

Paul Teufel, Malte Feucht

Brief company or organization description <20 words

Carbon Atlantis develops a low-cost, electrochemical ph-swing DAC technology.

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. Aim for 1000-1500 words.

[1] We use "project" throughout this template, but note that 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.

Carbon Atlantis proposes a novel DAC technology that is based on its electrochemical cell for energy-efficient pH-swing. It fundamentally reduces costs. The system is modular and constructed using readily available, industry-proven components (i.e., membranes), ensuring scalability.

This continuous, closed-loop system, as depicted in Figure 1 comprises two main components: an air contactor and an electrochemical backend. Fans mobilize atmospheric air through the air contactor. The air contactor exposes a basified solvent to the air, capturing the CO_2 as bicarbonates. A backend, which includes modules of stacked electrochemical cells, liberates the CO_2 molecules from the solvent at low pH regimes and regenerates it by applying an electrical current.

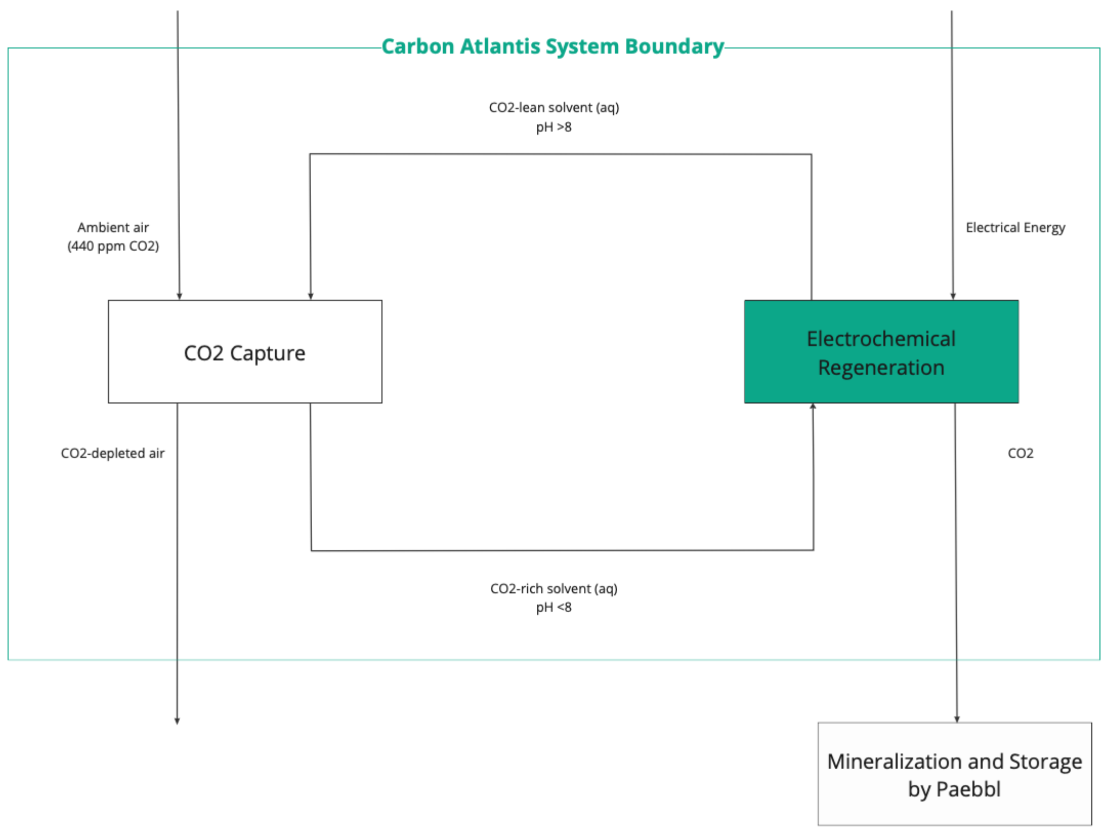

Figure 1: Carbon Atlantis Direct Air Capture System

Carbon Atlantis advantages include:

1. Cost-effectiveness: Very low levelized costs of \$50-75/tCO_2 at NOAK plant scale (>200 $ktCO_2$/y)

2. Energy-Efficiency: Overall system energy, achieving <1,100 kWh/tCO_2 even at pilot scale (<200tCO_2/y).

3. Scalability: Carbon Atlantis cell technology is inspired by proton exchange membrane (PEM) fuel cells and electrolysis technology. Thus, this allows us to rely on scaled supply chains concerning membranes and catalysts. All system components rely solely on widely available materials even when the system is scaled to a gigaton scale.

4. Flexibility: Carbon Atlantis has demonstrated high current densities for its cell technology, allowing adjustment of operations based on energy prices. Given a location-specific energy price, this will

enable us to run the system on an optimized current density to lower the overall levelized cost. Given low electrical energy costs, the system runs on high current densities and vice versa.

5. Environmentally friendly: Our electrolyte solution uses non-toxic, abundantly available salts.

6. Carbon neutrality: The system can and will be entirely powered by electricity from renewable sources.

7. Stability in different temperature environments: The electrochemical cell system can be operated at ambient temperature and does not require stable, high operating temperatures like fuel cells. It can, however, deal with temperatures of up to 90 °C.

8. Modularity: Carbon Atlantis leverages inherent modularity, combining single cells into standardized cell stacks. In the long term, a single stack should allow for a gross removal capacity of 15,000-20,000 tCO_2/y.

For permanent mineralization, Carbon Atlantis is partnering with Paebbl, a Rotterdam-based company. Paebbl's process uses the captured CO_2, ground silicate minerals (i.e., olivine), non-toxic additives, and water to feed them into an accelerated mineralization reactor. Under elevated temperature and pressure, the reactor produces an output mineral stream of carbonate minerals (i.e., $MgCO_3$) and amorphous silica (SiO_2). The sequestration product is a mineral carbonate ($MgCO_3$) which is thermodynamically stable, storing the CO_2 for > 1,000 years, as 95% of the construction materials will not be exposed to pH <2 or Temperature >350°C[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 $100/t and 0.5Gt targets? What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

Carbon Atlantis proposes a 260 tCO_2/y CDR project with Paebbl, a Rotterdam-based company that converts the captured CO_2 into mineral products ($MgCO_3$, $CaCO_3$). Today's concrete additives, so-called mineral fillers, typically do not address carbon emissions. Certain fillers can tackle present-day emissions by utilizing commodity CO_2 generated by fossil fuel combustion. However, integrating scalable and affordable DAC-sourced CO_2 would allow us to address historical emissions, thereby transforming the built environment into a carbon sink, using Paebbl novels technology for mineralization.

Both Carbon Atlantis and Paebbls technologies have been shown at elevated lab scales, i.e., TRL4+ for Carbon Atlantis. Paebbls's technology has additionally been shown as a proven batch process in reactors ranging from 1L to 2,000L. Carbon Atlantis' technology comprises 4 cell stacks that are connected to one absorber column. Each stack has a nominal capacity of 65 tCO_2/y. The joint project aims to demonstrate Carbon Atlantis electrochemical CO_2 separation technology at low cost and Paebbls continuous mineralization process at a larger pilot scale. Our joint project's key objective is to pave the way for a new business model that transforms the built environment into a permanent CO_2 storage solution, while also offering the potential for negative-cost CDR and storage. This is made possible by leveraging the sales value of the output material.

The current cost breakdown for the pilot project is $1,450/$tCO_2$, including mineralization. Capital costs contribute to 65% of the overall cost. To get levelized costs of <$100/$tCO_2$, levelized capital costs

[2] Lackner, 2003; Pabbl. Frontier application Fall 2022.

must decrease by 790%, while energy costs must decrease by a factor of 13%. Electrical energy prices must decrease from currently \$103/MWh to \$40/MWh.

We are implementing the following monitoring steps to quantify the amount of carbon removed.

1. Measure the CO2 captured using mass flow controllers at the outlet of Carbon Atlantis´ System and the inlet of Paebbls mineralization process.
2. Loss in ignition tests in the output mineral mixture, which determines the exact CO2 content of the mixture by Paebbl.
3. Supplementary laboratory analysis using x-ray fluorescence (XRF) done by Paebbl.

While running the process for longer continuous stretches, the output will be sampled at regular time intervals. Verification of the measurements and methodology will be done by a neutral third-party organization, with which Paebbl has already established a partnership.

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. Aim for 500-1000 words.

Risk 1- Stack Engineering: We handle hydrogen in our system. Working with hydrogen can be challenging when upscaling the system because it is a very volatile gas. The main problems that will arise here are leakage issues from the stack. However, from fuel cell technology, it is known that leakage issues of hydrogen arise at higher active areas of 1,000 cm2 and large cell per stack configurations. However, the financial risks are neglectable. For instance, a 3% Hydrogen loss would only marginally increase the costs per tCO2 captured for our system.

Risk 2- Robustness of the system: Long-term operations in real-world environments and extreme climatic conditions are challenging for stable operations throughout the year. Under hot climate conditions, solvent evaporation might occur, which would need a steady supply of fresh water to maintain system operations.

Risk 3- First of a kind project: Carbon Atlantis core technology is inspired by the fuel cell and proton exchange membrane (PEM) electrolysis technology. Both technologies are well understood. However, applying it to the use case of Direct Air Capture and building industry-sized plants is a new challenge for the Carbon Atlantis team. We plan to mitigate risks by partnering with experienced engineering, planning, and construction (EPC) companies for a successful scale-up. Partnerships are well underway.

Risk 4- Mineralization: This project poses the first-of-a-kind project for our mineralization partner Paebbl. In case of unexpected problems with the mineralization process, the plant location in Rotterdam poses an excellent location to mitigate these risks. We have an LOI with Carbfix for the geological injection of CO2 from a pilot project. According to the research conducted by the DemoUpCARMA[3] Project, we anticipate that the additional transport and storage costs, including the purchase of tanks, from the Carbon Atlantis facility in Rotterdam to the injection site in Helguvík, Iceland, would amount to approximately \$185/tCO2.

[3] http://www.demoupcarma.ethz.ch/en/project/Frequently-Asked-Questions/

Risk 5- Market: The voluntary market for carbon removal is still very nascent, rather not consolidated, and small. The market is expected to reach 2.6 GtCO2/y by 2030. The Inflation Reduction Act in the US is a strong signal by providing tax credits of up to $180/tCO2. The European Union does not have tax incentives for carbon removal yet. However regulations intended to generate corporate buying activity seem to be in the pipeline. Aside from high-margin, low-footprint businesses (Software, Insurance, Banking, and Consulting), the buyer base for the demand for carbon removals is largely unclear. Navigating these markets over the next years and already creating revenues through advanced market commitments will be key to scale-up our solution. Getting purchases from highly regarded and well-recognized buyers clubs such as Frontier will help us to establish trust with more reluctant buyers.

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)*	153 tons
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	March 2027
Levelized Price (\$/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	$1,450/tCO2

** 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).*

[redacted]