PRONOE

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

PRONOE

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

Paris, France

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

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Brief company or organization description <20 words

PRONOE restores the ocean's natural capacity to permanently remove CO_2 from the air, in a sustainable, scalable and asset-light manner.

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

CDR approach: Oceanic CO2 capture and storage

Atmospheric CO2 levels are naturally regulated by the dissolution of CO2 in the ocean. As CO2 dissolves, the surface layer of the ocean becomes more acidic [1]; this acidity is slowly transported to the deeper ocean layers over approximately 1,000 years, where it reacts with CaCO3 deposits on the ocean floor [2]. This process dissolves CaCO3 and restores the ocean's pH balance. Additionally, silicate rocks release alkalinity into the oceans over a much longer time (around 100,000 years), eventually leading to the re-deposition of CaCO3 [3]. Currently, CO2 emissions from human activities are not counterbalanced by natural ocean regulation, resulting in increased atmospheric CO2 concentration and ocean acidification.

The CO2 equilibrium between the ocean and the atmosphere is less than one year across most of the planet [4]. Consequently, CO2 could be captured from the atmosphere within this time frame by alkalizing the ocean surfaces, a process known as Ocean Alkalinity Enhancement (OAE). Once captured, CO2 remains in the ocean as bicarbonate ions (HCO3-), storing carbon for 100,000 to 1,000,000 years [5].

CDR approach: Chemistry behind oceanic CO2 capture and storage

The alkalinity of seawater, commonly referred to as Total Alkalinity (TA), is defined as the capacity to resist changes in pH that would make the water more acidic [6]. Increasing TA does not necessarily means removing CO2. The dissolution of CO2 in seawater involves 3 carbonated chemical species (i.e. CO2, HCO3-, and CO32-), related according to the following chemical equilibria [7]:

$$\mathrm{CO_2\ (aq) + H_2O \leftrightarrow\ HCO_3{}^- + H^+ \leftrightarrow\ 2CO_3{}^{2-} + 2H^+} \qquad \text{Equation 1}$$

The addition of alkalinity as carbonates (CO32-) to seawater would modify these equilibria and consume dissolved CO2 according to the following reaction [8], [9]:

$$\mathrm{CO_3{}^{2-} + 0.8\ CO_2\ (dissolved) + 0.8\ H_2O\ + \cdots\ \rightarrow 1.6\ HCO_3{}^- + 0.2\ CO_3{}^{2-} + \cdots} \qquad \text{Equation 2}$$

Moreover, the addition of alkalinity as hydroxyls (OH-) to leads to the following reaction:

$$\mathrm{OH^- + HCO_3{}^- + \cdots\ \rightarrow H_2O\ + CO_3{}^{2-} + \cdots} \qquad \text{Equation 3}$$

Ultimately, the CO32- obtained in Equation 3 entail the same CO2 removal as Equation 2.

Best-in-class, differentiated technology and approach

Ocean Alkalinity Enhancement (OAE) is broadly accepted as being a high-quality and **high-potential** (100 GtCO2/y) approach that entails **fast capture** (<1 y) and **long-term storage** (>10,000y).

The principle of OAE consists of **enhancing natural carbon cycles** – whereby atmospheric CO2 is captured and sequestered in seawater as dissolved inorganic carbon. This has **direct business implications**: no reliance on a third party for geological storage (**vertical integration**) and **broad**

[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.

geographical compatibility – typically, any coastal or offshore location can be addressed, providing more operational freedom than most capture-only technologies (e.g., DAC/DOC).

Despite unique **environmental co-benefits** through ocean acidification mitigation, the effective development of OAE approaches has been **historically hindered by three *different but interconnected* issues:** 1) **availability of alkaline minerals,** 2) **disposal of acid wastes, and** 3) **permitting.**

1) **Highly alkaline minerals**, either naturally occurring (olivine, basalt) or man-made (slack lime), typically considered **for Mineral OAE** (i) are unevenly distributed globally, (ii) are not extracted nor produced at a scale consistent with meaningful climate action, (iii) may contain environmentally-harmful heavy metals such as Iron or Nickel (Fe, Ni), (iv) may require energy-intensive grinding.
2) Instead of adding alkalinity, **electrochemical-based OAE** aims to remove acidity from the ocean, thus generating **large volumes of *dilute* acidic brines**.
3) In turn, most approaches are based on “rapidly dissolving” or Dissolved **hydroxyl-based alkalinity** (OH-), entailing uncertainties and/or permitting difficulties related to turbidity levels, large pH variations, dissolution rates, or secondary precipitation.

PRONOE tackles all three issues through its holistic approach for Sustainable Scalability, and its unique technology.

OAE takes many forms, PRONOE pursues **Dissolved Carbonate OAE from Coastal Outfalls**.

OAE from **Coastal Outfalls** is deemed the single best OAE approach for focused MRV, providing **high Verifiability** as exemplified by Isometric’s choice of this pathway to set the first Ocean CDR protocol. Leveraging legacy coastal outfalls, massive available water flows, and **operating within the scope of in-force permits** ensures we work within the highest **Safety and Legality** standards, while actively maximizing environmental co-benefits, and contributes to **rapid deployability**.

In a **paradigm shift**, PRONOE has developed a patent-pending process for dissolved carbonate alkalinity production with fully integrated, ex-situ acid neutralization. Our **zero-waste**-generating systems use **cheap, unground, ubiquitous, mildly alkaline mineral feedstocks**, alleviating mineral feedstock scalability issues.

In practice, we develop and deploy automated water treatment systems that are seamlessly integrated downstream of the operations of coastal industrial sites. These safely turn returns flows to the sea into less acidic, more alkaline flows within applicable regulations. See PRONOE’s “BlueBox” in

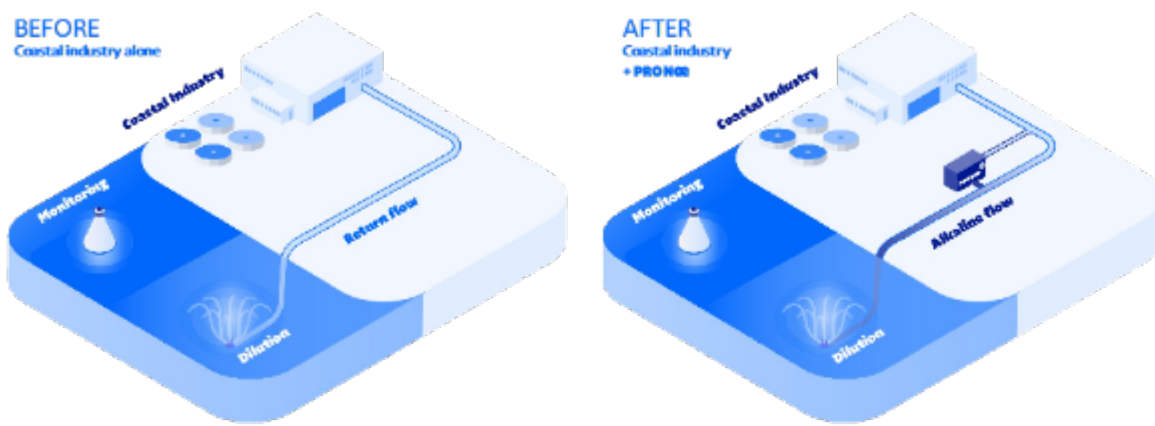

Figure ***1***.

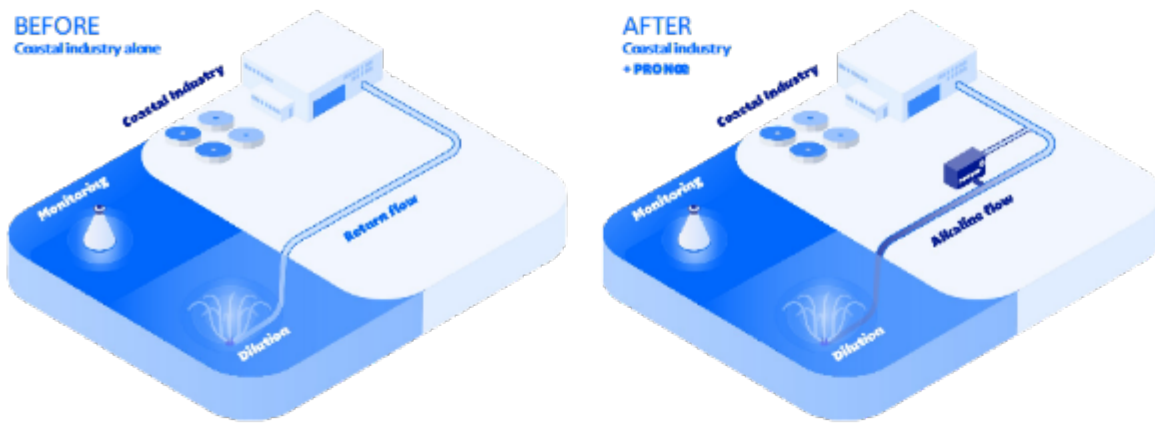

Figure 1 – PRONOE's co-location approach.

Based on electro-membrane technology, our systems are extremely compact, have **a low physical footprint (e.g. less than 30mx30m for a 10 ktCDR/year capacity system)**, and are installed on previously artificialized land. These systems require only electricity and operate at ambient pressure and temperature with **low power consumption at scale.**

Modular technology allows for ease of scale-up. **Automated systems** and no need for downstream CO2 logistics allow for **fully decentralized** CO_2 removal activities. Distributed PRONOE systems of 10 ktCDR/year and 50 ktCDR/year lead to easy-to-finance, rightly-sized projects and ultimately to competitive economics thanks to scale *and* learning effects.

Hardware standardization coupled with software-enabled operational flexibility is at the core of our approach. Our robust process accommodates **varying mineral and water feedstocks** to best leverage local resources: different mineral feedstocks and return flows. This operational flexibility enables us to co-locate with almost any industrial site with a return flow to the sea. This return flow can be an effluent, in the case of wastewater treatment plants or desalination plants, or cooling flows, in the case of seawater-cooled power plants, data centers, etc. Finally, the most electro-intensive step of our process can run in batches within a continuous process, enabling us to best use low-carbon or **intermittent** renewable **electricity**, off-peak hours.

Differentiation

Pathway differentiation.

To the best of our knowledge, PRONOE is the first CDR company pursuing **Dissolved Carbonate-based (CO_3^{2-})** Ocean **Alkalinity** Enhancement from Coastal Outfalls.

Technological differentiation results from process-level design and optimization and mastery of neutralization kinetics – it includes:

- **Fully integrated, ex-situ acid neutralization step, uniquely accommodating cheap, abundant, mildly alkaline minerals** that are not *readily* applicable to any other CDR approach**.** See Application Supplement: Alkaline Feedstock, 3. & 4.
- **Unique electro-membrane design, material and operation.** With over 30% reduction of membrane area and water consumption, as well as reduced pre-treatment intensity.

These differentiators impact key performance metrics, including:

- Significantly reduced CapEx and Electricity consumption for electro-membrane technologies
- Zero-acid-waste generation, and no heavy metal release
- Drastically reduced process water volumes, allowing for compact equipment, pumps, tanks,..

- High CDR net-negativity ratios (75%-95%)
- Significantly higher alkalinity addition at iso-pH variation (carbonates vs. hydroxyls), allowing meaningful CDR activities with applicable regulations (eg. pH <9)

Priority Innovation Areas

Our project addresses *ALL* Priority Innovation Areas for the 2024 prepurchase:

✓ *Projects that leverage existing industrial assets or processes to scale carbon removal quickly and at lower costs.*

✓ *Projects in APAC, the Middle East, Africa and Latin America.*

The proposed project (PRONOE demonstrator) will be placed at an existing desalination plant on the Canary Islands, a group of islands off the coast of West Africa. Such project is replicable in any coastal geography with industrial sites and ocean outfalls including Small Island States - and requires no other infrastructures than existing ones, with no need for dedicated downstream waste/CO2 logistics.

✓ *Projects that create redundancy across known, promising approaches.*

OAE is a high-potential CDR pathway, and one that takes many forms. PRONOE meaningfully contributes to a global portfolio of CDR and Ocean CDR solutions by exploring a differentiated pathway and new geographies.

✓ *Projects that can offer lower prices through additional revenue sources*

Our coastal industry partners benefit from products and services, reinforcing their interest in collaboration and lowering CDR prices.

✓ *Projects that provide local environmental and economic co-benefits that build community and policy support.*

Dissolved carbonate alkalinity has been used for pH remediation for decades in shellfish farming and aquaculture and falls within applicable regulations.

✓ *Electrochemical OAE: Approaches that avoid the production of problematic byproducts (e.g., hydrochloric acid) altogether or offer creative solutions to managing them at scale.*

Zero-waste-generation has been a self-imposed requirement since day one; we pursue the most feedstock-scalable, fully integrated, ex-situ acid neutralization strategy.

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

What PRONOE is building

PRONOE develops compact automated industrial systems that turn the return flows of coastal industries into a safe alkaline flow, which is monitored and dispersed in coastal areas. This safe alkaline flow locally mitigates the acidification of surface waters, offering potential environmental co-benefits. As described in Equation 2 and Equation 3 (section 1.a), the increased alkalinity restores the seawater chemistry by converting dissolved CO_2 into bicarbonates (HCO_3^-). The lower CO_2 levels in seawater trigger CO_2 capture from the air. Carbon is stored as bicarbonates for 100,000 to 1,000,000 years [5].

More fundamentally, we are building an asset-light, sustainable, scalable and fully decentralized approach to single-step CO_2 removal (capture+storage; CDR), that can adapt to any coastal geography and bring low-cost, high-quality CDR, while benefiting local communities and ecosystems worldwide.

<u>This project: Location & scale</u>

For this project, we will deploy an industrial demonstrator that removes more than 100t/year of CO_2 (net). This RFP will finance the field-testing and demonstration of PRONOE's process, including variable OpEx and Monitoring, Reporting and Verification (MRV) expenses.

Site selection is paramount for a successful first deployment; we selected an exceptional location for trailblazing Ocean Alkalinity Enhancement (OAE) from Coastal Outfall. Our project takes place in a world-leading hub for ocean sciences and desalination industry innovation, with strong political will and community acceptance. The pre-permitted alkalinity addition will occur at a contracted desalination plant in the Canary Islands (Spain, Europe), offshore West Africa. This location is disproportionally affected by water scarcity; with more than 50% of their water supply coming from seawater desalination, the Canary Islands have the highest density globally of desalination plants. Moreover, ocean acidification is particularly acute in this area.

Our alkalinity addition is done according to applicable legislation, achieving conservative levels of alkalinity in the dispersed flow [16]. Our systems will be located in a barren area within the industrial complex (**Error! Reference source not found.** and **Error! Reference source not found.**). That desalination site is a (net) renewable energy producer (wind and solar farms; **Error! Reference source not found.** and **Error! Reference source not found.**), contributing to a net-negativity (LCA) higher than 75% already at the demonstrator scale. We can pioneer fighting ocean acidification in Africa, while leveraging EU grant support and an advanced, established ocean observation network (Copernicus/Mercator). This project will help us build relevant knowledge to deploy in APAC, the Middle East, Africa and South America.

The process diagram is presented in section 2.a (**Error! Reference source not found.**).

<u>Beyond this project: Location & scale</u>

At scale, PRONOE's industrial systems have a gross CDR capacity of 10 or 50 ktCO_2/year, seamlessly integrated downstream of coastal industrial sites and utilities, installed in their artificialized grounds. These coastal sites include **desalination plants, wastewater treatment plants, and power plants**. Our view of pragmatic OAE from coastal outfalls relies on multiple, mid-sized industrial systems in various locations, as opposed to monumental green-field and dedicated CDR plants. This mimics the deployment strategy of desalination plants; desalination has been one of the industries with the fastest-

[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.

declining costs in the last 30 years. Beyond physical integration of our systems on site, PRONOE integrates with **existing value chains, supply chains and distribution networks**, enabling new circular economy business models.

The desalination industry disperses more than 25 Gm3/year of brines globally, enabling more than 150 MtCDR potential. The return flows to the sea of wastewater treatment plants (WWTP) and (nuclear) power plants are 8x and (2x) 40x larger, respectively. In Europe only, the number of addressable locations exceeds 20,000, considering coastal desalination plants and coastal European WWTPs alone.

Desalination is projected to grow at a rate of 7.5 to 9.5% per year. Driven by urbanization and electrification, return flows to the sea from coastal wastewater treatment plants and nuclear power plants are expected to be multiplied by 3x and 2x, respectively, by 2050.

By the mid-century, each of these utility verticals will have Gt removal potential.

Cost & capacity criteria

We align with Frontier's removal capacity target (0.5 Gt), aiming at removing 0.7+ Gt/year. This will require a supply chain effort for scaling up the manufacturing and assembly capacity of currently available industrial equipment required equipment that faces no physical feedstock limitations.

The cost breakdown at different scales is described in the techno-economic analysis (Excel) file. The cost and prices per ton proposed for this project of around 1500 $/tCDR are similar to other Ocean CDR projects and explained by the absence of scale effects and process and energy inefficiencies at a small scale.

Based on suppliers' quotations, laboratory tests, and today's feedstock prices, combined with industry-standard scaling and learning effects, we are confident we can reach a cost below 150 $/tCDR at Mt scale.
Meeting Frontier's removal price target (<$100) necessitates a further cost decline of electricity from assumed $60/MWh to $40/MWh (-33%), as well as a 30% decrease in the cost of mineral feedstock and transportation.

Quantifying CDR

Our MRV approach consists of several key components with varying measurement and modeling requirements depending on temporal and spatial scales (**Error! Reference source not found.**).

This approach is **consistent with best-in-class methodologies as set out by recently released independent standards**. First, return flows are monitored in land, upstream and downstream of our system to precisely monitor dissolved alkalinity addition. Second, the mixing and extent of the plume mixing zone downstream of the outflow are both modeled and measured. This serves to determine the alkalinity forcing function with a regional model or with sensitivity analysis in the air-sea gas exchange model. Third, the alkalinity forcing is used in a regional or global air-sea gas exchange model to quantify gross CDR, with historical data serving as a baseline. Lastly, various biogeochemical feedbacks that could lead to alkalinity losses are quantified, including biotic calcification response and secondary precipitation.

Our vision for developing MRV relies on two pillars:

(i) Collaborations with MRV actors in the private sector; being their first OAE project outside North America and connecting them to the European CDR ecosystem.

(ii) Research with local public centers. The selected site offers exceptional MRV characteristics given the previous environmental research in that very same coastline. PRONOE has been in contact with local actors working on the region, who have already gathered historical data to serve as a baseline [15], and mathematical models of the near-field that have been validated. The environmental response was also studied in the region, which helped fast-tracking permitting and will help minimize ecological risks. Experimental results proved the decrease in pCO_2 due to our alkalinity addition, which will be measured with fixed sensors at the dispersion points.

PRONOE's MRV approach is detailed in section 5.

Quantifying and qualifying environmental and social impacts

Ocean acidification impacts on natural ecosystems and human activities have been extensively discussed, namely the fact that critically endangered coral reefs provide food for half a billion people globally. Third-party, ex-situ ecotoxicity and ecological tests, as well as scientifically overviewed, responsible field deployments, are key to not only social license but also active community support. To that end, we published several expert committee-reviewed articles on the environmental impact of desalination-coupled OAE, and we will deploy best-in-class Whole Effluent Toxicity measurements based on the paradigm-shift direct, live monitoring of sentinel species' physiological status.

We are founding members of a global NGO (Water Positive) empowering local communities to become active stewards of sustainable water management and restoration. Working on this initiative, we understood the impacts and challenges of the communities disproportionally impacted by water scarcity. We identified synergies with local stakeholders to bring health benefits to coastal communities suffering desertification and water scarcity in many geographies in Africa, Europe, the Middle East, and South America. Additionally, our first deployment takes place in a highly touristic area, which will help us raise awareness about the role and importance of OAE as part of climate action.

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

Technical risks

There are risks associated with scaling any technology from the laboratory bench to full-scale operations. We avoid these risks by starting from proven, industrial, and modular technological components that have been downscaled, re-specified, assembled, integrated and optimized at a laboratory scale. PRONOE leverages unit operations that are well-known in many other industries and working with experienced providers of such technologies that already performed for the same (or similar) operations in a completely different industry. Moreover, we collaborated with these expert providers to define our test plan and methodologies to ensure rigorous and relevant data collection and ultimately allow for informed design decisions. In other words, we scale the process, not the individual technologies or unit operations, and the main technical risk lies with the integration of the unit operations.

Another technical risk lies with the performance of the neutralization and capture reactors. For example, low-mixing points in larger reactors lead to heterogeneities and lower conversions of the product of interest.

Project execution – Supply chain risks

As per the above, the PRONOE process combines existing technological components from various providers, with PRONOE acting as an OEM. This approach drastically mitigates technical risks, with standard systems engineering risks and interface management risks remaining, yet increases supply chain risks. Scaling our technology involves process design and optimization, unit operation specification, and project management to assemble, integrate, and test the system before delivery and on-site commissioning.

Based on our previous experience, we actively engage with industrial equipment and feedstock providers to iterate quickly on specifications and functional requirements and select them after a structured process, including site visits.

Project execution – Operating partner engagement risk

Our first approach for deployment involves co-locating our systems with existing coastal industries. Understanding the needs of the coastal industries is key to co-locating our activities and engaging them effectively and efficiently.

We successfully engaged with over 15 water treatment and energy corporations and documented their interest in our technology.

Successful interactions resulted in PRONOE issuing several studies and contracting a deployment site – putting PRONOE on track to being the first Ocean CDR project integrated into an existing desalination plant. Our strategy includes a strong industry presence (e.g., IDA, WEX Global conferences and membership), and having secured top-tier global advisors in the industry.

Monitoring, Reporting and Verification (MRV) risks

On one hand, our process locally increases the alkalinity of seawater enough to increase its CO2 capture capacity. On the other hand, this alkalinity variation is not enough to be measurable with most remote-operated equipment (e.g., pH meters) and is hard to measure remotely in the environment (e.g., total alkalinity). Thus, the general consensus in the scientific community is that MRV shall consist of direct measuring and mathematical modeling.

At PRONOE, we believe it is important to build robust MRV methods within the community of ocean scientists. In this way, we identified the credible partners to build our third-party-reviewed MRV approach with, including sensors and modeling.

PRONOE's MRV approach is detailed in section 5.

Environmental risks

Preventing ecosystem risks is paramount and at the core of PRONOE's vision. Environmental risks left unresolved will likely (and rightfully) trigger social license risks. Furthermore, our MRV ensures safe operations based on management systems to adapt our production based on environmental deviations (e.g., pH).

We will leverage established ocean outfalls that have thoroughly validated their plume's mixing rates, thereby minimizing the affected area. Ecotoxicity tests have been carried out by third parties with our alkalinity flow; we have several research programs ongoing, including biocalcification with IFREMER and the University of Alaska (NOPP). In the context of this project, PRONOE will set up a best-in-class paradigm-shift environmental monitoring plan.

We are constantly updating with the information published by referents like OceanNets and Ocean Visions on the environmental impact of OAE. In the context of this first project, we reached out to local oceanographers that have been studying for decades the carbon chemistry and biology of the region where we will deploy.

Moreover, we will strictly comply with the existing environmental regulations to ensure the safety of pH levels at the dispersion points – while actively working on reducing knowledge gaps. Local governmental actors and decision-makers on environmental issues reviewed the documentation compiled in collaboration with a government-endorsed third party and *approved the project*.

PRONOE's environmental risks are detailed in section Application Supplement: Ocean and Inland Water, points 4 and 5.

Market risks

The dynamics of the voluntary carbon credits market are uncertain, in total volumes, prices and quality expectations from purchasers. This is a risk, accounting for the relatively high price of our CDR certificates at the initial stages.

Navigating these markets over the next years and generating revenues through advanced market commitments will be key to scaling up our solution. Getting purchases from highly regarded and well-recognized buyers clubs such as Frontier will help us to establish trust with early buyers in the future. Through active participation in various leading CDR trade organizations, PRONOE is contributing to policymakers' awareness at European and international levels for the integration of Ocean CDR solutions in regulated markets.

Scalability risks

Capacity-wise, OAE is one of the CDR methods with the highest potential, and PRONOE's process is **highly scalable by design,** and **uniquely** not limited by feedstock availability and accessibility, CO2 transportation and storage infrastructures, the market size for co-products, nor waste disposal.

The non-reliance on partners for (geological) storage means PRONOE is both vertically integrated (capture + storage) and geography agnostic. Partnerships with coastal industries accelerate the deployment, leveraging existing infrastructure and environmental permits.

Our energy consumption represents a small fraction of that of the coastal industry where we co-locate. Considering the ongoing decarbonization programs of coastal industries via renewable sources, PRONOE operates within the over-capacity design margins of wind or solar farms.

Flexible use of various mineral feedstocks that are extremely cheap, abundant and do not need to be ground are key considerations of our process design.

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)*	321 tCDR_net
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Alkalinity addition: from March 2025 to March 2028 CDR: from March 2025 to April 2029
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	1546 $/tCDR_net

Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	1546 $/tCDR_net

[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).