



# Paebbl

## Carbon Dioxide Removal Purchase Application Fall 2022

### General Application - Prepurchase

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

Company or organization name

Paebbl AB

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

HQ: Stockholm (Swedish LLC), with team members in the Netherlands + Finland

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

Andreas Saari and Marta Sjögren

Brief company or organization description

Paebbl permanently converts captured CO<sub>2</sub> into useful materials via mineralisation.

#### 1. Project Overview<sup>1</sup>

- Describe how the proposed technology removes CO<sub>2</sub> from the atmosphere, including as many details as possible. Discuss location(s) and scale. Please include figures and system schematics. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar technology.

##### **SOLUTION OVERVIEW**

Paebbl takes captured CO<sub>2</sub> and mineralizes it efficiently in a continuous industrial process, using ground silicate minerals on-site, producing a CO<sub>2</sub>-negative mineral product and removing the need for a geologic injection well or pipeline to achieve permanent sequestration of CO<sub>2</sub>.

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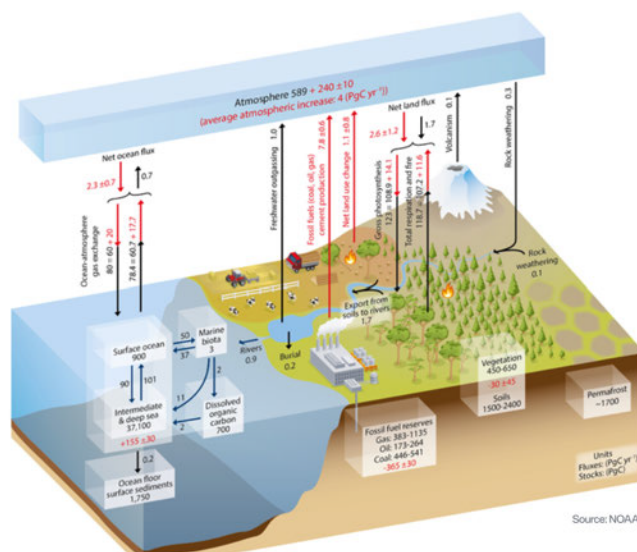
<sup>1</sup> We use "project" throughout this template, but note that term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

A secondary CO<sub>2</sub> benefit afforded by the solution is the substitution of currently CO<sub>2</sub>-intensive mineral fillers used widely in large-scale applications like polymers, paper and concrete, allowing for a second significant revenue stream and CO<sub>2</sub> positive effect for an at-scale operation. Our vision is to build a portfolio of CO<sub>2</sub>-storing applications for the carbonates. Over time, as the market for CCU matures and the market for novel CO<sub>2</sub>-negative materials opens up, we will prioritize the most planet-positive use cases.

Although our solution is designed to be CO<sub>2</sub> source-agnostic, we aim to partner with DAC in the first phase of our development (pilot plant). This means that if we are successful with integrating with a DAC provider, we will connect the value chain from DAC to CO<sub>2</sub>-storing end products.

## SOLUTION CHARACTERISTICS

The science of CO<sub>2</sub> mineralisation is well known; it is based on a natural process, rock weathering, which is a thermodynamically driven geological process of CO<sub>2</sub> turning into a carbonate mineral, and it is part of the Earth's carbon cycle. Every year, this process naturally removes around 1,1 GtCO<sub>2</sub> from the atmosphere.



Technologically accelerating this process could supercharge CO<sub>2</sub> removal and sequestration. Other projects (e.g. Project Vesta, UnDo) are already practicing enhanced weathering: revealing more rock surface area by grinding minerals and spreading them on land or sea accelerates the natural CO<sub>2</sub> drawdown process. Taking these ground minerals into an industrial setting with elevated temperature and pressure makes this process that usually takes hundreds or thousands of years proceed in minutes, providing an industrially viable process for CO<sub>2</sub> sequestration.

Compared to other ways to deal with captured CO<sub>2</sub> that lead to permanent sequestration (primarily geological injection), our on-the-ground mineralisation process reaches the same extremely long permanence for the same or lower price, but makes the output of that process useful, changing the economics of the process of permanently storing CO<sub>2</sub>.

[Bardow et al \(2020\)](#) describe several versions of the same kind of CO<sub>2</sub> mineralisation technology as ours and highlight its potential for further CO<sub>2</sub> savings by acting as a substitute material for cement

and other fillers in concrete. Below an optimal future scenario:

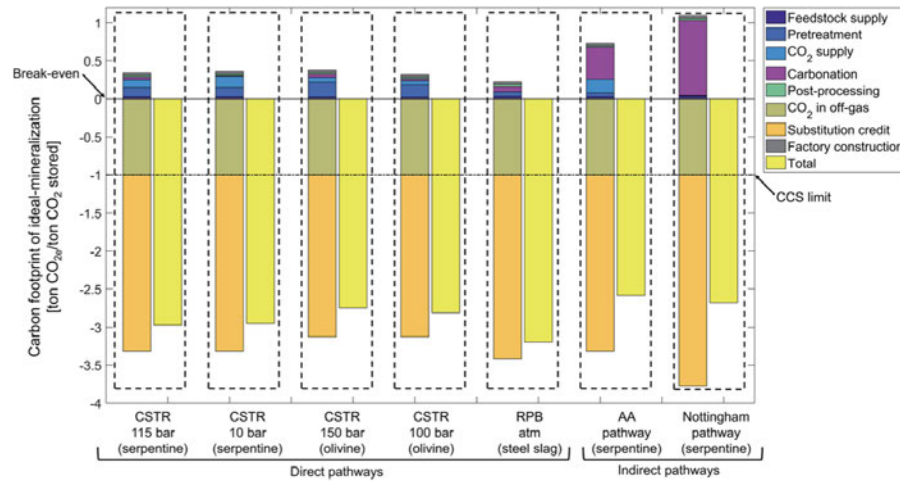


Fig. 10 Carbon footprint of the 7 CCU by mineralization pathways for the ideal-mineralization scenario. For each pathway, the left bar shows the contribution of each life cycle stage, and the right bar shows the total carbon footprint. Break-even is where the avoided CO<sub>2e</sub> emissions are equal to CO<sub>2e</sub> emissions caused throughout the life-cycle such that the total carbon footprint is zero. CCS limit is the maximum potential of CCS technologies. RPB – rotary packed bed, AA – Abo Academy.

Source: Bardow et al (2020)

## TECHNICAL OVERVIEW

Paebbl's proprietary technology is a single-step, aqueous, high-pressure continuous process. The inputs are CO<sub>2</sub> (currently >80% purity), ground silicate minerals like olivine, water and a mix of affordable, non-toxic additives.

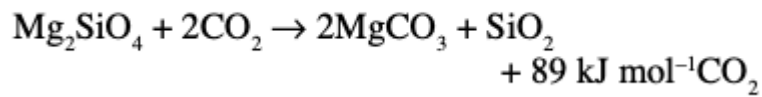
The inputs are fed into a high-pressure system (>50bar) with an elevated temperature (<200°C) where first the ground (≤100µm) input silicate minerals are mixed with water and a proprietary recipe of additives. The resulting slurry is pressurized to the operating pressure, after which the pressurized CO<sub>2</sub> is added. The CO<sub>2</sub> dissolves in the water, forming carbonic acid. In the slightly acidic conditions, the silicate minerals start dissolving, releasing metal cations into solution, which in turn combine with the carbonic acid, forming a solid carbonate mineral. The silicate matrix that is depleted of metal cations forms amorphous silica. The slurry is subsequently de-pressurized and cooled down, with further carbonate crystal precipitation. The output is an aqueous solution of carbonate minerals (e.g. MgCO<sub>3</sub>) and amorphous silica (SiO<sub>2</sub>) with residues of unreacted input silicates and small quantities of secondary compounds, like iron carbonate. The output slurry is then de-watered and dried, and an overwhelming majority of the water and additives will be recycled. An additional separation step allows for the possibility to recirculate unreacted input silicates.

The reaction kinetics are accelerated by the addition of the proprietary mixture of additives.

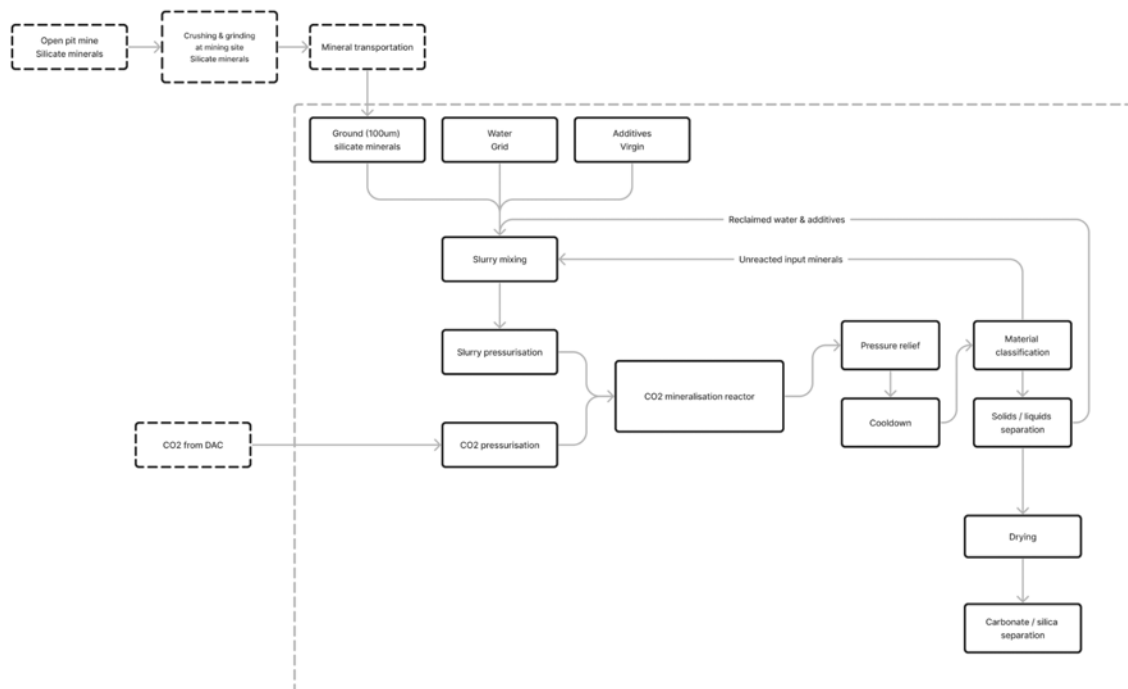
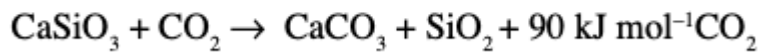
As the reaction is exothermic, the need for heating energy can be significantly reduced or entirely removed by controlling the solids loading of the process, leaving input material pressurization as the main driver of energy input. To the best of our knowledge, our patent-pending reactor uses significantly less energy than current reactor designs.

The simplified chemical reaction the process is based on is illustrated with two silicates, olivine (reactive, abundant) and wollastonite (more rare but very reactive).

### Olivine:



### Wollastonite:



Process flow diagram of Paebbl's process

## BACKGROUND AND CURRENT SCALE AND STATE OF TECHNOLOGY

Paebbl is based on 1.5 decades of research at KU Leuven and RWTH Aachen, done by and in collaboration with Pol Knops, our CTO and co-founder. His most recent applied research project was CO2MIN, funded by the German Ministry (part of EU GECCO) with the partners Heidelberg Cement,

RWTH Aachen, IASS Potsdam and Green Minerals (Knops' wholly owned former company).

During this and earlier projects, different versions of the pressurized and mixed on-the-ground mineralisation process were tested as batch-operated processes. The process has been run and repeated in vessels of varying sizes (lab-scale to 1,000L, see Kremer 2022). Limited empirical study has been put into a continuously operating mineralisation reactor (see Penner 2004 and O'connor 2005), though it is often mentioned as the obviously necessary step for a scaled-up mineralisation process.

Paebbl was founded to scale up and commercialize this research, and is currently in basic engineering for a continuously operating mineralisation reactor and pilot plant.

In parallel, we have started developing applications of the carbonates we produce as output materials. The paper, polymer, and concrete we've made with our material show good early test results (image below). Third party report on our early test results on replacing part of the concrete mix is available under NDA.



## DIFFERENTIATION

We define competition and comparable processes from the least specific to the most specific competition, being most comparable to other methods of permanently storing CO<sub>2</sub>, and of converting it to other useful forms.

### 1. Paebbl vs CCS

Like CCS, industrial mineralization is a permanent store of CO<sub>2</sub>. In contrast to CCS, industrial mineralization uses CO<sub>2</sub> as a raw material, resulting in solid carbonate powders. These

CO<sub>2</sub>-storing mineral fillers replace commonly used fillers which would have emitted CO<sub>2</sub> in their production. Our carbonates are a drop in replacement for ground limestone in the paper industry. They can also partly replace ordinary portland cement (OPC) and aggregate in the concrete industry.

Paebbl offers large industries the opportunity to decarbonize while still producing much the same products in the same factories. They can replace some or all of their normal filler feedstock with our CO<sub>2</sub>-storing solid carbonates, resulting in large CO<sub>2</sub> savings. In some applications, CO<sub>2</sub> avoidance and sequestration sum to more than 100% of the original CO<sub>2</sub> emissions.

According to our simulations, industrial mineralisation can be economically viable at operation sizes of 50-100Kton/year, while CCS often requires volumes of more than 1Mton CO<sub>2</sub>/year due to the high capital costs of pipeline & injection costs. This makes building many more, modular decarbonisation sites with permanent sequestration possible.

- Paebbl vs Other CCU

In contrast to most CCU pathways, the products we make out of CO<sub>2</sub> permanently sequester CO<sub>2</sub> with longer term co-benefits than e.g. fuels (which are re-emitted into the atmosphere rather quickly). CCU processes that make fuels or chemicals are great circular industries, but result in a re-emission of the captured carbon.

At the same time, upcycling CO<sub>2</sub> into polymers, another form that keeps the carbon fixed in a solid form, is a process that takes significantly higher energy input than mineralisation, which transforms the carbon molecule to a lower energy state.

- Paebbl vs other industrial mineralisation companies

To our knowledge, only a limited pool of companies are working on industrial mineralisation. These include Mineral Carbonation International (MCI) from Australia, and SCW Systems from The Netherlands, and companies specifically targeting a cementitious material as the output, like Brimstone (USA).

Similar to MCI, SCW and Brimstone, we use silicate minerals to sequester CO<sub>2</sub>.

Unlike MCI, SCW and Brimstone, we use a single-step, three phase, continuous process. We believe that our process is more energy efficient while using less harmful input materials. Our process does not risk dangerous residual materials in the output product, which is a risk when using stronger acids as reaction drivers.

To our knowledge, all four companies have proprietary process conditions, and are building IP around the process.

## CONCLUSION

Co-locating on-the-ground mineralisation with DAC can be a win-win: permanent storage of the captured CO<sub>2</sub> is achieved at extremely low cost, which is made possible by the sales of the CO<sub>2</sub>-storing output materials into the local economy - which further avoid emissions, replacing fossil-based materials. The combination also creates new jobs in the low carbon economy, a benefit to society.

The best locations for our technology are carbon capture sites with good shipping access. The total electrical energy input for our process at scale (TRL-9 NOAK) would be 0,7GJ/tCO<sub>2</sub>, with an additional



0,6GJ/tCO<sub>2</sub> of thermal energy used mostly for post-processing steps. The fuel energy input is heavily dependent on plant location and required logistics, but can be reasonably lower than 1,2GJ/tCO<sub>2</sub>.

- b. What is the current technology readiness level (TRL)? Please include performance and stability data that you’ve already generated (including at what scale) to substantiate the status of your tech.

We assess the current TRL of this mineralisation process to be 4.

Multiple papers have studied CO<sub>2</sub> mineralisation with olivine in a pressurized and stirred tank reactor. The clear majority of studies have focused on a batch operation of a stirred reactor. In recent academic and applied research projects, the scale of the operated batch reactor sizes have varied from lab-scale to a 1,000 liter reactor (see e.g. Kremer 2022). At the same time, a continuous flow loop reactor was studied and operated semi-batch-wise already in the early 2000’s in work supported by the NETL (see e.g. Penner, 2004 and O’Connor 2005). Some academic work has also been put in the study of suitable post-processing technologies for product valorisation through particle classification (e.g. Mitsos et al 2022).

For this project, we are building a fully continuous mineralisation pilot plant. As this plant is currently under basic engineering, we have no performance data from the exact equipment composition we are proposing for this project. However, comparable performance data from batch operation with a similar residence time can be found e.g. in Mazzotti (2005 IPCC Report)§ and from a continuous flow loop design, operated semi-batch-wise, from Penner (2004) and O’Connor (2005).

**Table 7.1** Mineral carbonation storage costs for CO<sub>2</sub>.

Ore (type of pre-treatment)	Conversion after 1 hour (%)	Cost (US\$/t ore)	Energy input* (kWh/tCO <sub>2</sub> stored)	Cost (US\$/tCO <sub>2</sub> stored)
Olivine (standard)	61	19	310	55
Olivine (activated)	81	27	640	59
Lizardite (standard)	9	15	180	430
Lizardite (activated)	40	44	180+2120=2300	210
Antigorite (standard)	62	15	180	250
Antigorite (activated)	92	48	180+830=1010	78
Wollastonite (standard)	43	15	190	91
Wollastonite (activated)	82	19	430	64

<sup>a</sup> The study assumes a coal fired power plant with 35% efficiency, corresponding to one tonne of CO<sub>2</sub> released per 1000 kWh electricity. The equivalent heat value for the same coal input is then 2,850 kWh. The two items in the sum break the total energy input into electrical + thermal; in all other cases it is pure electrical energy.

*Comparison of performance data with varying process and feedstock permutations from Mazzotti (2005 IPCC Report)*

Environmental and LCA performance from comparable processes can be best accessed from Bardow et al (2020 Rock ‘n’ use of CO<sub>2</sub>: carbon footprint of carbon capture and utilization by mineralization) and Bardow et al (2022, A climate-optimal supply chain for CO<sub>2</sub> capture, utilization, and storage by mineralization)

Bardow et al 2020: comparison of various mineralisation methods and their total CO<sub>2</sub> footprint.

The stability of the output minerals has not received rigorous study as the carbon-sequestering compound of the outflow, a carbonate mineral, is considered thermodynamically extremely stable and durable (e.g. Lackner 2003).

- c. What are the key performance parameters that differentiate your technology (e.g. energy intensity, reaction kinetics, cycle time, volume per X, quality of Y output)? What is your current measured value and what value are you assuming in your nth-of-a-kind (NOAK) TEA?

Key performance parameter	Current observed value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
Permanence (differentiates against most other CCUS methods, including biochar)	>>1 000 years	>>1 000 years	Thermodynamically stable mineral carbonate as “sequestration product”
Conversion degree reached after 1 hour of reaction with chosen energy use (=> residence time required per tCO <sub>2</sub> )	50%	90%	Several research and experimental projects to accelerate the project are underway and show promising data.
Energy cost per tCO <sub>2</sub> mineralised (GJ/tCO <sub>2</sub> )	7.1 (calculated for this pilot project without heat integration)	2,4	Heat integration, smart siting of plant to optimize logistics
Effective mineralisation cost (subsidized by output mineral product sales)	N/A (no sales)	\$0	<p>Our levelized cost of tCO<sub>2</sub> removed in our NOAK TRL-9 TEA is currently at \$97 with a number of conservative assumptions balanced by numerous known and unknown unknowns. If this calculation and our assumed reaction efficiency turn out to be true, we could sell the output mineral product of ~3 tons (~2 tons of MgCO<sub>3</sub> and 1 ton of amorphous SiO<sub>2</sub>) at \$34/tonne for breakeven, and \$44/tonne for a 30% GM.</p> <p>Currently, amorphous silica is sold as supplementary cementitious material</p>



			<p>(SCM) at market prices of \$200 - &gt;\$1000 / tonne, and the importance of SCMs is expected to rapidly increase with mounting pressure on finding alternatives for CO<sub>2</sub>-intensive OPC-type cementitious materials.</p> <p>Our output volume may be reduced by a residual amount when feedstock-dependent byproducts like Fe-, Cr- and Ni-compounds have been removed. The metals could potentially provide a tertiary revenue stream.</p>
Direct CO <sub>2</sub> mineralisation cost	\$259 (calculated variable OPEX at pilot scale, fully excluding fixed OPEX and disproportionately large CAPEX; levelized cost of net CO <sub>2</sub> removed is at ~\$20k)	\$97/ton CO <sub>2</sub>	<p>Economies of scale in feedstock purchasing, optimal siting, affordable clean energy, full heat integration, high degree of automation in process.</p> <p>Multiple papers have suggested the realism of this figure for standalone CO<sub>2</sub> mineralisation costs (one early summary in Hitch &amp; Dipple 2012), though the latest papers have been more skeptical (e.g. Mitsos et al 2022).</p> <p>The most relevant comparisons include the value and further CO<sub>2</sub> savings of the output product e.g. as cement replacement in the context of mineralisation cost. (Strunge and van der Spek (2022) and Bardow (2020, 2022). )</p> <p>The most significant swing factors for the cost are electricity price, feedstock transportation distance and method, process solids loading factor &amp; water and additive recirculating factors.</p>
Secondary CO <sub>2</sub> savings from co-beneficial use of end products	N/A (no sales)	0,5 - 1tonCO <sub>2</sub> e / 1tonCO <sub>2</sub> sequestered	<p>Replacing a GHG-intensive product like OPC (CO<sub>2</sub> footprint typically ~700kgCO<sub>2</sub>/tOPC) with a carbon-negative one.</p> <p>In a rough example, 1 ton of CO<sub>2</sub> and 2 tons of olivine form 1 ton of SiO<sub>2</sub> and 2 tons of MgCO<sub>3</sub>. If more than</p>

			just the 1 ton of SiO <sub>2</sub> can be utilized in e.g. concrete, savings of even more than 1ton of CO <sub>2</sub> per ton of sequestered CO <sub>2</sub> can be unlocked (See e.g. Bardow et al 2020)
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- d. Who are the key people at your company who will be working on this? What experience do they have with relevant technology and project development? What skills do you not yet have on the team today that you are most urgently looking to recruit?

We are a diverse and complementary team of entrepreneurs, scientists, engineers, and operators. The key team working on this project will be the Founders of the Company, together with senior members of the team and our external partners.

Leading the technical team will be Pol Knops, our co-founder and CTO and mineralisation expert with over 15 years of applied research experience in the field. Pol Knops has [over 20 research papers published in the field of mineralisation](#), and has demonstrated experience to collaborate and complete projects with a wide range of institutions, both academic and commercial, so as to advance the research of mineralisation further. Pol's complimentary experience also comes from his experience in building and running waste management plants earlier in his career.

Other members of the team will be [Jane Walerud](#), [Andreas Saari](#), and [Marta Sjögren](#), who have complimentary experience in finance, project management, and product development, and who together bring over 50 years of collective operational experience.

To build our pilot plant, we have commissioned [IV Industrie](#), [Well Engineering and Partners](#) (whose founder, [Dr Tom Bakker](#), is a strategic advisor to Paebbl), and [MTSA](#), leading pilot and demo scale engineering firms in Europe. Further, we are working with academic partners to de-risk our technical choices.

We are a small team, and will need to hire for several roles to accomplish this project. Amongst others, we will be adding a VP Engineering, a Chemical Engineering lead, a Mechanical Engineer, and Process Engineers. Recruitment processes for a number of these roles have started at the time of writing. Please note that these are permanent and full-time roles.

- e. Are there other organizations you're partnering with on this project (or need to partner with in order to be successful)? If so, list who they are, what their role in the project is, and their level of commitment (e.g., confirmed project partner, discussing potential collaboration, yet to be approached, etc.).

Partner	Role in the Project	Level of Commitment
DAC partner(s)	Supplying the captured CO <sub>2</sub> which we will then permanently store in carbonate materials	We are currently in confidential discussions with several, so we cannot communicate specific names nor terms of commitment
Early adopter(s) of our materials	As our vision is to turn CO <sub>2</sub> into useful filler materials that replace fossil-based	We have several live discussions with buyers, but no contract in

	alternatives, and will in turn be used in real life products that are widely used today, we will partner with early adopters of our novel carbonate materials.	place at the time of writing. Our goal is to close at least one LOI by 2Q23.
Engineering firms	Build the pilot and demo plants	Confirmed project partners
Third party LCA provider	To validate our own LCA calculations as we develop and scale the technology	Yet to be approached

- f. What is the total timeline of your proposal from start of development to end of CDR delivery? If you’re building a facility that will be decommissioned, when will that happen?

Underway since 02/2022 (feasibility study)

Pilot plant online Q4/2023, producing 06/2024

End of project: 12/2025 (100 tons delivered)

Not decommissioned; continues as R&D line

- g. When will CDR occur (start and end dates)? If CDR does not occur uniformly over that time period, describe the distribution of CDR over time. Please include the academic publications, field trial data, or other materials you use to substantiate this distribution.

Sequestration:

Our conservative estimate is that the CDR will occur between 6/2024 and 06/2026.

The pilot plant will store 40kg CO2/hour from Q4/2023. Our first 500kg/hour plant is planned to be operational from the end of 2024.

Product substitution / CO2 avoidance:

We have several potential customers for our material, and during the pilot phase, we’ll be supplying test material and producing test products in partnership with them.

As the first 500kg/hour plant comes online, we plan to have customers for our material as a substitute for ground limestone.

- h. Please estimate your gross CDR capacity over the coming years (your total capacity, not just for this proposal).

Year	Estimated gross CDR capacity (tonnes)
2023	50

2024	100
2025	1 500
2026	30 000
2027	60 000
2028	500 000
2029	1 500 000
2030	4 000 000

- i. List and describe at least three key milestones for this project (including prior to when CDR starts), that are needed to achieve the amount of CDR over the proposed timeline.

	Milestone description	Target completion date (eg Q4 2024)
1	Get permit to build pilot plant	1Q 2023 - 2Q 2023
2	Build pilot plant where we launch our patent-pending continuous mineralisation technology	Q4 2023 - Q2 2024
3	Complete a 3rd party LCA on our process and a specific application	Q2 2024

- j. What is your IP strategy? Please link to relevant patents, pending or granted, that are available publicly (if applicable).

<p>Our IP will be in key parts of the core mineralisation reactor as well as key pre- and post-processing steps. In addition to this, we are trademarking a family of filler materials that can give a product a “Stored CO2” label, which we assume might enable charging a green premium.</p> <p>We have recently applied for one reactor patent and are writing our second one, and have trademarked Paebbl and “Stored CO2” in many parts of the world.</p> <p>In addition to these, our IP strategy is supported by trade secrets and closely customizing our material to customer needs, making us harder to design out.</p>
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- k. How are you going to finance this project?

<p>We are a privately funded company, with private and institutional equity investment from long-term focused investors. We have raised enough financing for circa 2 years of runway (at the time of writing our projected runway is 2Q24), and have plans to raise further financing as we reach our milestones. Further to this, our plan is to complement the equity we have raised to date with non-dilutive financing. The non-dilutive financing will be used for CAPEX related to the pilot and demo plant build-up, as well</p>
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as research that advances our, as well as public, academic interests.

As a research-heavy and innovation focused company, our approach is to also collaborate with relevant and globally recognised academic institutions in some aspects of our R&D roadmap, where we have applied for grants to finance some of these projects.

- l. Do you have other CDR buyers for this project? If so, please describe the anticipated purchase volume and level of commitment (e.g., contract signed, in active discussions, to be approached, etc.).

Currently we do not have other CDR buyers for this project. However, we have the ambition to sell to other early adopter CDR buyers, and are in active discussions with several potential buyers.

- m. What other revenue streams are you expecting from this project (if applicable)? Include the source of revenue and anticipated amount. Examples could include tax credits and co-products.

Our vision is to turn CO<sub>2</sub> from a waste into a resource, which means that as a business we will have a dual business model between CDR and the sale of end-products that we derive from our process.

This way we will be able to adjust ourselves to be competitive on both CDR and output products. The dual revenue stream is important as we are entering commodity markets with our output materials, where scale is important to compete, and where pricing is very competitive. To reach a market competitive price on the output fillers, it will be helpful to “subsidize” our go-to-market initially through the CDR revenues. Over time, we assume less reliance on CDR as we scale and mature.

- n. Identify risks for this project and how you will mitigate them. Include technical, project execution, ecosystem, financial, and any other risks.

Risk	Mitigation Strategy
TECHNICAL	<p>Chosen critical equipment does not function as expected  → Run bench scale tests on all untested pieces of equipment with best available proxies</p> <p>Erosion becomes prohibitively high in reactor and supporting parts  → Pre-test more wear-resistant geometries and materials on bench scale  → Utilize advanced CFD simulations  → Decrease input particle size (check CO<sub>2</sub> and \$ balance on OPEX before proceeding)</p> <p>Conversion degree in reactor is not sufficient in planned max residence time  → Improve additive recipe  → Grind the feedstock finer (check CO<sub>2</sub> and \$ balance on</p>

	<p>OPEX before proceeding)</p> <p>Difficulties in controlling output particle separation per elemental composition</p> <ul style="list-style-type: none"> <li>→ R&amp;D program on novel separation methods (check CO<sub>2</sub> and \$ balance on OPEX before proceeding)</li> <li>→ develop applications for bound-together or partially reacted particles</li> </ul>
EXECUTION	<p>Hiring takes longer than planned or we have mis-hires and lose time</p> <ul style="list-style-type: none"> <li>→ Run company on OKRs with redundancy in critical projects and staffing; preferably 2-3 points of failure instead of 1</li> <li>→ Utilize university collaborations for outsourced short-notice labor</li> </ul> <p>Delays in the plant build-up (most likely to be supply chain-related)</p> <ul style="list-style-type: none"> <li>→ Front-load ordering critical long-lead time items, even prior to basic engineering being fully finished; to do this, prioritize basic engineering of areas with already known long lead time items (like pumps)</li> <li>→ Have at least one backup supplier for every component</li> <li>→ Map out rental options in case bought equipment is delayed or unavailable</li> </ul>
FINANCIAL	<p>Failure to raise enough financing: although we still have 18 months of runway at the time of writing, the current macro conditions make it difficult to predict how the financing climate will be when we need to raise more capital.</p> <ul style="list-style-type: none"> <li>→ We aim to fundraise in 2023 with a market-adjusted story. Showing commercial traction and progress towards technical milestones will be a key determining factor for a successful fundraise.</li> </ul> <p>Failure to raise project financing for the CAPEX: as a young company, this poses some risk in certain geographies.</p> <ul style="list-style-type: none"> <li>→ We are exploring several options across our key markets, and will if all else fails be able to finance the pilot plant build-up with our existing equity.</li> </ul>
ECOSYSTEM	<p>We get pushback from local communities as we aim to expand mining operations</p> <ul style="list-style-type: none"> <li>→ We need to work actively with local communities to make sure that our interests are aligned, that we protect the environmental surroundings in our production and that of our mining partners.</li> </ul>
COMMERCIAL	<p>Unit economics aren't viable; the business model does not work</p>



	<p>→ We are an early stage company, and as a result need to test our commercial hypotheses in the coming 12-24 months. The viability of our business model will be subject to our ability to negotiate COGS to meet ever increasing competitive pressure for raw materials that we too will need.</p> <p>OPEX is too heavy if we don't automate the process enough  → We aim to automate as much of the process as possible, but the reality is that the pilot plant will have more manual labor than the demo or full scale plants.</p>
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## 2. Durability

- Describe how your approach results in permanent CDR (> 1,000 years). Include citations to scientific/technical literature supporting your argument. What are the upper and lower bounds on your durability estimate?

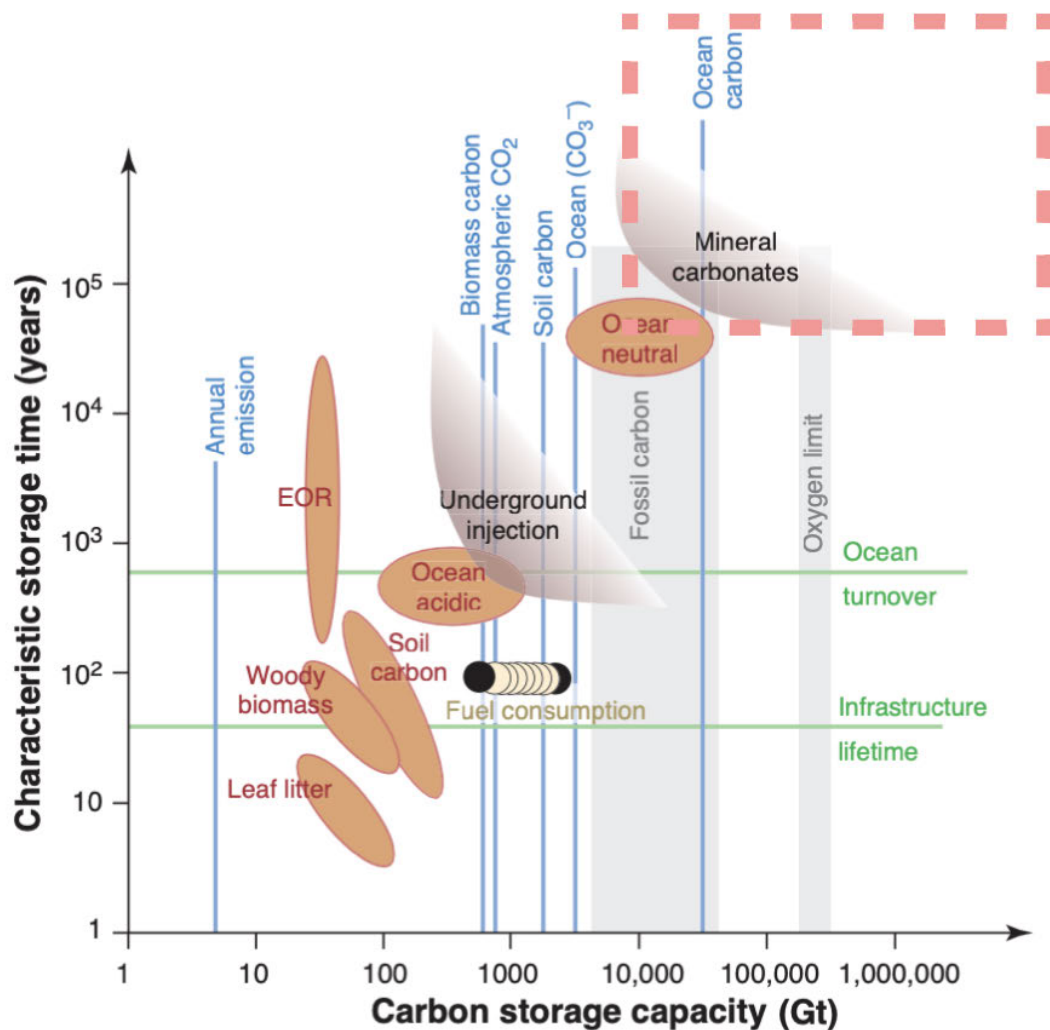
The sequestration product is a mineral carbonate ( $\text{CaCO}_3$  or  $\text{MgCO}_3$ ), which is thermodynamically stable and one of the most long-lasting compounds on Earth.

Even if the carbonate mineral were burnt, the resulting metal oxide would be reactive enough to sequester a significant amount of even atmospheric concentrations of  $\text{CO}_2$  in relatively short time (see the general lack of free  $\text{CaO}$  and  $\text{MgO}$  in nature; they carbonate driven by thermodynamics).

Lackner presented the following in his 2003 work, and let's also remember Wallace Broecker's famous quote.

**Quote from Wallace Broecker, Columbia University**  
(Broecker, *Elements* 3, 295-298, Oct. 2008)

- “I am convinced that, in the long term, we must turn to solutions that involve chemical neutralization (immobilization) of CO<sub>2</sub>, as opposed to simply storing it in gaseous form. Hence, I consider petroleum reservoirs and saline aquifers as interim storage solutions. Ultimately, we must learn to economically bind CO<sub>2</sub> with the magnesium and calcium contained in silicate rocks, whether it be under *in situ* or *ex situ* conditions.”



**Estimated storage capacities and times for various sequestration methods.** The "fossil carbon" range includes at its upper end methane hydrates from the ocean floor. The "oxygen limit" is the amount of fossil carbon that would use up all oxygen available in air for its combustion. Carbon consumption for the 21st century ranges from 600 Gt (current consumption held constant) to 2400 Gt. "Ocean acidic" and "ocean neutral" are the ocean's uptake capacities for carbonic acid and neutralized carbonic acid, respectively. The upper limits of capacity or lifetime for underground injection and mineral carbonates are not well constrained. EOR stands for enhanced oil recovery.

Source: Lackner, 2003

- b. What durability risks does your project face? Are there physical risks (e.g. leakage, decomposition and decay, damage, etc.)? Are there socioeconomic risks (e.g. mismanagement of storage, decision to consume or combust derived products, etc.)? What fundamental uncertainties exist about the underlying technological or biological process?

The risk for CO<sub>2</sub> re-emission from our sequestration product is considered extremely low; a carbonate mineral is extremely stable.

However, let's consider two anticipated use cases and their end-of-life scenarios:

**Paper:** Paper is made from 50-100% wood fiber. The remainder is mostly calcium carbonate, added to cut production costs; calcium carbonate costs about 10-20% as much as wood fiber.

When paper is deposited in landfill at the end of its lifecycle, some of the CO<sub>2</sub> may be released - but this CO<sub>2</sub> and other carbon compounds are primarily released by the decomposing organic matter. The calcium carbonate is considered a stable mineral product that does not decompose; however, the effect of potentially forming organic acids would have to be investigated.

If the paper is burnt instead, then the carbonate - both limestone and our magnesite - will release CO<sub>2</sub> and then quickly recapture it in the presence of CO<sub>2</sub> from the burning wood fiber and humidity.

**Concrete:** irrespective of whether only amorphous silica or also Mg- or Ca carbonates were used in the production of the concrete, the curing process locks in these stable minerals. If the concrete is demolished and re-ground, the silica and carbonate minerals will simply get ground finer, but stay as stable mineral compounds.

3. Gross Removal & Life Cycle Analysis (LCA)

- a. How much GROSS CDR will occur over this project's timeline? All tonnage should be described in **metric tonnes** of CO<sub>2</sub> here and throughout the application. Tell us how you calculated this value (i.e., show your work). If you have uncertainties in the amount of gross CDR, tell us where they come from.

Gross tonnes of CDR over project lifetime	150
Describe how you calculated that value	Our continuously operating pilot plant will have a sequestration capacity of ~40kg /h. We propose the first 3,750h of operation, corresponding to a scenario of an ambitiously much-run pilot plant in a 18-month period (full operating hours would be 8,000/a).

- b. How many tonnes of CO<sub>2</sub> have you captured and stored to date? If relevant to your technology (e.g., DAC), please list captured and stored tons separately.

Paebbl has stored circa 2kg of CO<sub>2</sub> since founding the Company.

We are entering a phase where we store 1kg CO<sub>2</sub>/day with our R&D equipment; when we install the next delivery of R&D equipment in Q123, we will increase our capacity to 100kg CO<sub>2</sub>/ day.

However, our CTO, Pol Knops, has close to 2 decades of mineralization experience including several academic and applied research projects, through which he has stored on the order of a few hundred kilograms of CO<sub>2</sub>.

As the technology is at R&D level, we have been working with bottled CO<sub>2</sub>; our technology has not yet been run with captured CO<sub>2</sub>.

- c. If applicable, list any avoided emissions that result from your project. For carbon mineralization in concrete production, for example, removal would be the CO<sub>2</sub> utilized in concrete production and avoided emissions would be the emissions reductions associated with traditional concrete production. Do not include this number in your gross or net CDR calculations; it's just to help us understand potential co-benefits of your approach.

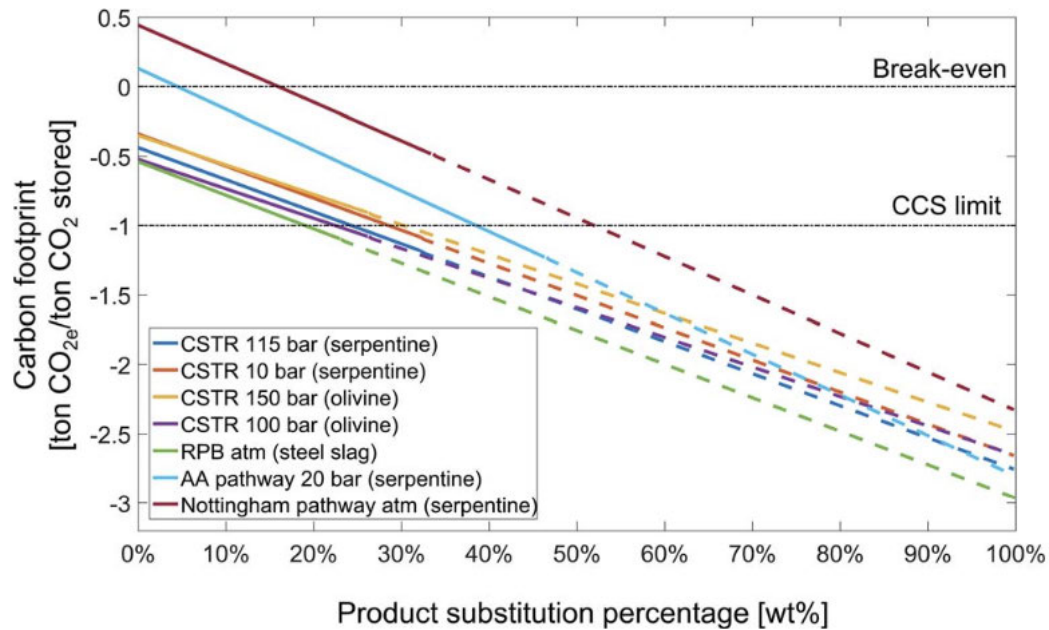
The output of our CO<sub>2</sub> sequestration process is a combination of MgCO<sub>3</sub> and amorphous SiO<sub>2</sub> roughly in a ratio of 2:1.

Amorphous silica is a currently accepted and used supplementary cementitious material as such, already being used to replace OPC, and our product can be a drop-in, carbon-negative alternative. The resulting avoided emissions depend heavily on the allowed substitution level per cement type to still reach performance standards. The allowed substitution of OPC with supplementary cementitious materials like amorphous silica is often in the range of 5 - 50%.

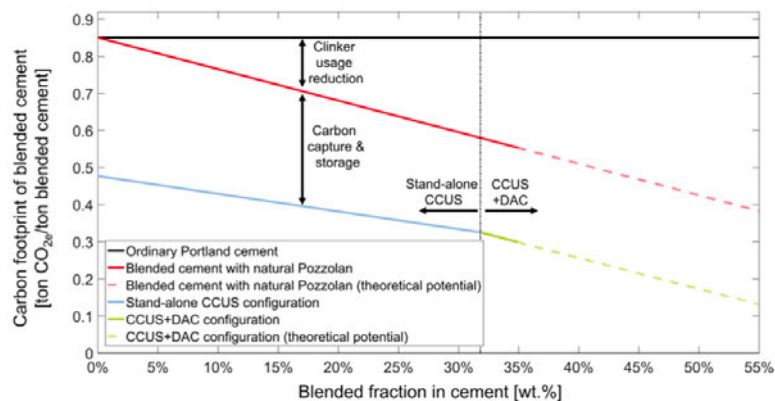
Another option is opened up if we mix the MgCO<sub>3</sub> into the concrete mixture as well. The resulting potential avoided emissions have the potential to take these kinds of concrete mixtures into the range of carbon-negative concrete (with caveats for sensible supply chain design).

This potential is well described by Bardow et al (2020, [Rock 'n' use of CO<sub>2</sub>: carbon footprint of carbon capture and utilization by mineralization](#)). Bardow further illustrates this potential in the 2021 paper "[From Unavoidable CO<sub>2</sub> Source to CO<sub>2</sub> Sink? A Cement Industry Based on CO<sub>2</sub> Mineralization](#)".





**Fig. 13** Carbon footprint of the 7 CCU by mineralization pathways as function of product substitution percentage (the mass of substituted product divided by the maximum possible mass of products ( $\text{SiO}_2 + \text{MgCO}_3/\text{CaCO}_3$ )) for state-of-the-art scenario. Solid lines represent the substitution by  $\text{SiO}_2$  only. Dashed lines show the additional substitution by  $\text{MgCO}_3$  or  $\text{CaCO}_3$ . Break-even is where the avoided  $\text{CO}_{2e}$  emissions are equal to  $\text{CO}_{2e}$  emissions caused throughout the life-cycle such that the total carbon footprint is zero. The CCS limit is the maximum potential of CCS technologies. RPB – rotary packed bed, AA – Abo Academy.



**Figure 4.** Carbon footprint of blended cement from the combined mineralization and cement production as a function of the blended fraction in cement.



*Bardow et al (2021)*

In our own early tests together with an Austrian partner, we reached 10 - 20 % CO<sub>2</sub> savings in various types of concrete – with only ~20% carbonated olivine. We are continuing work to empirically explore the optimal balance of cementitious material substitution, filler substitution and output material properties.

At the same time, [Kremer et al \(2022\)](#) have shown potential in using the output mineral carbonate as a substitute for ground or precipitated calcium carbonate, or even carbon black, in applications like paper and rubber. The potential of these uses is illustrated in the below table.

**Table 10: Results carbon footprint evaluation of carbonated mineral products.** Assumptions and detailed results are shown in Supplementary Table 1-2. \*The conventional product for cement is CEM I 42.5 R with a clinker content of 100 %. \*\*The conventional product for paper filler is CaCO<sub>3</sub>. \*\*\*The conventional product for rubber filler is carbon black. §Note the carbon footprint has been calculated on a gate-to-gate approach. Negative values mean that more CO<sub>2</sub> is stored than the GHG emissions are emitted during the carbonation process. #Global emission reduction potentials are based on current production volumes of the conventional product and the calculated carbon footprint reduction: ##only clinker is assumed to be replaced (cement has an average clinker content of 73.5 %<sup>49</sup>; ###a maximum of 2.5 % of filler is assumed in paper products<sup>50</sup>; ####based on the annual production of tires using 29 % of filler<sup>51</sup>.

Product	Product description	Carbon footprint of conventional product [kgCO <sub>2</sub> e/t]	Carbon footprint of product with carbonated mineral [kgCO <sub>2</sub> e/t]	Carbon footprint reduction	Maximal global CO <sub>2</sub> e emission reduction potential of product with carbonated mineral [MtCO <sub>2</sub> e/a] <sup>#</sup>
Blended cement 5 %	5 % carbonated material as filler, 95 % conventional clinker	850* <sup>49</sup>	794	7 %	9 <sup>##</sup>
Blended cement 20 %	20 % carbonated material as main cement constituent, 80 % conventional clinker	850* <sup>49</sup>	625	27 %	136 <sup>##</sup>
Paper filler	100 % carbonated material as filler	286** <sup>47</sup>	-277 <sup>§</sup>	197 %	6 <sup>####</sup>
Rubber filler	50 % carbon black, 50 % carbonated material as filler	5700*** <sup>52</sup>	2712	52 %	23 <sup>#####</sup>

*Source: Kremer et al 2022*

- d. How many GROSS EMISSIONS will occur over the project lifetime? Divide that value by the gross CDR to get the emissions / removal ratio. Subtract it from the gross CDR to get the net CDR for this project.

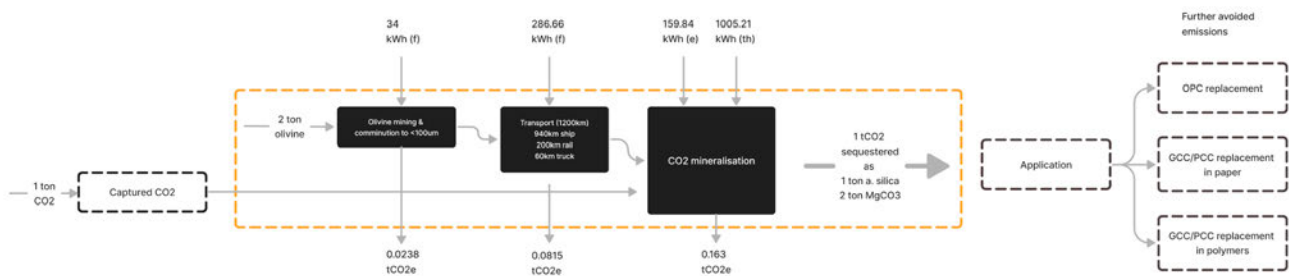
Gross project emissions over the project timeline (should correspond to the boundary conditions described below this table)	40.28 tCO <sub>2</sub>
Emissions / removal ratio (gross project emissions / gross CDR—must be less than one for net-negative CDR systems)	0.2685

Net CDR over the project timeline  
(gross CDR - gross project emissions)

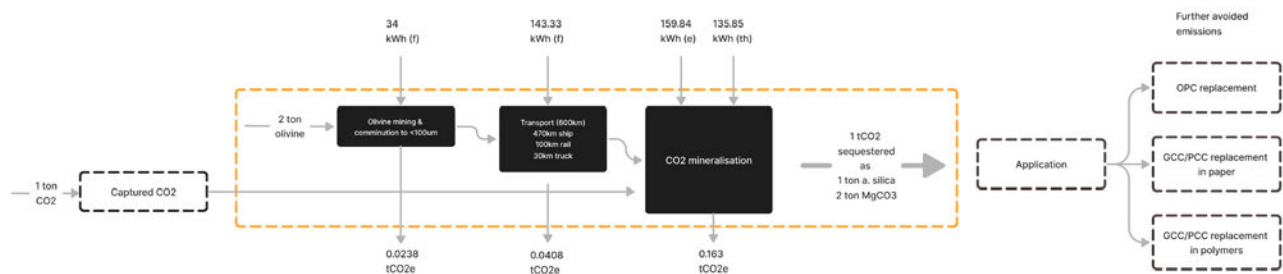
109.7

e. Provide a process flow diagram (PFD) for your CDR solution, visualizing the project emissions numbers above. This diagram provides the basis for your life cycle analysis (LCA). Some notes:

- The LCA scope should be cradle-to-grave
- For each step in the PFD, include all Scope 1-3 greenhouse gas emissions on a CO<sub>2</sub> equivalent basis
- Do not include CDR claimed by another entity (no double counting)
- For assistance, please:
  - Review the diagram below from the [CDR Primer](#), [Charm's application](#) from 2020 for a simple example, or [CarbonCure's](#) for a more complex example
  - See University of Michigan's Global CO<sub>2</sub> Initiative [resource guide](#)
- If you've had a third-party LCA performed, please link to it.



The LCA for the pilot scale. For the full scale, diagram with change in relative energy inputs below. Most of the efficiency gains are driven by optimized siting and process heat integration.



f. Please articulate and justify the boundary conditions you assumed above: why do your calculations and diagram include or exclude different components of your system?

We consider the core CO<sub>2</sub> mineralisation process along with its key factors of production in this LCA. To consider the total impact of our process for the environment, we take into account the inputs and outputs of a mining operation in reality carried out and environmentally book-kept and compensated by a partner organization. Mineral transport is included. In this LCA, we exclude embodied emissions from process equipment, factory construction and wastewater treatment (process water included).

For a TRL 6+ plant we would include currently excluded factors.

We exclude the assessment of capturing CO<sub>2</sub> (done by partner)

- g. Please justify all numbers used to assign emissions to each process step depicted in your diagram above. Are they solely modeled or have you measured them directly? Have they been independently measured? Your answers can include references to peer-reviewed publications, e.g. [Climeworks' LCA paper](#).

Process Step	CO <sub>2</sub> (eq) emissions over the project lifetime (metric tonnes)	Describe how you calculated that number. Include references where appropriate.
Olivine mining, crushing and grinding to d100 100um	3.58t	Calculated from literature values. <i>Moosdorf 2017 and Hangx &amp; Spiers 2009</i>
Olivine transportation	12.23t	Calculated from literature values with a transportation distance of 1200km, of which 940km by ship 200km by rail 60km by truck <i>Referencing Bremen et al 2022 with the transportation distances and CO<sub>2</sub> intensities of the transportation methods.</i>
Olivine transportation		In the pilot scale, we consider the case presented by Bremen et al (2022): 1200km total transportation, of which 940km by ship
CO <sub>2</sub> pressurization (e)	3.31t	Aspen for energy consumption. Assuming grid electricity CO <sub>2</sub> intensity of 220g/kWh, which was the average European mix value in 2021 (EEA)
Slurry pressurization (e)	0.50t	Aspen for energy consumption. Assuming grid electricity CO <sub>2</sub> intensity of 220g/kWh, which was the average European mix value in 2021 (EEA)
Slurry heating (th)	4.23t	30% solids loading and utilizing heat of reaction. Aspen for energy.

		CO2 intensity of heat energy from Direct electrical heating in the 2040 EU energy mix scenario of 60/40 renewable/non-renewable (IEA, Ostovari et al 2022)
Mixing (e)	1.65t	Own estimate for energy consumption. Assuming grid electricity CO2 intensity of 220g/kWh, which was the average European mix value in 2021 (EEA)
Dewatering (e)	1.65t	Own estimate for energy consumption. Assuming grid electricity CO2 intensity of 220g/kWh, which was the average European mix value in 2021 (EEA)
Drying (th)	12.96t	Own estimate for energy consumption. CO2 intensity of heat energy from Direct electrical heating in the 2040 EU energy mix scenario of 60/40 renewable/non-renewable (IEA, Ostovari et al 2022)
Process water	0.19t	Calculated from literature values. <i>Bremen et al 2022</i>

#### 4. Measurement, Reporting, and Verification (MRV)

Section 3 above captures a project's lifecycle emissions, which is one of a number of MRV considerations. In this section, we are looking for additional details on your MRV approach, with a particular focus on the ongoing quantification of carbon removal outcomes and associated uncertainties.

- a. Describe your ongoing approach to quantifying the CDR of your project, including methodology, what data is measured vs modeled, monitoring frequency, and key assumptions. If you plan to use an existing protocol, please link to it. Please see [Charm's bio-oil sequestration protocol](#) for reference, though note we do not expect proposals to have a protocol at this depth at the prepurchase stage.

For the direct measurement of CO2 sequestration in our mineralisation process, we employ a two-step monitoring process:

1. Mass flow controllers for incoming CO2 stream
2. Loss on Ignition tests on the output mineral mixture, which determines the exact CO2 content of the mixture
3. Supplementary laboratory analysis with XRF

While running the process for longer continuous stretches, we will sample the output product with regular time intervals, but especially immediately after reaching reaction conditions and before shutdown, with at least hourly checks during the day.

- b. How will you quantify the durability of the carbon sequestered by your project discussed in 2(b)? If direct measurement is difficult or impossible, how will you rely on models or assumptions, and how will you validate those assumptions? (E.g. monitoring of injection sites, tracking biomass state and location, estimating decay rates, etc.)

Thermodynamics: a carbonate mineral is one of the most stable compounds on Earth. We will be able to measure the inputs and the outputs of the closed continuous process to a very high level of detail, knowing exactly how much CO<sub>2</sub> comes in as an input, and the exact composition of the output materials.

- c. This [tool](#) diagrams components that we anticipate should be measured or modeled to quantify CDR and durability outcomes, along with high-level characterizations of the uncertainty type and magnitude for each element. We are asking the net CDR volume to be discounted in order to account for uncertainty and reflect the actual net CDR as accurately as possible. Please complete the table below. Some notes:
- In the first column, list the quantification components from the [Quantification Tool](#) relevant to your project (e.g., risk of secondary mineral formation for enhanced weathering, uncertainty in the mass of kelp grown, variability in air-sea gas exchange efficiency for ocean alkalinity enhancement, etc.).
  - In the second column, please discuss the magnitude of this uncertainty related to your project and what percentage of the net CDR should be discounted to appropriately reflect these uncertainties. Your estimates should be based on field measurements, modeling, or scientific literature. The magnitude for some of these factors relies on your operational choices (i.e., methodology, deployment site), while others stem from broader field questions, and in some cases, may not be well constrained. We are not looking for precise figures at this stage, but rather to understand how your project is thinking about these questions.
  - See [this post](#) for details on Frontier's MRV approach and a sample uncertainty discount calculation and this [Supplier Measurement & Verification Q&A document](#) for additional guidance.

Quantification component Include each component from the <a href="#">Quantification Tool</a> relevant to your project	Discuss the uncertainty impact related to your project Estimate the impact of this component as a percentage of net CDR. Include assumptions and scientific references if possible.
Storage	<i>Negligible; the amount of CO<sub>2</sub> going into the system and the post-processing analysis of materials gives an extremely high degree of certainty to the quantity of CO<sub>2</sub> being mineralised.</i>
Leakage	<i>Negligible; a carbonate mineral is extremely stable, and our process output has known CO<sub>2</sub> content.</i>
Materials	<i>Low; the process equipment uses steel (with a high embodied carbon content with current manufacturing methods), but the carbon footprint of steel is well known. Transportation emissions from delivering these materials to our site can easily be calculated.</i>
Energy	<i>Low to medium; different sources of energy have a large impact on the total CO<sub>2</sub> footprint of our process, but not the permanence of sequestered CO<sub>2</sub>. Controlling these sources and knowing what kind of energy we are using, always opting for newly built renewable energy where possible, allows us to efficiently mitigate the uncertainty related to e.g. grid electricity carbon intensities.</i>

*Secondary impacts of energy demand*

*Low; with heat integration and smart siting of plants, our process is energy-efficient. In addition, especially when co-deploying with DAC, we may well build new renewable energy resources together with our plants.*

- d. Based on your responses to 4(c), what percentage of the net CDR do you think should be discounted for each of these factors above and in aggregate to appropriately reflect these uncertainties?

0% for storage  
0% for leakage  
8% together for Materials, energy and secondary impacts of energy demand.

- e. Will this project help advance quantification approaches or reduce uncertainty for this CDR pathway? If yes, describe what new tools, models or approaches you are developing, what new data will be generated, etc.?

As we are piloting a first of its kind continuous process, very little process data exists today beyond lab/batch scale. This project will be vital for our scaling up efforts as we will gain crucial data on reaction kinetics, particle precipitation and separation, residence time, and a variety of other important parameters, which we will need to scale from pilot to demo and beyond. The data will be generated by running and optimizing the pilot plant reactor(s), and then collaborating with our academic and commercial partners to implement this data into learnings that benefit both Paebbl's development, and academic studies related to mineralisation. One specific uncertainty reduction from the data generated will be toward vendors of specialist equipment. They currently cannot supply equipment to early stage mineralisation companies under standard market terms (e.g. guarantees) as there is not enough data to be able to assess risk related to wear and tear of their equipment. The data that we generate will help other companies as we will be able to serve as a precedent customer case study.

- f. Describe your intended plan and partners for verifying delivery and registering credits, if known. If a protocol doesn't yet exist for your technology, who will develop it? Will there be a third party auditor to verify delivery against that protocol or the protocol discussed in 4(a)?

Currently no registering or verification partner. Based on our best available information, on-the-ground CO<sub>2</sub> mineralisation is in the process of being accepted as a permanent method of CO<sub>2</sub> sequestration in the ETS scheme; this might result in the formation of a verifying body.

We would be happy to partner up with neutral third parties to develop a robust verification protocol for on-the-ground CO<sub>2</sub> mineralisation.

## 5. Cost

We are open to purchasing high-cost CDR today with the expectation the cost per tonne will rapidly decline over time. The questions below are meant to capture some of the key numbers and assumptions that you are entering into the separate techno-economic analysis (TEA) spreadsheet (see step 4 in Applicant Instructions). There are no



right or wrong answers, but we would prefer high and conservative estimates to low and optimistic. If we select you for purchase, we'll work with you to understand your milestones and their verification in more depth.

- a. What is the levelized price per net metric tonne of CO<sub>2</sub> removed for the project you’re proposing Frontier purchase from? 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), but we will be using the data in that spreadsheet to consider your offer. Please specify whether the price per tonne below includes the uncertainty discount in the net removal volume proposed in response to question 4(d).

We propose a purchase volume of 100 net tonnes at a price of 1,200\$/tonne CO<sub>2</sub>. Our levelized cost of net CO<sub>2</sub> removed is at a very high \$16,439/tCO<sub>2</sub> for this project due to all CAPEX and engineering costs for a first pilot plant being accrued under this project. We are willing to take a negative margin and finance the capex through other channels.

Additionally, given that the fixed operational costs are disproportionately high in this project due to its small scale (>\$3,000/tCO<sub>2</sub>), we are not asking those to be fully covered by this project either. The variable opex is at a reasonable \$188/tCO<sub>2</sub>.

The gross CO<sub>2</sub> sequestration offered by our project is 150tons. When we deduct process emissions of 40.3 tonnes, we are left with 109.7 tonnes of net removal. Our suggested 8% reduction due to verification risk (primarily driven by material and energy emissions) would result in a net adjusted volume of 100 tonnes CO<sub>2</sub>.

- b. Please break out the components of this levelized price per metric tonne.

Component	Levelized price of net CDR for this project (\$/tonne)
CAPEX	Our ask: 200 (12,526 actual cost)
OPEX (excluding measurement)	Our ask: 920 (3,913 actual cost)
Quantification of net removal (field measurements, modeling, etc.) <sup>2</sup>	80
Third party verification and registry fees (if applicable)	-
Total	1,200

- c. Describe the parameters that have the greatest sensitivity to cost (e.g., manufacturing efficiencies, material cost, material lifetime, etc.). For each parameter you identify, tell us what the current value is, and what value you are assuming for your NOAK commercial-scale TEA. If this includes parameters you already identified in 1(c), please repeat them here (if applicable). Broadly, what would need to be true for your approach to achieve a cost of \$100/tonne?

<sup>2</sup> This and the following line item is not included in the TEA spreadsheet because we want to consider MRV and registry costs separately from traditional capex and opex.

Parameter with high impact on cost	Current value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
Feedstock mineral transportation distance	1200 (km)	300 (km)	<p>Siting is strategic for a full-scale plant; inbound and outbound logistics have to be optimized.</p> <p>As CO<sub>2</sub> is available everywhere via DAC, and some source of renewable energy can likely always be deployed in the intersection of good shipping connections, silicate mineral availability and output material consumption, siting becomes a fairly straightforward optimisation problem.</p> <p>In any scenario, transportation distance with trucks needs to be minimized.</p>
Feedstock mineral costs mined & ground	36.70 (USD)	8.40 (USD)	<p>Economies of scale at mining with the possibility of vertical integration.</p> <p>More efficient end of currently posted literature values for mineral grinding and milling efficiency (Renforth 2012).</p>
Heat integration	N/A	80 (%)	<p>Heat exchangers will not be installed at pilot scale. However, the heat of reaction is assumed to be partially taken advantage of, and we assume to be able to run a 30% solid/liquid ratio in the inflow to the process. Cooling does not reclaim any of the heat at pilot scale to be used at the drying step, and in the TRL-9 NOAK plant we assume a conservative 80% heat recovery rate in addition to a 30% solids loading and a 90% conversion degree within our reactor.</p>
Electricity price	103 (USD/MWh)	42 (USD/MWh)	<p>New-build wind energy LCOE is between \$26-50 (Lazard, 2021) where solar PV LCOE is between \$28-41. We know from a private correspondent that even this year in the EU, new 5-7 year power contracts with wind have been negotiated for the price of \$42/MWh.</p>
Water & additive recirculation rate	80 (%)	90 (%)	<p>Optimized de-watering, drying at full scale should give a very high water recirculation rate, The additives are likely reclaimed with the water, but might have to be separated via an</p>

			additional step (e.g. gravimetric separation).
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d. What aspects of your cost analysis are you least confident in?

Capital costs for a TRL-9 plant: huge error bars; our cost estimate is a very rough one done with the help of our engineering firm (IV-Industrie) working on the pilot plant design, only based on key components of the plant.

Solids loading: can we run as high as 30% or even beyond? If not, heating costs will increase significantly.

Scaling up to economies of scale in mineral procuring and processing costs.

e. How do the CDR costs calculated in the TEA spreadsheet compare with your own models? If there are large differences, please describe why that might be (e.g., you're assuming different learning rates, different multipliers to get from Bare Erected Cost to Total Overnight Cost, favorable contract terms, etc.).

No major differences; we have conservatively and roughly estimated total plant costs as 4x equipment costs, and have budgeted accordingly.

f. What is one thing that doesn't exist today that would make it easier for you to commercialize your technology? (e.g., improved sensing technologies, increased access to X, etc.)

Planet-aligned increased access to olivine. Currently only 10Mt are mined globally, setting quite a high price per ton relative to other (more energy intensive) CO2 storage options (which is not entirely a fair comparison given that CCU replaces other, more energy intensive products).

6. Public Engagement

In alignment with Frontier's Safety & Legality criteria, Frontier requires projects to consider and address potential social, political, and ecosystem risks associated with their deployments. Projects with effective public engagement tend to:

- Identify key stakeholders in the area they'll be deploying
- Have mechanisms in place to engage and gather opinions from those stakeholders, take those opinions seriously, and develop active partnerships, iterating the project as necessary

The following questions help us gain an understanding of your public engagement strategy and how your project is working to follow best practices for responsible CDR project development. We recognize that, for early projects, this work may be quite nascent, but we are looking to understand your early approach.

- a. Who have you identified as relevant external stakeholders, where are they located, and what process did you use to identify them? Please include discussion of the communities potentially engaging in or impacted by your project's deployment.

To date, we have identified several external stakeholders that will have social, environmental, and political considerations related to our business and process. The process we used to identify these stakeholders was an end-to-end stakeholder mapping and relative risk assessment review. This was partially done in conjunction with our first institutional fundraise, but also more recently as we have had to navigate permitting and the implications of the European energy crisis on our own plans.

At the time of writing, Europe is facing a significant energy crisis. As a result, relevant to us, increased pressure is put on industry and its energy requirements. Our understanding is that this will affect CO2 credit pricing under ETS, and as a result lead to a potential delay in decarbonisation of key industries. The relevant external stakeholder is the EU Commission and its subsidiary organizations.

Another key hurdle is getting mineralisation to be accepted as an alternative to CCS under the EU taxonomy. The most meaningful stakeholder to engage with here is the EU Commission. We are in a HLEG application process with the EU for the CO2 removal policy development group, with an aim of influencing the policy toward more NETs that will drive the green agenda on the continent, including wider investment into mineralisation.

Another key stakeholder are mining operations and those affected by the scaling of mining operations. This is a highly local activity, one which we will need to engage with as we assess where we scale supply of olivine. So far, we are in dialogue with 3 European olivine mines to assess potential collaboration, and the implications of their scaling capacity and environmental considerations related to this.

Our approach is to work in collaboration with local ecosystems in all aspects of our operations, with the intention to provide planet-positive employment opportunities on all levels.

- b. If applicable, how have you engaged with these stakeholders and communities? Has this work been performed in-house, with external consultants, or with independent advisors? If you do have any reports on public engagement that your team has prepared, please provide. *See Project Vesta's [community engagement and governance approach](#) as an example and Arnestein's [Ladder of Citizen Participation](#) for a framework on community input.*

We are very early in our public engagement. Up until October 2022, we have been in stealth mode, with no official public communication. Our plan is to both have a transparent website (in fact, we think that this is crucial as part of building credibility), as well as to proactively engage on relevant topics through our in-house team, as well as with independent public policy and advocacy advisors. Because CO2Value (in particular mineralisation) is a relatively new type of technology, there is limited information about how it would impact local communities — either positively or negatively. More research will be needed to understand these impacts on a project-by-project basis along with proactive engagement with potentially affected communities.

Our vision as we scale (beyond demo scale) is to co-locate with industry, where helping industries decarbonize would extend the life of their industrial sites. Living industries provide employment opportunities and support their local communities. The industries will also be part of the green transition.

- c. If applicable, what have you learned from these engagements? What modifications have you already made to your project based on this feedback, if any?

From interacting with the EU Commission and our advisors we have learned that we need to develop a multi-level communication strategy, one in which we clearly communicate about each aspect of our process with a data-centric approach. We need to adjust messaging to effectively educate the market about mineralisation, building a narrative not only for Paebbl but also a broader range of mineralisation stakeholders. To date, a lot of academic research has been published, but most of the efforts have not been commercialized; the challenge is to distill the academic research into a clear net-CO2 equation of this CDR pathway.

- d. Going forward, do you have changes to your processes for (a) and (b) planned that you have not yet implemented? How do you envision your public engagement strategy at the megaton or gigaton scale?

Our goal is to develop our technology to meet the needs of gigaton scale, however we are far from this currently. One of the biggest challenges to reaching gigaton scale CO2 sequestration will be the amount of silicate minerals that we will need for the process. To ensure that we are scaling responsibly, we will work with local stakeholders in each geography we are operating in to make sure that we respect the laws and regulations and are at the forefront of “environmentally-friendly” mining.

## 7. Environmental Justice<sup>3</sup>

As a part of Frontier’s Safety & Legality criteria, Frontier seeks projects that proactively integrate environmental and social justice considerations into their deployment strategy and decision-making on an ongoing basis.

- a. What are the potential environmental justice considerations, if any, that you have identified associated with your project? Who are the key stakeholders? Consider supply chain impacts, worker compensation and safety, plant siting, distribution of impacts, restorative justice/activities, job creation in marginalized communities, etc.

The most significant environmental justice consideration is the mining efforts needed to scale our technology to gigaton scale. We are very focused on minimizing our scope 1, 2, and 3 emissions, and will need to work with (and in some cases set) best practices when it comes to mining related activities. We are not working with any toxic materials, so there will be no environmentally dangerous waste materials related to our operations.

As we are solving a global problem, we also plan to work with a globally distributed set of partners (rather than working with a couple of MNCs that dominate the silicate minerals market), providing local green employment opportunities and investment into local ecosystems that are part of our stakeholder groups.

We see our kind of technology as a potentially significant source of wealth creation in areas that have been and will be hard-hit by the effects of climate change.

<sup>3</sup> For helpful content regarding environmental justice and CDR, please see these resources: C180 and XPRIZE’s [Environmental Justice Reading Materials](#), AirMiners [Environmental and Social Justice Resource Repository](#), and the Foundation for Climate Restoration’s [Resource Database](#)

- b. How do you intend to address any identified environmental justice concerns and / or take advantage of opportunities for positive impact?

Our aim is to set a high bar for our suppliers and partners as regards to our ESG standards and expectations. Our investors include [Article 9 SFDR](#) registered funds, so we have very stringent reporting towards these investors. We see this as an advantage, as we are able to set a high enough standard of our operations to scale responsibly, not only toward the environment but also the communities that are affected by our operations.

We see Paebbl's technology as one of the enablers of the green transition, and will work proactively to inform communities of how our technology is impacting society, with clear and transparent net emissions reporting through our external channels. By decarbonizing existing industrial plants onsite, we will extend the lifespan of those industries and support their communities. The transition to a low carbon economy will mean many new employment opportunities for people in particular in industrial ecosystems, and our vision is to be part of the new economy by offering training and education that can help people transition to the new low carbon economy.

Finally, by strategically siting our technology to emerging markets and creating significant local equity ownership in the operation, we see CO<sub>2</sub> - materials as a significant opportunity for environmental justice.

Finally, we see our own emissions (for as long as we have them) as a way to invest in society. We have made a pledge to always remove more CO<sub>2</sub> than we emit. We currently have set the ratio to 1.2x, meaning that we will offset 20% more than our total emissions through quality CDR projects on an annual basis, starting from 2022.

## 8. Legal and Regulatory Compliance

- a. What legal opinions, if any, have you received regarding deployment of your solution?

We have gone through legal due diligence with our institutional investors, through which we have been challenged on a number of topics, including but not limited to: regulatory definitions of the Green Deal and where our operations fit under New Industry regulations in the EU, the CO<sub>2</sub> emissions regulation in the EU, and a number of topics related to IP. We also know that our output materials will need to pass regulatory and compliance tests, all of which we are proactively investing efforts into ahead of time.

- b. What permits or other forms of formal permission do you require, if any, to engage in the research or deployment of your project? What else might be required in the future as you scale? Please clearly differentiate between what you have already obtained, what you are currently in the process of obtaining, and what you know you'll need to obtain in the future but have not yet begun the process to do so.

As our operation is a standard industrial plant (similar conditions as a paper mill) that does not operate any toxic materials, we will only need standard plant permits. However, we will need to abide by the Pressure Equipment Directive as part of the process operates under high pressure (50-100 bars). This is standard practice for all plants that use high pressure equipment.



- c. Is your solution potentially subject to regulation under any international legal regimes? If yes, please specify. Have you engaged with these regimes to date?

We are not aware of any international legal regimes other than the EU regulations, which we have cited above.

- d. In what areas are you uncertain about the legal or regulatory frameworks you'll need to comply with? This could include anything from local governance to international treaties. For some types of projects, we recognize that clear regulatory guidance may not yet exist.

We are unsure how CDR will be regulated, if at all. If CDR ends up being regulated, we will need to comply with the relevant regulations. We are also unsure of how DAC might be governed in the future, which is a concern as we aim to partner with DAC companies in the first phase of our development. For the output materials, certain use cases, like building materials (even fillers) will need to fulfill a set of legal requirements, which are country specific.

- e. Do you intend to receive any tax credits during the proposed delivery window for Frontier's purchase? If so, please explain how you will avoid double counting.

We do not envisage receiving tax credits during the proposed delivery. If this were to change, we will need to set up a mechanism to avoid double counting.

9. Offer to Frontier

This table constitutes your **offer to Frontier**, and will form the basis of contract discussions if you are selected for purchase.

<b>Proposed CDR</b> over the project lifetime (tonnes) <i>(should be net volume after taking into account the uncertainty discount proposed in 4(c))</i>	100
<b>Delivery window</b> <i>(at what point should Frontier consider your contract complete? Should match 1(f))</i>	Pilot plant online Q4/2023, producing 06/2024  End of project: 12/2025 (100 tons delivered)
<b>Levelized Price</b> (\$/metric tonne CO <sub>2</sub> ) <i>(This is the price per tonne of your offer to us for the tonnage described above)</i>	1,200

# Application Supplement: CO<sub>2</sub> Utilization

(Only fill out this supplement if it applies to you)

## CO<sub>2</sub> Feedstock

1. How do you source your CO<sub>2</sub>, and from whom? If your approach includes CO<sub>2</sub> capture and it's described above (e.g., general application and one of the supplements), simply respond N/A here.

We work at this stage with DAC companies supplying air-captured CO<sub>2</sub>. We are in negotiations with multiple companies, but have not locked in one for this project as yet.

In this project, the CO<sub>2</sub> will likely be transported from a DAC pilot facility to ours, causing some additional emissions and costs.

The alternative is to integrate a DAC module directly at our pilot plant site. This is something we are now opening dialogues for.

2. What are alternate uses for this CO<sub>2</sub> stream?

Depending on location, it most often is injected into a geological formation to mineralise. Sometimes it might be compressed and transported to customers like greenhouses, or more significantly, it might be converted through other CO<sub>2</sub> conversion processes to hydrocarbons, that further serve as bases for carbon-neutral chemicals and fuels, or potentially carbon-negative polymers.

To provide an energy equation perspective to geological storage, according to a [recent report by the IEA](#), geological sequestration through injection, CO<sub>2</sub> mineralisation is emerging as an alternative for long-term underground CO<sub>2</sub> storage, with the potential to lower the energy demand for CO<sub>2</sub> compression by [up to 30%](#) compared to traditional injection.

## Utilization Methods

3. How does your solution use and permanently store CO<sub>2</sub>? What is the gross CO<sub>2</sub> utilization rate? (E.g. CO<sub>2</sub> is mineralized in Material at a rate of X tCO<sub>2</sub> (gross) / t storage material).

We turn gaseous or liquid CO<sub>2</sub> into a permanent, stable state carbonate mineral.

However, we argue that co-benefits are just as important as permanence, which we propose as a benefit in our technology: we replace filler materials that would have been produced anyway, usually using fossil-based materials.

Our technology is currently operating at a 1-to-2 ratio by utilizing olivine; i.e. to mineralise 1tCO<sub>2</sub>, we need to use roughly 2 tons of olivine. We assume a conversion degree of 80%, which we have proven at batch scale, and which we assume to be able to increase to 90%. The exact mass ratio of CO<sub>2</sub> to feedstock mineral will be determined by the conversion degree and the exact mineral composition of the feedstock mineral; the MgO- and CaO content needs to be maximized for the best results.

4. What happens to the storage material (e.g. concrete) at the end of its service life, and how does that impact its embodied carbon storage over time? How do you know?

As the carbon-sequestering output product we produce is a carbonate mineral, it is considered extremely stable and long-lasting due to its thermodynamically low energy state.

If the carbonate mineral is put as filler into concrete and the concrete is demolished and ground at the end of its life for re-use as aggregate, the carbonate mineral just stays in the aggregate as mineral, potentially ground to a smaller particle size.

If for some reason the entire recycled concrete is calcined, the CO<sub>2</sub> will likely be released from the carbonate mineral, and some of it will get absorbed back into the output product, which is a reactive metal oxide that naturally combines even with atmospheric CO<sub>2</sub> (thermodynamics).

If the carbonate mineral is used as a filler in e.g. paper or polymers, it will stay as an inert product unless burned at a very high temperature. In that case, the reactive metal oxide compound will again absorb back CO<sub>2</sub> from either the burning gasses or atmospheric concentration.

5. How do you ensure that the carbon benefits you are claiming through a CO<sub>2</sub> utilization process are not double counted? *(E.g. If sourcing CO<sub>2</sub> from a DAC system, or selling your product to a user interested in reducing their carbon footprint, who claims the CDR benefits and how could an independent auditor validate no double counting?)*

We have two very clear lines of business: (1) CO<sub>2</sub> removal, which is where the beneficiary of the carbon credits generated are the buyers of CDR (and where we split the CDR revenue with the DAC company, likely taking a smaller fraction than them), and (2) output materials that are CO<sub>2</sub> neutral and over time CO<sub>2</sub> negative. The products we create from the process will be sold to customers as a CO<sub>2</sub> neutral solution, one that they can use to replace their (higher emissions) alternatives. Those customers will be able in turn to claim CO<sub>2</sub> credits for having replaced their supplies with our CO<sub>2</sub>-storing material. Importantly, these customers will not be able to benefit from CO<sub>2</sub> credits that have previously been sold through CDR.

We aim to be audited by third party auditors on an annual basis; we see this as a crucial aspect of our operating ethos.