ZeroEx GmbH

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

ZeroEx GmbH

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

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

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Brief company or organization description <20 words

ZeroEx develops ERW projects in Western Germany using highest-quality mafic feedstock byproducts and is implementing a novel measurement approach

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

About ERW

[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.

Enhanced Rock Weathering (ERW) is a rapidly developing CDR strategy that accelerates the natural process of silicate rock weathering, a key component of the global carbon cycle (Moon et al., 2014). The slow dissolution kinetics of silicate minerals is a primary factor limiting natural weathering rates. ERW overcomes this limitation by utilizing crushed silicate rocks with high surface area, to promote mineral dissolution reactions leading to CDR (Schuiling and Krijgsman, 2006). This silicate dissolution releases positively charged base cations into the water, while carbon (ultimately derived from atmospheric CO_2) becomes fixed in solution as dissolved bicarbonate anions. These weathering products are progressively transported from the land into rivers, and eventually into the ocean, where most of the sequestered carbon remains stable for millennia (Renforth and Henderson, 2017).

About ZeroEx

ZeroEx is a German ERW company. Following a successful non-commercial pilot project in 2023, during which we gained valuable experiences in both the operational and the scientific aspects of ERW, we are now prepared to scale up the method at our project locations in Western Germany.

Our key focus for the 2024 deployments, targeting up to 150,000 tons of feedstock contingent on sufficient project financing being secured, is to validate our novel and unique measurement approach at scale and to leverage learnings from the pilot phase. Using ion exchange resin-based devices able to generate time-integrated data for relevant cation and anion fluxes in the soil leachate (yielding kg/ha/yr), we can increase the accuracy and reduce the cost of Measurement, Reporting and Verification (MRV). The approach combines the operational simplicity and robustness of yearly soil sampling with the higher relevance of regular aqueous phase measurements. In addition, it can be applied to a wide range of substances, allowing also for monitoring of non-carbonic acid weathering and potential heavy metal leaching.

We have successfully passed the preliminary assessment of our pilot facility by Puro.Earth (https://puro.earth/CORC-co2-removal-certificate/supplier-listing/zeroex-57) and are currently advancing to full certification. In addition, we aim to align our practices with other existing and future standards, especially the Community Quantification Standard under development by Cascade Climate. We have actively contributed to this development as participants in the "deep measurements problem solving sessions" and by providing MRV cost data.

What differentiates ZeroEx

Two key point differentiate ZeroEx from other suppliers in the ERW space:

1. The use of a novel measurement approach with the potential to improve the accuracy of CDR quantification, further our understanding of relevant soil processes, and reduce the cost of MRV.

The cornerstone of ZeroEx's measurement approach are highly reliable and demonstrably accurate devices utilizing ion exchange resins, developed by German soil scientists and validated in several peer-reviewed studies (references listed at the bottom of this section).

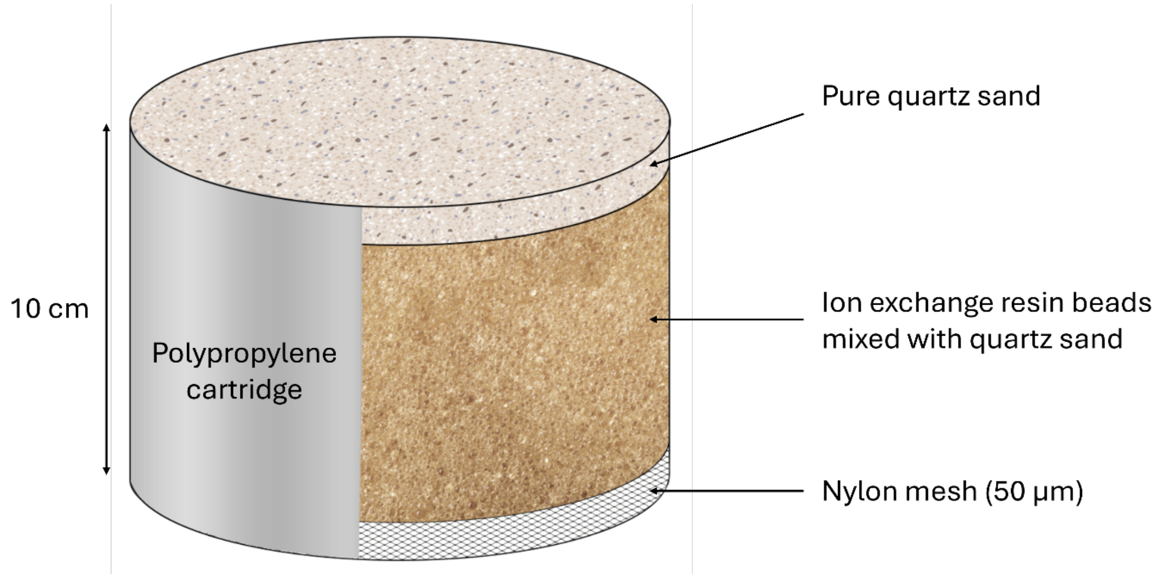

Figure 1: Schematic cross section of a Self-Integrating Accumulator (SIA) (based on Weihermüller et al., 2007 and Lang & Kaupenjohann, 2004).

The Self Integrating Accumulator (SIA) method integrates solute fluxes over time within the soil profile. SIAs consist of cylindrical polypropylene cartridges measuring 10 cm in diameter and height, open at the top and capped with a permeable nylon mesh at the bottom. These cartridges are filled with a mixture of quartz sand or silt and ion-exchange resin beads. This combination facilitates the capture of both cations and anions from the soil leachate. Ions accumulated within the SIA throughout the deployment period remain adsorbed by the resin beads until extraction, allowing a direct calculation of time-integrated fluxes.

The SIAs can be installed at different depths within the soil profile and accumulate ion fluxes for up to 12 months. The ion fluxes of interest for ERW operations can be split into three major categories:

- Base cation fluxes (Ca^{2+}, Mg^{2+}, K^+, Na^+) resulting from silicate weathering, allowing for the calculation of inorganic carbon fluxes (i.e. CDR rates) assuming charge balancing of the cations by bicarbonate anions (HCO_3^-).
- Anions indicative of non-carbonic acid weathering, primarily sulfate (SO_4^{2-}) and nitrate (NO_3^-). The fluxes of these anions can be used to make deductions from the CDR calculated from cation fluxes to account for the contribution of non-carbonic acids to weathering.
- Environmentally relevant trace element fluxes related to the weathering of silicate minerals, e.g. Ni, Cr, and Cu.

The SIA method has been validated for the quantification of all three types of fluxes in past studies. Therefore, while the use of SIAs in MRV for ERW represents a novel field of application, we are confident that accurate measurements can be generated using existing and extensively tested protocols. By pioneering the large-scale deployment of this technology in ERW, ZeroEx is contributing significantly to advancing robust, affordable and reliable methods for CDR quantification in ERW projects.

ZeroEx will install up to 2000 SIAs in 2024, including dedicated research plots for method intercomparison. Here, in addition to the SIAs, conventional porewater sampling will be conducted using suction cups, as well as soil-based mass-balance measurements. The SIAs will accumulate ion fluxes for 12 months, with at least five rounds of measurements planned over the project duration. The findings from both the research plots and the commercial deployments will be published in collaboration with academic partners.

2. The focus on implementing ERW at a local scale in carefully selected regions with vast supplies of very high-quality feedstock.

ZeroEx operates in regions with a high local supply of superior feedstock material as well as suitable soils and climate conditions. Currently, our efforts are concentrated on the Eifel volcanic region, in western Germany, where up to 1 million tons per annum of by-product streams from existing quarrying operations have been identified, in part already secured via long-term offtake agreements. The feedstock material has grain sizes < 2 mm, a stoichiometric CDR potential generally above 0.4 t_{CO2}/t_{rock} and up to 0.56 t_{CO2}/t_{rock}. It contains low concentrations of potentially toxic trace elements, complying with German regulations, and a highly reactive mineralogy dominated by pyroxenes and feldspathoids (e.g. nepheline, leucite).

As outlined above, we aim to establish operations at scale in 2024. Following this, we plan to expand to regions with similar characteristics (e.g. Eger Graben region in Czech Republic, Massif Central in France). This approach is replicable in countless other regions worldwide with comparable geological settings (primarily alkaline volcanic provinces). Within these regions, ERW operations are built up at a hyper-local scale, keeping average transport distances between feedstock sources and fields below 30 km, thus improving efficiency and providing economic co-benefits directly to host communities.

We recognize that, while the local approach to ERW can clearly scale to remove several million tons of CO_2 annually, it only represents a medium-term catalyst on the road to removing over 1 Gt_{CO2}/yr. We view these favorable regions as low-hanging fruits – low-cost, high-efficiency environments, in which the method can be quickly expanded to reach significant economies of scale, particularly regarding MRV. Process optimization and advanced model parametrization based on these early deployments will then allow for further expansion in secondary target regions applying all lessons learned and relying more heavily on simulations for MRV.

Contribution to ERW innovation

ZeroEx's measurement approach using SIAs, as outlined in detail above, presents a novel and convincing solution to many of the major MRV-related challenges that the ERW sector is currently facing. However, the method needs to be validated and optimized at scale, generating data that will enable its introduction into industry standards and its widespread adoption. ZeroEx's deployments will generate this data, and at the same time drive down the method's cost by introducing economies of scale to both the manufacturing of the devices and to the sequential extraction and analysis of the ion exchange resins.

We see SIAs as a key component of all future ERW operations, primarily due to the following benefits:

- Direct and integrated measurement of dissolved weathering products, both cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and anions (SO_4^{2-}, NO_3^-), including environmentally relevant trace elements such as nickel and copper
- No need to determine exact water balances for every project site, which are required to convert concentration measurements from porewater samples to fluxes and finally CDR (a major and often overlooked challenge and source of uncertainty)
- Unlike soil-based mass balance measurements, quantification of non-carbonic acid weathering is possible (via anion fluxes), as well as the determination of time lag from cation exchange (via

installation of SIAs at different depths)

- Installation and ion accumulation for 12 months without any maintenance required, leading to significantly lower cost than other aqueous phase measurements
- Operational simplicity and stable samples (resin beads) provide advantages over porewater sampling, especially in the Global South where cold chains can be difficult to maintain and accessibility of project sites may be limited

We are aware that most people are still unfamiliar with the SIA method and its use in soil sciences and have therefore compiled a short and non-exhaustive list of key publications: Lang & Kaupenjohann, 2004; Bischoff, 2007; Predotova et al., 2011; Safi et al., 2011; Siegfried et al., 2011; Schweiker et al., 2014; Grahmann et al., 2018; Musyoka et al., 2019; Beusch et al., 2019; Grunwald et al., 2020; Vizuete-Jaramillo et al., 2022; Wey et al., 2022.

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

ZeroEx will conduct the largest-scale ERW deployments in mainland Europe to date, with up to 150,000 tons of locally sourced, high-quality feedstock material deployed in 2024. The deployments will take place in the Eifel region in Western Germany, on up to 3,750 ha of land (application rate of 40 t/ha).

Feedstock exploration and byproduct utilization:

Recognizing that the climate in Western Germany may not be ideally suited for ERW due to lower average temperatures compared to the global south, ZeroEx focuses strongly on feedstock exploration. To date, 132 quarries have been tested to identify the most suitable feedstock from both a CDR and regulatory perspective, making ZeroEx the first company to have developed a comprehensive overview of the potential in Germany. Setting a cutoff at a stoichiometric CDR maximum of >0.4, while taking local regulations regarding heavy metal and asbestos concentrations in feedstock into account, over 1 million tons per annum of suitable byproducts have been identified. Of these, 370,000 tons per annum have been secured through long-term offtake contracts, providing security for planning and future scaling.

Due to local regulations, most operating quarries install de-dusting machines to counter dust emissions from crushing operations, providing a continuous source of high-quality byproducts for ERW operations. Combined with crushed sand derived as a byproduct from gravel production, ZeroEx can rely solely on byproducts without the need for additional crushing or milling. While purely utilizing byproducts will not suffice to reach a 1 $GtCO_2$/yr scale, it represents a low-emission path for initial commercial projects to achieve notable scale.

Regulatory environment and local project set-up:

Projects in Germany must adhere to some of the world's strictest regulatory frameworks for soil and groundwater protection. By working within frameworks such as DüV and BBodSchV, ZeroEx

[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.

minimizes environmental risks and positions itself for international scaling without the need for significant protocol and process changes. All feedstocks are rigorously tested by the German LUFA and are authorized for use by organic farmers, posing an attractive opportunity since organic farmers are otherwise limited in their choice of fertilizers.

In the targeted project regions in Western Germany, all quarries are located in the center of large agricultural areas. This allows projects to be set up locally with average transportation distances of 35 km from quarry to field (3 km for the 2023 project), reducing both costs and emissions. Using a decentralized setup with several quarries and smallhold farmers onboarded, these distances can be maintained even with larger quantities of more than 1 million tons of feedstock.

Based on the learnings from non-commercial pilot projects in 2023, totaling 10,000 tons of feedstock spread across five different regions, ZeroEx has built a large network of local subcontractors with contracts already negotiated to allow for a minimum scale of 400,000 tons per annum of feedstock for future projects.

ZeroEx aims to prove the success of its approach from both an MRV and operational perspective in a strictly regulated European setting, enabling international scaling with minimal changes to internal protocols and processes. For future expansion plans, ZeroEx is currently analyzing feedstock and scouting potential deployment areas in several countries in sub-Saharan Africa and Southeast Asia, and is developing pilot projects in Ukraine.

With the current project setting and scale we currently estimate cost per ton of CO2 removed from the atmosphere of ca. USD 429 . At USD 429 MRV will be the largest cost component. We view this as an investment into the future and the advancement of the ERW space as a whole and expect our MRV costs to drop significantly over the coming years, as outlined below.

Measurement strategy

The field of ERW is undergoing rapid scientific advancement, with new methods for CDR quantification published frequently. While the approaches described here align with current best practices and contribute to scientific progress, ZeroEx acknowledges that advancements from our own operations and ongoing academic research will likely necessitate improvements and adaptations to our MRV methodology in the coming years.

ZeroEx utilizes a robust MRV approach that combines several complementary and redundant methods and measurements (see Annex 1 for more detail). This strategy ensures reliable results even if a particular method encounters unforeseen limitations within a specific project setting. This multifaceted approach includes the direct measurement of weathering products in soil porewater, the monitoring of changes in key soil geochemical parameters (pH, total inorganic and organic carbon, base saturation and exchangeable fractions, as well as the simulation of weathering processes using sophisticated biogeochemical models. The cornerstone of our CDR quantification approach are highly reliable and demonstrably accurate devices utilizing ion exchange resins, developed by German soil scientists and validated in several peer-reviewed studies (see section 1a). By pioneering the large-scale deployment of this technology in ERW, ZeroEx is contributing significantly to advancing robust, affordable and reliable methods for CDR quantification in ERW projects. Established soil-based mass balance approaches for the quantification of the extent of weathering (Reershemius et al., 2023; Suhrhoff et al., 2024) will be used for further validation on selected plots and represent a backup method that could be employed at large scale on reserve samples if necessary.

Bringing down the cost of MRV

The relatively high cost of MRV is due to the fact that the core method deployed (and described in detail in 1a) is novel in the ERW context and has not yet been deployed at a scale large enough to enable significant economies of scale (e.g. production output of 300-600 devices per year). We expect, based on conversations will all parties involved in the manufacturing, ion extraction, and analysis, that substantial cost reductions (ca. 60 %) will occur already for the second or third round of deployments. This will be mainly achieved due to larger volume contracts with contract manufacturers and prospectively by internalizing manufacturing processes and the procurement of specialized machinery reducing the need for manual assembly.

In addition, the initial deployments will generate high-quality data sets of relevant soil parameters and leachate fluxes, enabling the training of predictive biogeochemical models. While we do not expect these models to partially replace empirical measurements in the near future, they may contribute to a gradual reduction in required sampling densities, especially in well characterized regions such as central Europe.

Further cost reductions

Following the pilot projects in 2023, ZeroEx has standardized relevant processes and increased efficiency but is still working with a small team, with many tasks handled manually. This leaves significant room for further improvement and cost reductions on the pathway to 100$/tCO2. The main potentials for cost reduction are tied to the improvement of operational processes and a higher degree of digitization, as elaborated below:

Data Management and Tracking: Currently, most analysis results are exchanged as .pdf or .csv files between laboratories and sampling management teams, leading to an increased need for manual labor to consolidate data. ZeroEx aims to set up custom interfaces with subcontractors to directly integrate data into its databases and automatically connect analysis results to the geolocations of samples taken.

Logistics management: Currently, delivery locations are discussed individually with each farmer in person, and coordinates are shared with the logistics provider via a shared file detailing locations and delivery schedules. This process requires constant communication between all parties involved. ZeroEx aims to streamline this by onboarding all logistics contractors onto a central platform. This platform will allow farmers to adjust delivery points directly in the system and upload as well as manage their plot data. Additionally, integrating white-label logistics management software will significantly reduce the time spent on organizational efforts, improving overall efficiency and reducing the need for constant manual coordination.

Sampling and Spreading Management: Harvest periods and potential sampling and spreading timeslots are primarily dependent on local weather conditions, causing dates to constantly shift and requiring manual modification based on emails or phone updates from the farmers. ZeroEx aims to develop tools that provide farmers and sampling contractors direct access to the list of planned sampling slots, with the ability to modify them without the need for further communication.

Field Work and SIA Installation: As ZeroEx is the first organization deploying SIAs on a large scale, the installation process is still labor-intensive and not optimized for time-efficient deployment, necessitating large, costly field teams and supervisors. ZeroEx is discussing options with its partners to develop SIA-specific tools to reduce the labor and time needed for installation.

In addition to operational improvements, economies of scale apply to all relevant aspects of the supply chain, including feedstock procurement, logistics, sampling, and laboratory analyses.

Feedstock: Larger volume contracts enable further cost reductions and volume discounts. Setting up storage facilities at farmers' sites reduces the need for storage capacity at the quarry, enabling the negotiation of cheaper prices.

Laboratory Analyses: Contracting larger analysis volumes allows for the establishment of ERW-specific analysis chains that improve efficiency and significantly reduce costs charged by the provider. Additionally, achieving certain scales justifies the cost-efficient setup of field laboratories.

Sampling & Logistics: Internal process optimization reduces the need for organizational tasks to be managed by subcontractors, subsequently lowering costs.

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

ZeroEx recognizes and addresses the following areas of risk and uncertainty in its proposed project:

Uncertainties related to fundamental soil processes

Over the past few years, significant progress has been made in validating ERW as a viable CDR method. However, significant uncertainties remain, particularly regarding the true rates of weathering and removal in different settings, and its influence on organic carbon cycles.

Both processes have the potential to impact the overall efficiency of the methods as well as the timeline for CDR delivery. Our biogeochemical models (based on Bertagni et al., *preprint*) simulate the relevant processes dynamically and based on site-specific parameterization. Despite this, the accuracy of the model outputs is still limited, making it difficult to fully predict their impact on our operations.

We will, however, address both aspects through appropriate measurements, both as part of our standard MRV as well as in dedicated research plots. The latter will involve the installation of SIAs at different depths to resolve time lags in cation export, as well as the monitoring of changes in organic carbon stocks at different depths intervals down to 90 cm.

Uncertainties related to the measurement approach

A key component of our measurement approach, ion exchange resin-based Self-Integrating Accumulators (SIAs), have been validated extensively for the quantification of cumulative cation and anion fluxes in soil leachates. However, the upcoming project marks the first application of this method on such a large scale and in an ERW context. Consequently, there are some (albeit limited) uncertainties regarding this specific application.

These uncertainties relate primarily to the best and most practical way of installing the devices (underneath disturbed or undisturbed soil, depending on depth of installation and tillage), and to their potential limitations under certain soil conditions (very rocky soil --> high preferential flow, waterlogged soil --> influx from below). We minimize these uncertainties by collaborating closely with Dr. Wolf-Anno Bischoff, the inventor of the method, with more than two decades of practical experience applying it to a wide range of settings and research questions. In addition, we will carry out column and mesocosm experiments in collaboration with Dr. Mike E. Kelland to further validate and optimize the approach in a controlled environment.

As our MRV approach also includes dense topsoil sampling and reserves of all samples are kept in storage, traditional soil-based mass balance measurements could serve as a fallback in case of unexpected difficulties with the SIAs.

Environmental risks from the release or accumulation of toxic trace elements

The potential release or accumulation of toxic trace elements (e.g. Ni, Cr, Cu) during enhanced weathering of feedstock material is one of the major areas of concern regarding the environmental safety and sustainability of ERW (Dupla et al., 2023). ZeroEx addresses this risk through both mitigation and monitoring measures.

All feedstocks utilized in ZeroEx's deployments comply with German fertilizer regulation (DüMV), which dictates strict limits for relevant trace elements (explicitly applying to silicate rock powder as a soil amendment). Compliance is guaranteed through careful selection of source quarries and comprehensive QA/QC during operations.

Regardless of the inherent safety of ZeroEx's feedstocks, extensive monitoring measures will be implemented. These include the analysis of ca. 10 % of all soil samples for their full chemical composition via ICP-MS to enable comparison between baseline and post-application conditions. In addition, a subset of all SIAs will be analyzed for the most relevant elements, to quantify possible leaching from the topsoil into the groundwater.

Biomass sampling and analysis on research plots will aim to identify potential plant uptake of toxic trace elements.

Feedstock supply risk

Project execution risks primarily involve securing a sufficient supply of high-quality feedstock material that complies with all relevant regulations. Unexpected changes in feedstock quality, resulting e.g. from heterogeneities of the deposits, could lead to the exclusion of individual quarries.

ZeroEx has mitigated this risk by identifying several suitable feedstock sources in the region and signing framework contracts with the respective operators. The total available feedstock capacity significantly exceeds the volume planned for upcoming deployments, ensuring that any supply disruptions can be managed by utilizing alternative sources.

Financial risks

Financial risks are primarily tied to the limited ability to accurately project weathering timeframes and delivery volumes at a specific point in time using geochemical simulation models, due to a lack of comprehensive data in the sector. This uncertainty impacts potential financing costs and bears the risk of additional expenses, as project prolongation results in the need for more measurement cycles, where future costs are also subject to inflation.

ZeroEx mitigates this risk by favoring offtake agreements with pre-payment components to cover operational costs at the start of the project, thereby limiting the need for financing to measurement costs in subsequent years. Additionally, conservative safety factors are applied to every projection, on top of modeling results, to maintain a safety buffer of additional feedstock spread for potential delivery failures.

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)*	1.150t
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q4 / 2028
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	429 $/t

Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	434 $/t

[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).