Airhive

Carbon dioxide removal prepurchase application

Summer 2023

General Application

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

Public section

The content in this section (answers to questions 1(a) - (d)) will be made public on the Frontier GitHub repository after the conclusion of the 2023 summer purchase cycle. Include as much detail as possible but omit sensitive proprietary information.

Company or organization name

Airhive

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

London, UK

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

Rory Brown

Brief company or organization description <20 words

Airhive is building a geochemical direct air capture technology that leverages fluidisation to deliver fast, low cost CO_2.

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

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

your project addresses any of the priority innovation areas identified in the RFP, tell us how. Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

Summary

Airhive is building a geochemical direct air capture (DAC) system to accelerate carbon dioxide removal, by leveraging fluidisation of a nano-structured mixed mineral sorbent in a proprietary reactor system.

Our technology increases the speed of mineral carbon dioxide uptake by fluidising our sorbent, creating a turbulent sand-storm in a contained reactor. While geochemical sorbents typically have high CO_2 capacity, strong kinetics and low cost, they are limited by slow CO_2 uptake, long cycle times (days and weeks) and high regeneration temperatures. Airhive has developed a sorbent recipe and synthesis method, which, when combined with fluidisation, hugely accelerates the rate of carbon dioxide uptake and improves the sorbent's thermodynamic efficiency. The result is a technology with high capital efficiency, lower energy requirements, and the capacity to rapidly scale given we are leveraging an engineering process–fluidisation–that is proven at industrial scale in other applications and has a strong existing manufacturing base.

Detailed description

Step 1: Adsorption. We use a bespoke horizontal fluidised bed reactor that is fitted into a half-length (i.e. 20 ft) shipping container for our carbonator. Our proprietary geochemical-based sorbent is uplifted and fluidised by passing air from below into the central reactor chamber via a distribution plate. The upflow of air through the mineral sorbent causes "fluidisation", where the sorbent particles and gas mixture behave in a turbulent fluid-like manner– akin to a chaotic dust-storm inside the reactor.

This uniquely enables the sorbent to reap the benefits of fluid dynamics: rapid contact and chemical binding with CO_2 at ambient temperatures and pressures. The dispersed gas-solid contact area of the horizontal fluidised reactor bed achieves very low pressure drops (<3 mbar) and therefore low fan energy requirements. CO_2-depleted air is released from the top of the reactor via a filtration system. The small fraction of particles that are attrited in each cycle are cycled into a small connected pelletiser.

Step 2: Desorption. We also exploit fluidisation for desorption, using a separate containerised electro-calciner reactor which electrically heats and unbinds the carbon dioxide from the saturated carbonate mineral. After cooling the CO_2 and recycling the heat, a pure stream of carbon dioxide remains, suitable for compression, transport and storage or utilisation.

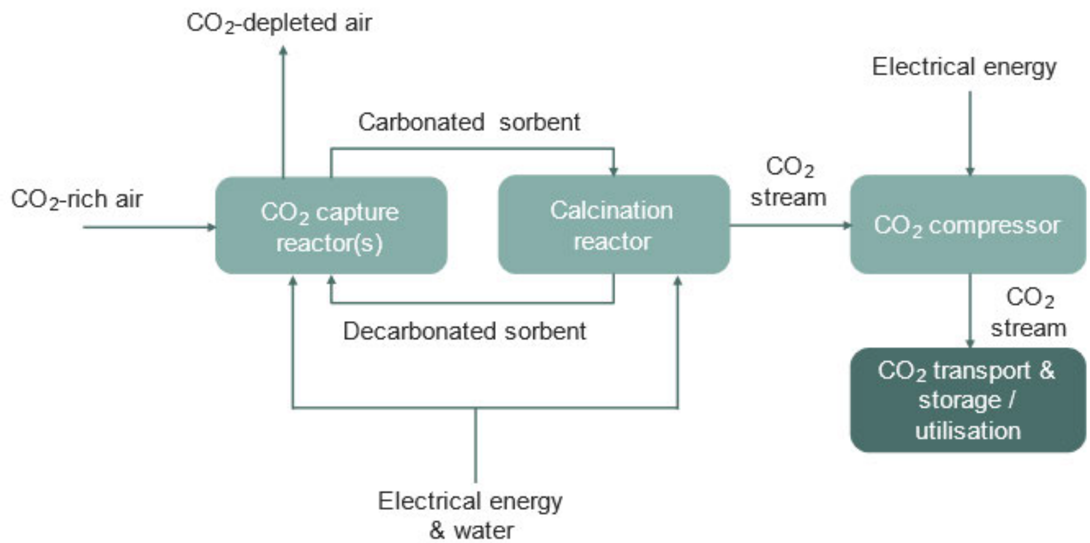
The calciner design is nearly identical to the carbonator, with an upflow of fluidising gas (now steam, not air) and arranged vertically rather than horizontally. The fluidisation under steam allows for efficient heat recovery and inherent regeneration of our sorbent material (Donat et al, 2011). The electro-calciner system also includes a heat recovery system and is built from more heat-tolerant steel. After the desorption step in the electro-calciner, the mineral oxide is returned to the carbonator for re-carbonation in a closed recycle loop. Both steps run simultaneously to maximise capital and energy efficiencies.

At commercial scale, a single calcination reactor will serve an estimated eight carbonators of the same size, as calcination occurs at approximately X8 the speed of carbonation. The use of similar closed reactor vessels for both adsorption and desorption steps enables:

- The use of a geochemical sorbent that is highly customised to optimise its performance across key performance metrics: kinetics, conversion, cycle time and calcination temperature.
- Modular manufacturing and consolidated supply chains for both systems.

- Little-to-no particle loss into surrounding air and nearby ecosystems.

A simplified schematic of our system is presented below (see submitted TEA for more detailed PFD with mass and energy balances).



Sorbent. We are in Phase 2 experimentation for our sorbent development, where we are testing how doping and impregnation enhance reactivity, capacity and long-term performance. We are also testing how advanced, fluidisation-based calcination methods improve performance through nano-structuring: i.e. internal honeycomb-like pore structure with high surface areas in the order of hundreds of square metres per gram.

In optimising our sorbent's kinetics, capacity, conversion and carbonation and calcination temperatures, we are building on recent progress in material science for geochemicals used in carbon capture/chemical looping in fluidised bed applications, including work by our scientific advisors and CTO, Jasper Wong (e.g. Donat et al, 2015, Gonzalez et al, 2020, Erans et al, 2018, Blamey et al, 2015, Zhang et al, 2023).

Addressing priority innovation areas

Airhive's system represents a next generation hybridisation between enhanced geochemical CDR and DAC approaches, by taking the high CO_2 capacities and low costs of geochemical minerals and using fluidisation to accelerate their capture rates to deliver cycle times of less than two hours. We suggest this addresses one of Frontier's stated priority areas: "Approaches to geochemical CDR that accelerate weathering rates."

We are also addressing another priority innovation area: 'Novel approaches to CDR and crosscutting technologies', specifically 'Integration of Airhive's CDR process technology into existing industries via changing/adapting processes'. Our upcoming pilot in Teesside, an industrial area at the centre of one of the UK's first two Net Zero Clusters, is a launchpad to scope integration of our commercial scale DAC technology into a wider decarbonised industrial cluster, which we will do via a partnership with Heriot-Watt University to use their cutting-edge PrIsMa platform.

Our technology also addresses the 'Novel approaches to kinetic enhancement that come with limited penalty to overall net-negativity, e.g., via chemical or biological accelerants (because in-field rock weathering rates are typically slow)' knowledge gap. Our process is based around the enhancement of mineralisation kinetics in part via the enhancement of our capture materials. Our sorbent development involves combining metal oxides, carbonates and salts that enhance the rates of adsorption and desorption by improving the speed of CO_2 diffusion and reaction through the solid material. And by electro-calcining our mixed material under fluidisation conditions to create sorbent nano-structuring, we're improving the speed of carbon dioxide uptake over many cycles in our reactor. In experimental work, we have validated the capacity of our evolving sorbent to capture ~100% of CO_2 from a single parcel of air in <1 second, and achieve cycle times of under 100 minutes.

We also address the 'Material - stability and recyclability' and 'Crystallinity effects on mineralisation kinetics' knowledge gaps. Airhive's sorbent enhancement methods include a proprietary recipe for mixing and calcining minerals to prepare the sorbent, which creates crystalline nano-structure and nano-activity within the porous interior of the geochemical minerals while retaining the naturally abundant, low-cost and easy-to-handle advantages of these granular particles. These novel synthesis methods create i) a fine-tuned adsorption phase (improving the speed of CO_2 adsorption) and ii) structurally-supporting skeleton phase, stabilizing the sorbent over many cycles. This internal crystallinity (large active phases and smaller dispersed, structurally supporting phases) and high internal surface area (>100 m^2/g and with reactive pores <150 nm) enable enhanced uptake rates and capacities. Importantly, this nano-behaviour is also achieved in relatively large particle sizes (500-1000 micron) that are operable in fluidised bed reactors, meaning safe, cheap and non-toxic minerals are able to perform in this reactor with the properties of nano-particles.

Differentiation

Our system has a number of strong differentiators from existing DAC approaches.

- **Fluidisation to accelerate carbon dioxide removal.** Ours are unique among DAC technologies in using fluidisation for adsorption. We are able to achieve highly accelerated uptake into our geochemical sorbent through fluidisation at ambient temperatures, which is reflected in our very low per tonne capital cost, competitive energy requirements and low land footprint per tCO_2.
- **Fluidisation is a proven industrial process**. Fluidisation is widely used in other industrial applications, typically in vertical fluidised beds up to 30m in height for chemical production and horizontal fluidised beds in food and pharmaceuticals. The fundamental technology behind our process is therefore already operating at industrial scale, giving us confidence in our ability to reach commercial deployment over an accelerated timeframe.
- **Novel geochemical sorbent**. Through our core team and scientific advisers, we are engineering and testing new natural geochemical sorbent mixtures specifically optimised for DAC and fluidisation. These sorbents combine the best of chemi-sorbents' high uptake capacities and low costs with the accelerated uptake rates more commonly associated with highly engineered and more expensive physi-sorbents.
- **Modularity**. A nearly identical core design and containerised shell for both carbonation and calcination modules enables manufacturing at the same facility, and therefore for production to be rapidly iterated and refined. This is anticipated to provide for a fast drop in CAPEX costs as we scale.
- **Thermochemical energy storage**. Our technology has the potential to be used as a thermochemical energy storage vessel, holding out the potential for partial system operation when low carbon energy is not available. This will be explored in our upcoming pilot.

How the carbon is stored for >1,000 years

We will co-locate our proposed facility with the Northern Endurance Partnership's CO_2 transportation and storage infrastructure currently under development to serve our proposed project location. This infrastructure involves injection into an offshore saline aquifer, the most mature type of geological CO_2 storage and known to be durable over geological timescales. See 1b. and Geological Storage

Supplement for specifics on geological storage for our proposed project.

b. **Project objectives:** What are you trying to build? Discuss location(s) and scale. What is the current cost breakdown, and what needs to happen for your CDR solution to approach Frontier's $100/t and 0.5Gt targets? What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

Proposed facility: location and scale

We will build our first commercial facility in Teesside, North-East England. We plan for our first facility to be 4,000 tCO_2 in installed capacity, and anticipate it to operate at an 85% lifetime average capacity factor, delivering 68 $KtCO_2$ gross removals over a 20 year project lifetime. 4,000 tCO_2 represents three full-scale (i.e. containerised) carbonation units and a single calciner, in addition to compression and CO_2 pipeline integration.

Teesside is part of the East Coast Cluster that is one of the UK's first two Net Zero Clusters. Phase 1 of development at Teesside is underway, with 5 low carbon electricity generation facilities and eleven decarbonised industrial production facilities selected to proceed from a competitive application process and a number of facilities now under construction. Phase 2 procurement is expected to begin in Q4 2023. Teesside will therefore soon see decarbonised industry co-locate with DAC and other engineered carbon removal methods, all supported by commercial and industrial low carbon energy provision and a CO_2 transportation pipeline connected to a North Sea injection site (using a saline aquifer) currently being developed by the Northern Endurance Partnership.

In August 2023 we will begin building our first pilot in Teesside, in partnership with Teesside University's Net Zero Industry Innovation Centre (NZIIC). The pilot project involves a significant stakeholder engagement workstream that is intended to support our scale up and integration into existing and new low carbon industry and infrastructure on Teesside (see Section 7). And in mid-2024 we will build a fully funded 1,000 tCO_2 commercial pilot for a strategic partner and CO_2 utilisation offtaker (see Section 2 for details), which will support achieving TRL 7 and de-risking the project proposed here.

Current costs

The (rounded) costs for the proposed project's technical stages and additional verification and registry elements are summarised in the table below (see Section 6 and TEA for calculations).

Stage / element	Cost
Levelised capital cost	$182 / tCO_2
Levelised fixed operational cost	$69 / tCO_2
Levelised energy cost	$92 / tCO_2
Levelised other variable operational cost	$3 / tCO_2

Transportation & storage	$32 / t$CO_2$
MRV	$19 / t$CO_2$
Registry costs	$22 / t$CO_2$
Uncertainty discount	$111 / t$CO_2$
Total	$530 / t$CO_2$

Pathway to below $100/t$CO_2$ and deliver 0.5 GtCO_2

Airhive's target is at least 5 MtCO_2 by 2030, and 0.5 GtCO_2 by the second half of the 2030s. As Section 6 and our submitted TEA describe in detail, to bring the price below $100/t$CO_2$ we must:

- **Lower the cost of key components** through i) economies of scale, ii) improved component design and iii) optimised manufacturing processes.
- **Improve the capital efficiency of future facilities** by i) increasing the capacity factor and ii) optimising process conditions.
- **Improve system energy efficiency** further by i) increasing the rate of heat recovery in the calciner and ii) capturing and recycling energy produced from hydrating the calcined sorbent.
- **Leverage anticipated cost reductions** in i) low carbon energy and ii) CO_2 transportation and storage.

To deliver 0.5 GtCO_2, we must:

- **Build and deploy approximately 357,000 carbonation modules**. If average plant size is 5 MtCO2, this means 3,570 carbonation modules per plant. It's difficult to quantify what percentage of global fluidised bed production capacity this would represent, but to put this in the context of the number of shipping containers, there are currently 5-170 million (spot estimate 17 million) full length shipping containers in active use, and a single container ship carries 9-11,000 full length shipping containers.
- **Licensing our technology to scale rapidly.** Early on we will build, own and operate our own facilities to take advantage of operational learning, but to accelerate our scale-up we anticipate licensing our technology to project development partners.
- **Build partnerships with low carbon energy and CO_2 storage providers**. Our technology needs large volumes of clean energy and geological CO_2 storage to be deployed at scale, so partnerships with public and private sector providers of both will be critical to scaling rapidly. We are in early discussions with both types of providers and anticipate developing strategic partnerships as we scale. And by building our first pilot and our proposed project in the UK, which has made some of the fastest advances in deploying low carbon electricity and biggest commitments to develop new CO_2 storage sites in the global North, we are well-placed to leverage this fast-growing enabling infrastructure.
- **Have a large market for CDR-based credits.** The market for durable removals is growing rapidly (BCG, 2023) albeit insufficiently, and is likely to be further accelerated by emerging government fiscal support (e.g. the US Inflation Reduction Act's tax credit for DAC, and the impending UK market-based subsidy for engineered removals) and regulatory regimes (especially on MRV).

More details on our pathway to meeting cost and scale targets are provided in the TEA and Section 6.

Quantification

We will begin formalising our quantification approach from Q4 2023, using our pilot plant in Teesside as the test case. Our preferred course of action on MRV is to adhere to emerging best practice via the CO_2RE Principles for Credible Removal, which are currently being road-tested with a variety of UK carbon removal projects and likely to inform UK government support and regulation of the carbon removal sector. The CO_2RE Principles comprise detailed quantitative and qualitative metrics that encompass "traditional" MRV considerations, e.g. GHG balances, storage permanence and material footprint, as well as wider environmental, social, system integration, legal and business model considerations.

For the durability of sequestered CO_2, this is expected to be estimated by the CO_2 T&S asset operator prior to commencement of operations. It is likely that durability risks will be specified and set as a fixed adjustment to the net tonnes delivered to their asset by CDR suppliers in order to account for any expected leakage in the removal credits issued on the basis of using this CO_2 T&S asset for durable storage, as recommended in the UK government GGR MRV Task and Finish Group report (BEIS, 2021). We expect that periodic adjustments will be made to this durability estimate through the lifetime of our project.

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

1. Technical

1.1 Real system under-performs modelling and prototype results

Transferring technical performance criteria that we have achieved at the prototype scale to the continuous operation of a system of shipping container-sized fluidised bed carbonators and electro-calciner is the main technical risk for the proposed project.

- This risk will be mitigated by making progress in overall performance during our two upcoming intermediate-sized continuous system pilot projects, beginning in August 2023 and Q2 2024 respectively, with lab-scale material science and reactor development continuing in parallel.

2. Project execution

2.1 Lack of permitting for facility development in Teesside. Applications from project developers for Phase 2 expansion are expected in Q4 2023, and there is a risk of non-selection that means an alternative site must be identified.

- We plan to mitigate the risk of non-selection by leveraging our pilot to build out our industrial partnerships and knowledge of the cluster. If not selected, alternative sites in i) existing and new Net Zero Clusters in the UK, or ii) overseas, will be identified.

2.2 Facility cost overruns. Cost overruns are the norm rather than the exception in engineering projects, especially with a first of a kind or one-off project (Flyvbjerg & Gardner, 2023). We will mitigate this risk in three ways.

- First, our funded 1,000 tCO_2 commercial pilot, which will be built and operational in mid-2024, will use an identically sized carbonator and strongly overlap with the specifications of the

- proposed project, enabling us to leverage the technical and cost knowledge developed during engineering design, construction and operation to control costs during the design and development of the proposed project.
- Second, our Teesside-based pilot starting in August 2023 will enable us to understand location-specific conditions and costs.
- Third, our developing partnerships with large corporate project developers and engineering consultancies (see non-public sections) will enable high standards of governance and coalitional expertise that are crucial to effective project development (Ansar & Flyvbjerg, 2022).

3. MRV

3.1 Lack of recognised MRV framework for proposed project. There is relatively low MRV risk associated with our project as a DAC + geological storage, given the high Verification Confidence Level for this type of CDR and existing published DAC protocols. But the wider set of MRV protocols are still under development, and marketplaces, buyers and governments have not yet developed market-wide standards on what is expected from in-house and third-party MRV. There is a risk that our specific MRV protocol is not accepted by some or all marketplaces, buyers and governments.

- We will mitigate this risk by consulting across stakeholders as we develop or adopt an MRV protocol, and aligning our approach to emerging best practice such as CO_2RE's Principles for Credible Removal, which we will begin road-testing on our upcoming Teesside-based 50 tCO_2 pilot.

4. Ecosystem

4.1 Shortcall in fiscal support for DAC in the UK. The UK government consulted on a market-based fiscal support mechanism for engineered removals–limited to DAC and certain typical of BECCS/BiCRS–in Q3 2022, and has stated its intent to announce the preferred support mechanism in 2023. There is a risk that this fiscal support is not provided or delayed, or is insufficient to support DAC suppliers and buyers agreeing a price.

- We will mitigate this risk by identifying and initially selling to credit buyers with lower price sensitivity.

4.2 Delays in completion to CO_2 transportation and storage. There is a risk that the CO_2 transportation and storage infrastructure currently being developed for Teesside is not completed in time for our facility's operation, because of construction delays or economic or policy reasons.

- We will mitigate this risk by scoping, during our Teesside pilot, alternative options for sequestration of captured CO_2, such as in long-lived products, as an interim measure. And if delays are expected to be multi-year or indefinite, we will pivot to another site from a list of alternatives that we'll scope concurrently to developing this preferred site.

5. Financial

5.1 insufficient financing is available to build the facility. We anticipate funding the facility via project finance, which relies on a track record of delivery and robust estimates of future revenue streams for debt servicing. Raising sufficient capital to build this facility is a risk.

- We will mitigate this risk by using a legal-financial structure for our 1,000 tCO_2 pilot in 2024 that replicates project financing to build a track record for project financing, and by working with our strategic partners to underwrite the financing.

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)*	943 tCO_2
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q1 2026
Levelized Price (\$/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	\$530 / tCO_2

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

[redacted]