Frontier

Parallel Carbon

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

Parallel Carbon

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

Ingatestone, United Kingdom

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

Ryan Anderson, Aranzazu Carmona Orbezo

Brief company or organization description <20 words

Direct air carbon capture and water electrolysis for affordable carbon dioxide removal and hydrogen production, in parallel.

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.

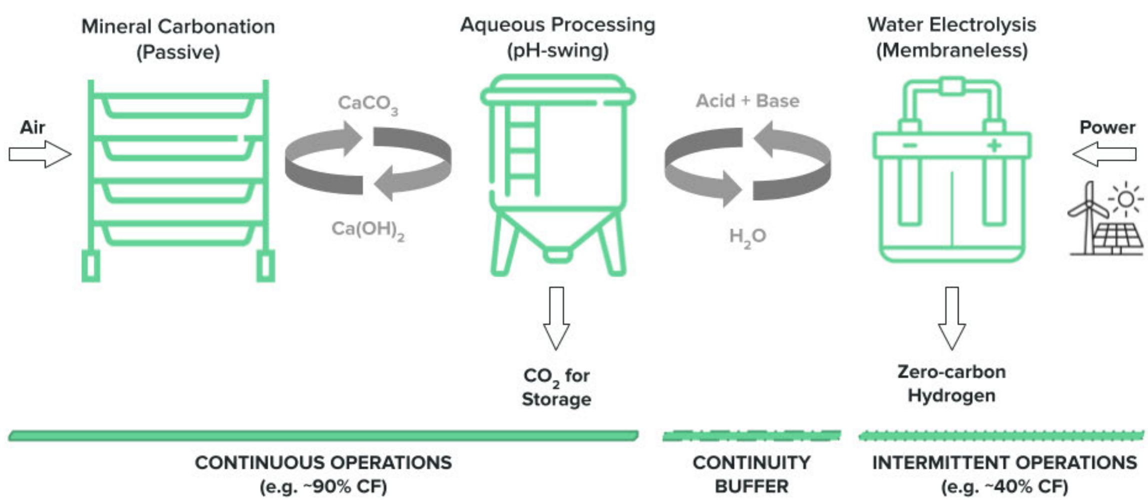
Parallel Carbon has developed a new direct air capture (DAC) technology to create an affordable and scalable carbon removal pathway. The DAC process extracts CO_2 from the atmosphere through a combination of mineral-air reactions, electrochemistry, and clean power. Captured CO_2 is supplied to an offtaker capable of long-term storage (e.g. via mineralization in concrete or sequestration in underground geologic formations). Our first CO_2 storage partner will use CO_2 to cure concrete.

The DAC system's electrochemical processing also generates a zero-carbon hydrogen co-product which can be used onsite, sold, or combined with DAC-CO_2 to produce low-carbon fuels and chemicals (e.g. methanol). This feature enables our technology to remediate the climate through emissions reduction and removal, in parallel.

Parallel Carbon's DAC+H_2 Technology

Parallel Carbon's DAC utilizes calcium looping driven by pH-swing aqueous processing (instead of a traditional high-temperature calcination step). Acids and bases used in the pH-swing process are produced on-site through water electrolysis powered by renewable energy.

Semi-wet $Ca(OH)_2$ solids passively extract CO_2 from ambient air and form $CaCO_3$ over hours/days. We liberate CO_2 from carbonates and regenerate our sorbent using acid-base reactions. The pure CO_2 stream is compressed and mineralized in concrete for smaller projects or injected underground for storage at larger scales.



Parallel Carbon decouples DAC energy demand from power availability. Continuous (24/7) carbon-free energy (e.g. nuclear, geothermal, variable renewables with battery energy storage) is much more expensive than intermittent renewable power. Our electrolyzer uses low-cost power to produce the acids and bases we use for DAC when the wind blows and the sun shines. Instead of using a battery to store power (and increase the cost of electricity), our highly economical approach stores acids and bases in tanks on-site, acting as a 'continuity buffer'. We are therefore able to operate our DAC process continuously (e.g. 90% capacity factor) while using intermittent renewable power (e.g. 20–50% capacity factor).

Producing zero-carbon hydrogen while performing DAC offers an innovative approach to integrating CDR with industry. Our zero-carbon hydrogen will be used to eliminate industrial emissions (e.g. displacing fossil-fuel derived H_2) for crosscutting climate benefits.

Differentiation and Advantages

Parallel Carbon's process uses an electrolyzer 'back-end'. An electrolyzer produces revenue on its own, and in some markets produces revenue sufficient to pay for itself. Since only the air contactor and aqueous processing equipment 'front-end' are dedicated to DAC, we offer one of **the most capex-efficient DAC process designs**.

Compared to other calcium looping DAC processes, Parallel Carbon's aqueous pH-swing step increases the reactivity of $Ca(OH)_2$ compared to thermal calcination alternatives. The improved reactivity is the result of particle characteristics, electrolyte content, and moisture control, each of which are unfeasible for thermal calcination. The result is an increase in the sorbent's CO_2 capture efficiency, and our tests indicate Parallel Carbon's **air contactor can be 3x smaller** in comparable locations, reducing equipment cost. The sorbent's CO_2 capture efficiency also does not degrade during cycling, but this may change as the process scales and is introduced to more realistic air environments.

Since Parallel Carbon employs an aqueous regeneration process, we can optimize our sorbent carbonation with engineered moisture control. Other, high-temperature calcium looping DAC processes aim to deploy predominantly in locations with high humidity. If they control moisture through engineered methods, they may incur an energy penalty during calcination due to excess water content. The use of an aqueous process for calcium looping DAC **reduces energy intensity 300–800kWh/tCO$_2$.** Overall, our process uses 1.2MWh/tCO$_2$ and 55kWh/kgH$_2$.

The process's operational compatibility with intermittent renewable power also enhances our scalability. We will deploy alongside low-cost, fast-to-build solar and wind power instead of relying on geothermal or nuclear power which are more expensive and have much longer project development timelines. What's more, solar and wind power potential are **more spatially aligned with known CO_2 storage reserves** than potential low-cost geothermal resources.

Importantly, by building DAC powered by behind-the-meter, off-grid, or otherwise curtailed wind and solar power, we can **avoid creating marginal emissions from grid electricity**. Because of our low capex, we can operate economically even at low renewable power capacity factors (<30%). This operational flexibility also **improves carbon accounting accuracy for DAC's scope 2 emissions**, relying less on models and more on receipts.

The combined reduction in energy intensity and power price could **reduce the marginal cost of DAC nearly \$100/tCO$_2$** with our process.

Our DAC projects are designed to maximize potential deployment speed. Our air contactor and electrolyzers are modular, shipped to site, and have robust supply chains. The air contactors are made of common warehouse racking equipment and pallets of injection molded trays. The sorbent feedstock is CaCO3 which is the backbone of the cement industry and locally available almost anywhere in the world. The electrolyzer is assembled from components widely available in the rapidly growing water electrolyzer manufacturing industry. The remaining equipment, including tanks, compressors, and piping is standardized before delivery.

The expected result is **faster deployments, on budget, and with the lowest costs** among DAC technologies.

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.

Parallel Carbon intends to build a DAC facility that stores up to 454tCO_2/yr in concrete for >1,000 years. The project location remains TBD, but will likely be in New Jersey to Texas. At the same time, hydrogen will be sold to a local buyer [TBD]. Upon successful delivery of initial CO_2 and CDR credits, we intend to grow capacity at the chosen location to >2,000tCO_2/yr capacity.

For this project, it will cost approximately $1,200 to capture one tonne of CO_2 and produce roughly fifty kilograms of H_2 per day. After accounting for the net effects of our LCA and revenue from hydrogen, CDR will cost almost $1,000 per tonne. The largest cost factors for this project are the capex and the cost of power. The small scale of this project does not allow for the economies of scale we expect for future commercial deployments. Similarly, the small scale creates challenges for sourcing clean power, so we expect to pay high power prices to secure low-carbon electrons.

We will approach and surpass Frontier's $100/t target as the following factors converge:

- Capex – Capacity cost ($/t$CO_2$/yr) falls approximately 85%
- Power – Renewable electricity sourced with 50% capacity factor at $30/MWh
- Revenue – Hydrogen revenue exceeds $2.5/kg

Each of these factors is highly achievable.

Our capacity cost will fall roughly 50% from project economies of scale alone. Efficiencies in electrolyzer performance and modular manufacturing economies of scale will drive out a significant chunk of the remaining capex.

Today, intermittent wind and solar PV electricity costs average $40/MWh (approximately). Good locations regularly achieve costs under $30/MWh, and in some locations PPAs have been signed for less than $15/MWh. Continued deployment is expected to continue reducing costs over time. By integrating DAC with solar PV, we eliminate unnecessary costs (e.g. inverters, land, etc.). Achieving $30/MWh and 50% capacity factor power are achievable this decade.

Hydrogen is often produced from unabated fossil fuels at a cost near $1.5/kg. Water electrolyzers offer a pathway to produce low-carbon hydrogen with costs near $3/kg using $30/MWh power. Since fossil-derived H_2 emits roughly 10kgCO_2e/kgH_2 more than renewable-derived electrolytic hydrogen, an internal carbon price of $150/t$CO_2$ would tend to drive abatement. Since our CDR cost target is $100/t, we aim to sell H_2 for $2.5/kg using $30/MWh power to drive faster adoption of zero-carbon hydrogen. That is, we ensure our hydrogen is the most economically attractive option to drive industrial decarbonization.

We will exceed Frontier's 0.5Gt deployment potential target through:

- Standardization of projects, modular equipment design and manufacture
- Deploying with intermittent clean power sources (solar PV and wind turbines)

Standardized project designs and construction, along with modular equipment, keep projects on time, on budget, and on specification. Simple supply chains with minimal customization between projects is our goal. Achieving gigaton-scale carbon removal with DAC is likely only feasible through underground CO_2 injection. Economical CO_2 sequestration usually requires at least 100,000t/yr injection rate, so our full-scale commercial project will be designed around this capacity. The most economical renewable power projects often exceed 50MW. To achieve 100ktCO_2/yr project scale with intermittent renewable power (i.e. capacity factors 20–50%) requires 85–210MW projects. Achieving 0.5GtCO_2/yr CDR capacity therefore requires 425–1,050GW of renewable power capacity. For comparison, over 200GW of wind and solar capacity was added globally in 2021 [IEA] with >5,000GW expected to be installed by 2030. The 100ktCO_2/yr scale is sufficient for Parallel Carbon to achieve <$100/t CDR with 5,000 projects, but building 500kt or 1.0Mt projects could also be possible in favorable locations and would reduce costs further. With standardized equipment and EPC playbook, the largest variation between projects will be the number of electrolyzer modules delivered to appropriately match the renewable power resources and capacity factor expected at the site. There is also reason to believe that our DAC projects can spend less time in the planning and construction phase. Solar projects can get built in 6-9 months if the grid interconnection queue is avoided. Since our process does not require continuous power or grid connection, projects can begin operation with fewer institutional hurdles.

Carbon removal will be quantified by:

- Measuring the CO_2 gas by mass/volume flow rate
- Sub-hourly marginal emissions accounting if we use grid electricity
- Partnering with MRV solutions providers with our CO_2 offtaker for third-party validation

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.

Our DAC tech is essentially an industrial operation. We expect land will be prepared before we build a site which may include clearing trees, disturbing soil, and affecting hyperlocal ecology. Our goal will be to preserve, protect, and restore nature such that we counteract our footprint with equal (or greater) benefits.

Our early-stage technology still has a few engineering hurdles to ensure operational safety. The DAC process employs acids and bases. We make these onsite thereby avoiding the risks of spilling during transport. However, production operations still must undergo hazard assessment to ensure safe operations. The DAC process also makes hydrogen which comes with known risks. Finally, the DAC process is designed to expose our mineral sorbent to moving air. If this creates dust, it could negatively impact locals. Our top priority is measuring and mitigating any material loss. Each of these technical risks is managed frequently in industry and solutions already exist. Measuring air quality will be critical to 1) satisfying local health and safety requirements, 2) designing mitigation measures, and 3) ensuring employee and community health are unaffected.

Project execution risk is also top of mind. We must secure permits, siting and supply chains for renewable power, CO_2 storage, DAC+H_2 equipment, along with offtake contracts, community engagement, environmental impact assessment, and third party LCA and MRV. The burgeoning ecosystem of companies within the CDR and climatetech value chain is simplifying much of this process for us. The most pressing project risk will be manufacturing and supply chain delivery timelines for our DAC+H_2 equipment. We're currently exploring in-house manufacture of some long-lead time components to mitigate risk.

Our ability to sign contracts for renewable power with clear additionality is a steep challenge for an early stage company. Power purchasing creates MRV risks for Scope 2 carbon accounting as well. We prioritize off-grid or behind-the-meter PPAs, but our smaller/earlier CDR projects may use VPPAs or other bundled RECs until we can build larger projects.

Financing risks exist and persist for DAC technologies. Recent pullbacks in venture capital have already slowed funding and delayed projects. Beyond VC funding, FOAK financing pathways remain uncertain for larger DAC projects. Continued scarcity of funding may pause/stop projects from getting

built on time, or cause capacity to be scaled down and result in under-delivery. However, numerous entities are working to solve the FOAK funding problem, and support for early-stage DAC projects is growing from multiple directions, namely Frontier and those inspired by Frontier's mission.

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)*	454 tons
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Dec 31 2026
Levelized Price (\$/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	\$1,100/ton CO_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]

[redacted]

[redacted]