E-quester
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

E-quester Inc.

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

Toronto, Canada

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

Todd Scheidt, David Sinton

Brief company or organization description <20 words

E-quester achieves carbon- and energy-efficient atmospheric CO_2 capture through electrolysis

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

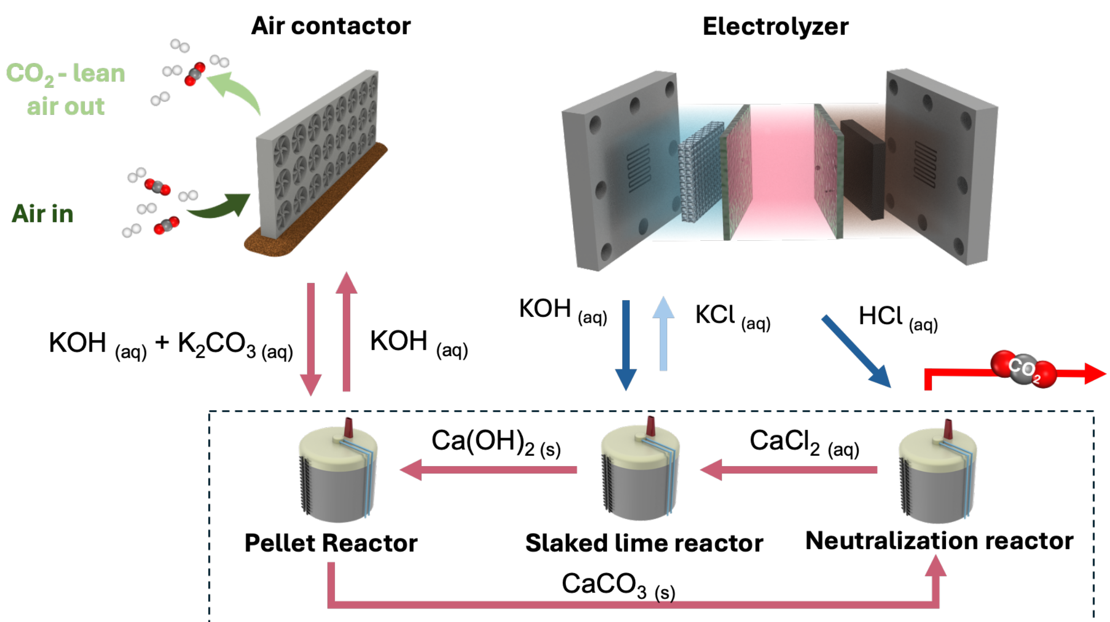
The conventional regeneration of DAC capture absorbents involves a calcium caustic cycle that requires high temperatures and thermal energy inputs, with associated emissions that diminish their net environmental benefits. E-quester's approach electrifies CO_2 capture and release in a manner that

[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.

is low-capex, low-opex and low-emission. Achieving these required new approaches to air contacting and the capture fluid regenerator: We use a liquid sorbent to capture CO_2 from the atmosphere and subsequently extract pure solid-form carbonate followed by a pH-swing electrochemical step where we release a stream of CO_2 and regenerate the capture solution. The system operates at ambient temperature and pressure to enable lower energy consumption per ton of CO_2 captured than existing solutions and reduces system complexity to minimize both capex and opex as our solution scales.

Electrochemical CO_2 capture and release methods have garnered significant attention for their potential to employ renewable electrical energy in place of thermal energy. Our early work demonstrated a cyclic approach to regenerating the capture liquid in a three-compartment system, achieving 6.4 GJ/tCO_2 at 100mA cm^2 and a low emission intensity of 11kg CO_2e/tCO_2 [ref: Joule, 2023 - Regeneration of direct air CO_2 capture liquid via alternating electrocatalysis] However, With our focus on scale, we sought to further reduce capital and operating costs by replacing the iridium catalyst used previously, with carbon. We noted advances in organic redox-active molecule, promising even more efficient routes to CO_2 release. The common downside of using redox couple chemistry was low stability due to exposure of the organic molecules to oxygen (with O_2 to CO_2 concentration at 500:1 in air). To integrate the energy efficiency benefit of redox chemistry while ensuring no air-organic contact, we developed our three-compartment regeneration system. The result of this innovation is a combination of low energy cost, fast kinetics and high stability over 200 hours operation [ref: Energy Environ. Sci, 2024 - Direct air capture of CO_2 via cyclic viologen electrocatalysis]. Building on these electrolyzer concepts, we developed an integrated three-compartment electrolyzer which reduced energy cost to 3.9GJ/tCO_2 at 100mA/cm^2. With the electrolyzer optimized, we again assessed overall process costs and turned upstream to re-engineer air contacting. We developed an air contactor that directly produces a solid-form carbonate – avoiding a full chemical loop in the incumbent process – and thereby providing a low-capex feedstock for our electrolyzer. The team's rapid progression reflects an approach free from methodological bias, and guided only by a shared passion for DAC that is low-cost, low-energy and low-emission.

Below is a diagram representative of the three main steps in carbon capture and removal process prior to the development of the new contactor method. The IP for our new contactor is in progress, we will share details of the design once the IP filing and publications are complete.



Air contactor and pellet reactor: An alkaline KOH is passed through the air contactor to react with CO_2 from air to form carbonates (in mix with the original KOH solution). Direct regeneration of the mixture solution via pH-swings wastes energy. Therefore, a pellet reactor is introduced to separate carbonates from hydroxides. Carbonates are separated by causticization with $Ca(OH)_{2(S)}$ in the pellet reactor. This process forms solid $CaCO_{3(s)}$ and $KOH_{(aq)}$ which allows separation by phases.

Air contactor: $KOH_{(aq)} + CO_{2(g)} \rightarrow K_2CO_{3(aq)}$

Pellet reactor: $Ca(OH)_{2(s)} + K_2CO_3(aq) \rightarrow CaCO_{3(s)} + 2KOH_{(aq)}$

Electrolyzer: The inputs to our electrocatalysis system consist of water and salt electrolyte (KCl). With the aid of hydrogen evolution and hydrogen oxidation redox reactions, water is dissociated into OH- and H+, combing with K+ and Cl-, respectively to produce KOH and HCl.

Cathode: $H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Overall reaction: $KCl_{(aq)} + H_2O_{(l)} \rightarrow KOH_{(aq)} + HCl_{(aq)}$

Neutralization reactor: HCl then reacts with $CaCO_3$ to liberate the CO_2 and form CaCl2

$$HCl_{(aq)} + CaCO_{3(s)} \rightarrow CaCl_{2(aq)} + CO_{2(g)} + H_2O_{(l)}$$

Slaked lime reactor: The $CaCl_{2(aq)}$ is then further reacted with KOH formed at the cathode of the elctrolyzer to regenerate $Ca(OH)_{2(s)}$ for the pellet reaction and $KCl_{(aq)}$ for the electrolyzer, completing the cycle.

$$CaCl_{2(aq)} + KOH_{(aq)} \rightarrow Ca(OH)_{2(S)} + KCl_{(aq)}$$

Geological sequestration (for carbon storage > 1000 years): E-quester's captured CO_2 will be sequestrated underground for permanent storage. We will work with industry leaders in sequestration and MRV to ensure the highest levels of confidence in captured volumes and the integrity of the wells where the captured CO_2 is stored.

These articles, Regeneration of direct air CO_2 capture liquid via alternating electrocatalysis and Direct air capture of CO_2 via cyclic viologen electrocatalysis, provide additional details on the secured IP that we have shared publicly. The IP filings are further detailed in our response to question 2j. We continue to invest in improving the performance and scalability of our technology and have multiple patents and associated manuscripts in progress – on the electrolyzer tech and the direct-to-solid-form contactor concept. Although we cannot share details on the workings of these upgrades, we provide the details of the patented components, and the additional energy and cost savings achieved with the upgrades.

Below are E-quester's three key differentiation factors, which will enable us to be best-in-class:

1. **Electrochemical regeneration.** An electrochemical process for CO_2 direct air capture, utilizing a pH- swing process that operates at ambient temperature and pressure. This system also enables cycling up and down to align with the availability of low-cost renewable generated electricity and the modular design facilitates scaled manufacturing and serviceability which will further lower overall cost per ton of CO_2 captured.
2. **Air contactor advance**. The air contactor approach enables a fast kinetics and direct production of a solid form of carbon, a carbonate salt. We can't share full details of this approach yet as we are filing the necessary IP protection and have publication of a paper with the details pending. However, we can share that by replacing both the mechanical contactor and the pellet formation chemical process with a passive system, we achieve a +70% reduction in capex compared to the conventional liquid sorbent-based air contactors. The contactor is also area-efficient, with 1000-fold the areal capture rate of biomass approaches.
3. **Business- and scale-oriented team**. We have designed for scale from Day 1, in our team make-up and our technological foci. Todd has 20+ years of experience managing large capital projects and manufacturing for some of the largest companies in the world. Dave is a

leading carbon-tech engineering researcher, with a track record of transitioning technologies from the lab to industry through entrepreneurship. The team combines this leadership with an innovative early-career engineering team. The team is mission-oriented and methodologically-agnostic – a powerful combination and one that is rare among companies emerging from academia. We have a “design for scale” ethos that balances lab performance with the pragmatic engineering trade-offs like taking advantage of off the shelf components where possible and dividing our work into scaling and research tracks to learn quickly from field testing while continuing to invest in research to refine the performance of our technology.

Based on these differentiating factors, our technoeconomic analysis shows that our design will deliver <\$100/tCO_2 for our NOAK plant assuming renewable electricity costs of <\$32/MWh, which is well within the ranges already being achieved for scaled wind and solar developments. Achieving >0.5 Gt/yr for our modular design is limited by our ability to rapidly mature and scale the manufacturing of additional units and secure the needed renewable energy supply.

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

E-quester’s mission is to power the permanent removal of +1 gigaton of CO_2 from the environment by 2050.

Through our work in the lab, we have captured at the kg-scale to date. We are currently building our first 1t / yr test unit that is on schedule for July. This 1t unit will be followed by an integrated unit with a capacity of 10t that we will start testing in fall 2024. We have high confidence in these milestones as our lab has previously built larger scale electrochemical stacks for CO_2 utilization, so we are repurposing both the know-how and infrastructure for our CO_2 capture purposes. Our current operations have capacity – the electrolyzer stacks, power supplies and all balance of plant ready – for 100t/yr.

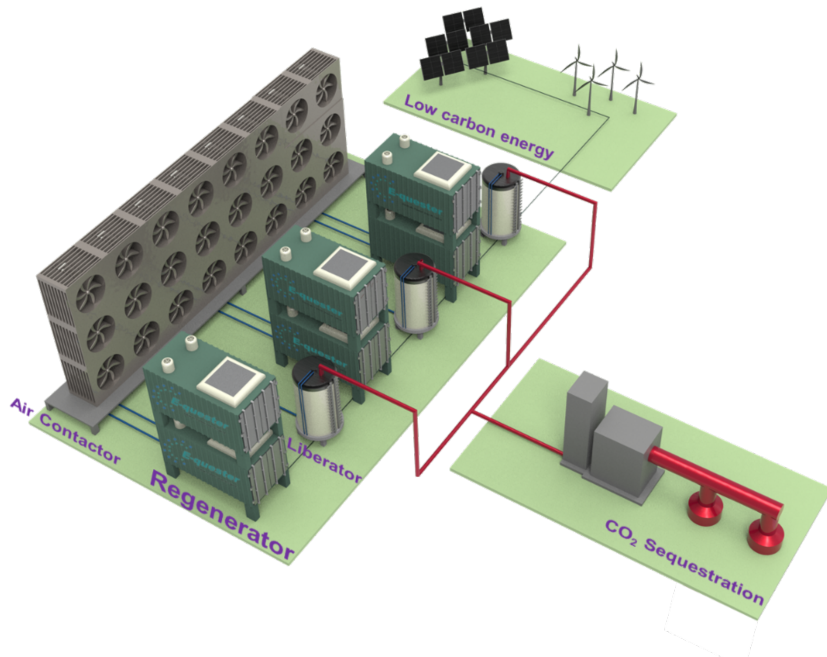
Starting in 2025 we will begin operation of our Calgary field pilot. Phase 1 of the pilot will come online in Q3, 2025 at a nameplate capacity of 100 t/yr. We will follow with our Phase 2 unit that will have a nameplate capacity of 1000 t/yr in Q3, 2027. This timeline enables us to operate the Phase 1 unit long enough to gather the insights needed before finalizing the improvements for the second-generation unit.

While our 100t pilot will go live in 2025, we know that it will not operate at full capacity as we work through common first-of-kind scaling challenges. We estimate that our cumulative net CO_2 captured surpass 200t in 2026, and 700 tons in 2027. (Credit to Climeworks for sharing their learnings from Orca)

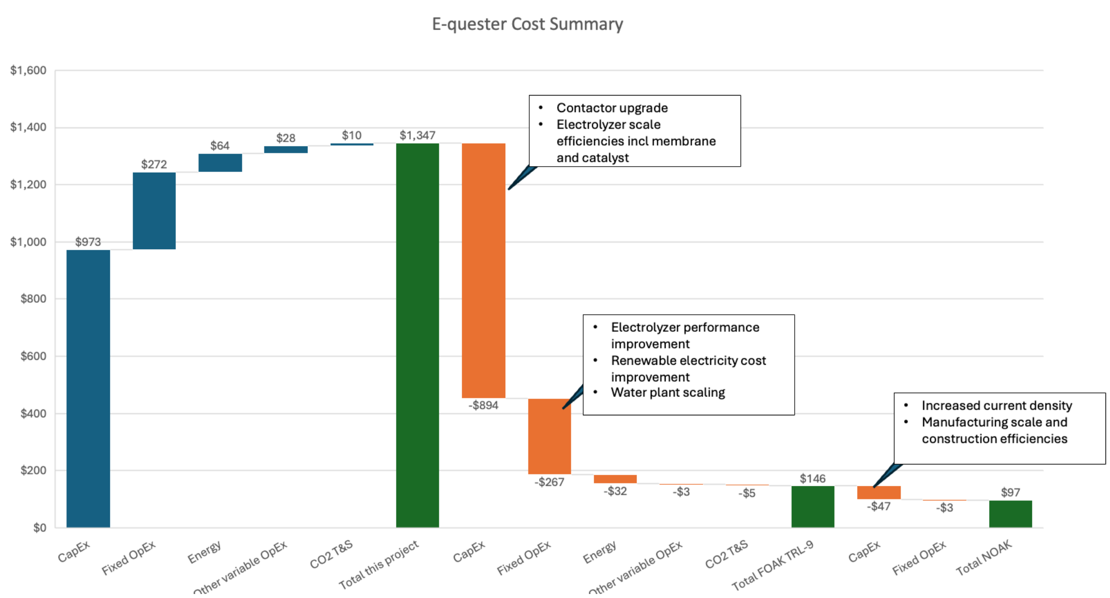
Our pilot site will be a shared site being developed by the CCS Knowledge Centre and will be announced later in 2024. The site will include MRV and sequestration in an existing well and an umbrella operating agreement which will enable us to seamlessly plug into the infrastructure at the shared site.

Below is a diagram outlining our future carbon capture and removal industrial scale plant:

[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.



Below is a breakdown of the costs of our system from the Frontier TEA and how they are expected to evolve as we progress towards our NOAK plant.



Next steps to achieve Frontier's cost and scale criteria:

1. **Iterative component optimization** – per our introduction, we focus on the components of our system that have the greatest potential for reducing the cost/tCO_2 captured. With each win we assess the overall process anew. We are currently optimizing the air contactor and

electrolyzer performance and will continue to aggressively push the boundaries of science using the latest research and tools at each step of our scaling journey as we identify, address, and implement each improvement (e.g., membrane crossover or durability)

2. **Plant design optimization** – scaling from 100t→1000t→1Mt we expect our team and partners to constantly improve the plant design to optimize the impact of the system across our cost, environmental, and social metrics
3. **Scaled manufacturing** – to achieve Gt scale at <$100t will require the new components of our system to progress down the cost curve to "giga-scale". Most importantly, millions of electrolyzers will need to be produced per year and follow a path like other giga-scale manufactured products such as car batteries.
4. **Renewable energy cost and scaling** – a critical assumption to Gt scale DAC is the parallel development and scale-up of continuous, low-cost renewable electricity. Solar with storage is currently the most promising but we expect that there will be numerous sources including wind, nuclear, solar, and potentially fusion coming together to provide this energy between now and 2050.

To quantify the carbon removed, we will work with both the MRV and sequestration partners from our pilot site. We will provide an uncompressed stream of captured CO_2 to the sequestration line for compression to supercritical and injection. The MRV process begins with the use of a mass flow meter to track the volume of CO_2 at the outlet of our system. This will be coupled with NDIR sensors to continuously monitor the purity of the CO_2 stream. We will also engage in periodic sampling and lab analysis of the CO_2 stream to ensure purity and ongoing monitoring of the integrity of the wells.

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

As with all startups, we experience inherent risk and uncertainty, however, we are actively working to mitigate these. Our greatest areas of uncertainty are:

1. Maintaining performance as we scale the system from the lab to 24/7, real-world conditions
2. Cost and availability of component materials (catalyst, membrane, pumps), which have limited suppliers globally
3. Longevity of electrolyzer components – the components of our electrolyzers have operated for 1000s of hours under a wide range of conditions in other uses cases such as salt-water electrolysis and fuel cells, however the same level of reliability needs to be developed for the CO_2 direct air capture use case.
4. Securing pilot project funding – we have ongoing discussions with several publicly funded organizations to fund our first pilot, most require some level of private funding to match complement their funds

Approach to de-risking the identified barriers:

1. **Levering our current pilot facility**. Having scaled CO_2 electrocatalysis previously to the largest such electrolyzer in the world (40,000 cm^2), we are adapting this pilot plant to electrochemical CO_2 capture. With this advantage – unique among research groups worldwide – we will save much of the time and financial cost of the pilot step (estimated savings of 3 years, $5M).
2. **Mitigating the scale-up process risk**: The foundation of our direct air capture technology is built upon well-established electrochemical principles, allowing us to leverage industry expertise in enhancing our system design. Here we draw on our scaling experience, translating electrolyzer tech from bench-to-pilot. This comprehensive approach involves iterative testing, modeling, and validation at intermediary scales to minimize uncertainties.
3. **Mitigating the supply chain risk:** We are proactively developing strategies in the laboratory to address the supply chain risk associated with the specialized catalyst and membrane materials. We are exploring the use of more widely available and economical alternatives to these materials. Additionally, these risks will be mitigated over time as the electrolyzer and

fuel cell supply chains and markets mature, as many of the components are similar. Fortunately, the remaining components in the air contactor and CO_2 liberator tank rely on common materials such as steel and PVC piping that are readily available.

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)*	Net volume: 15,500 Uncertainty discount: 5% Proposed CDR: 14,700
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q1, 2026-Q4, 2028
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	$1,347 / tCO_2
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	$1,600 / tCO_2 for 300 tons. This price covers the levelized cost of the CO_2 captured and sequestered by our pilot units plus a 20% margin to support further development of E-quester's technology and corporate capabilities

[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).