Frontier

Arbon

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

Arbon

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

New York

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

Xiaoyang Shi

Brief company or organization description <20 words

Arbon has developed a reusable material to capture CO_2 from air in a dry condition, and releases CO_2 when wet.

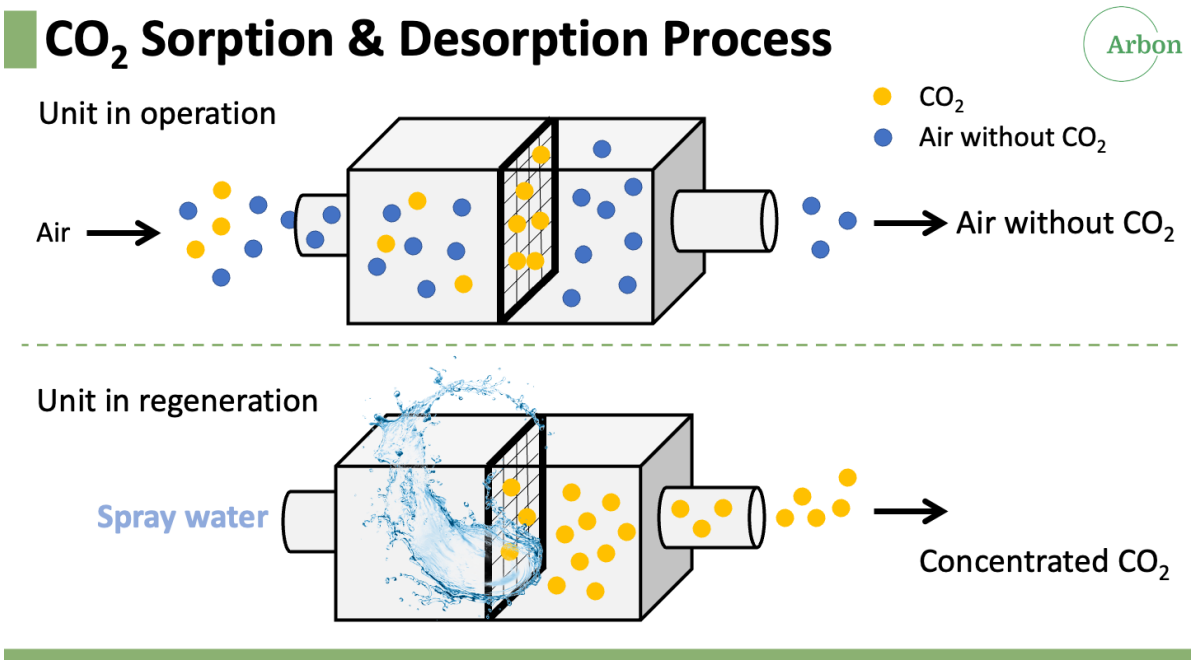
1. Public summary of proposed project[1] to Frontier

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

[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.

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. Aim for 1000-1500 words.

Our company Arbon (www.arboncapture.com) has developed a reusable material to capture CO_2 directly from the air in a dry condition, and releases CO_2 when wet. The released high concentration of CO_2 can be utilized and stored permanently. Arbon's core technology on moisture swing adsorption only uses water in the whole process. Our sorbent has exhibited remarkable stability and does not degrade after 10,000 cycles. It has a high energy efficiency without consuming heat during regeneration, which is considered the most significant bottleneck for the high energy cost of traditional direct air capture technologies.



Arbon's innovative sorbent technology can capture CO_2 directly from the ambient air, building off ten years of laboratory breakthroughs led by our co-founder at Columbia University, as validated in peer-reviewed publications in top energy journals, such as Angewandte Chemie International Edition 2020 59 (18), 6984-7006; Angewandte Chemie 2016 128 (12), 4094-4097; and Joule 2020 4 (8), 1823-1837. These findings have been featured on the homepages of Columbia Engineering and Arizona State University.

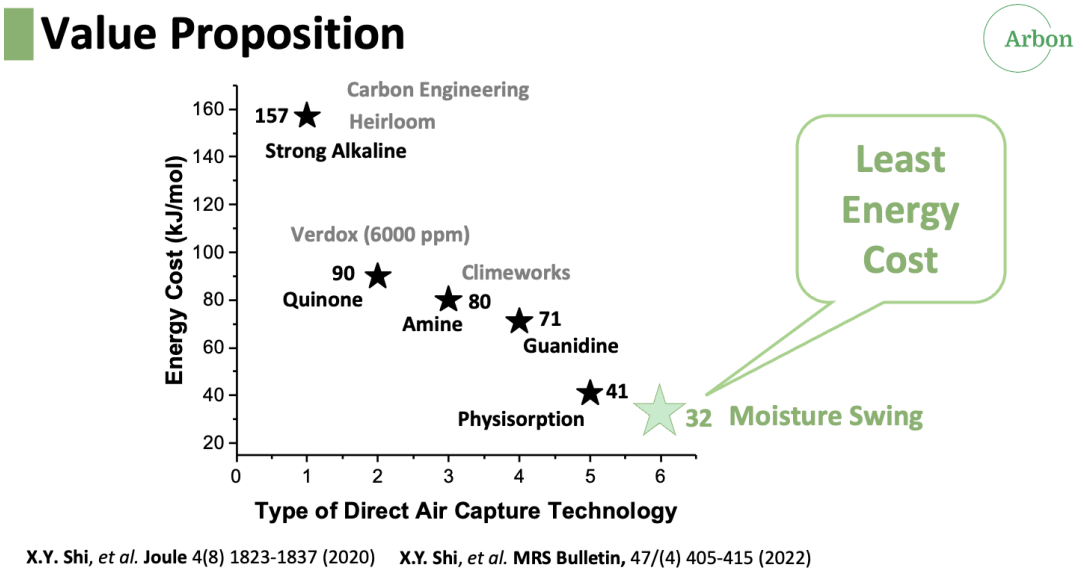
Arbon's moisture swing CO_2 sorbent exhibits disruptive leading technology advantages:

1) high selectivity (it only captures CO_2, not H_2O from the air);

2) high stability (it can capture and run 10,000 cycles without degradation);

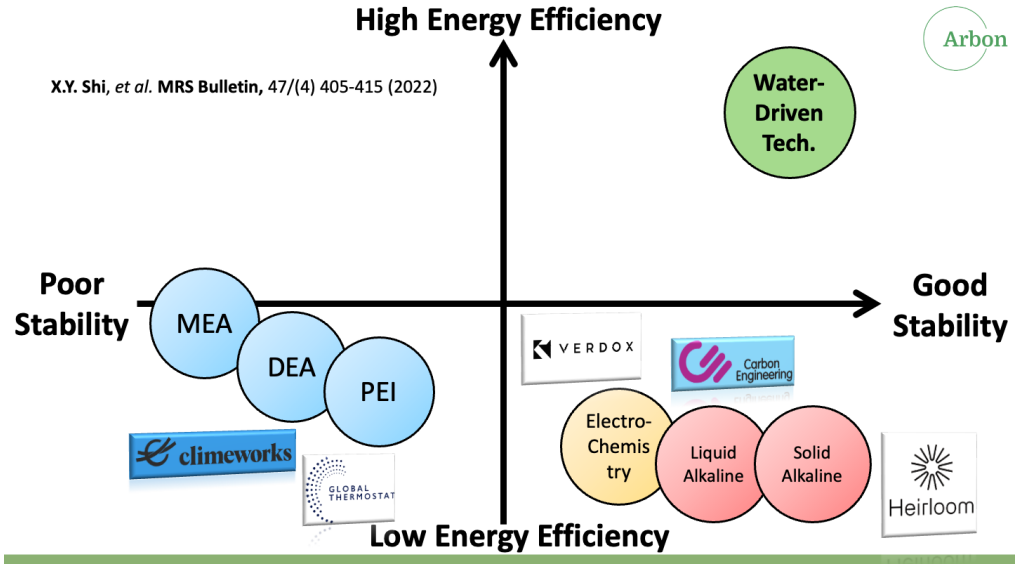
3) low energy cost (1/3 energy cost compared to traditional amine, and 1/6 compared to strong alkaline. For example, the Ca-based calcination process and Na-based decomposition and hydrolysis

process require the heat of adsorption of 179 kJ/mol of CO_2 and 135 kJ/mol of CO_2, respectively. The average value of reported heat of sorption of amine-based sorbents was estimated at around 80 kJ/mol to 120 kJ/mol of CO_2 based on the average value of reported heat of sorption of CO_2 by amine solution. The heat of sorption of IER has been reported with a low value of 32 kJ/mol of CO_2 compared with other sorbents.);



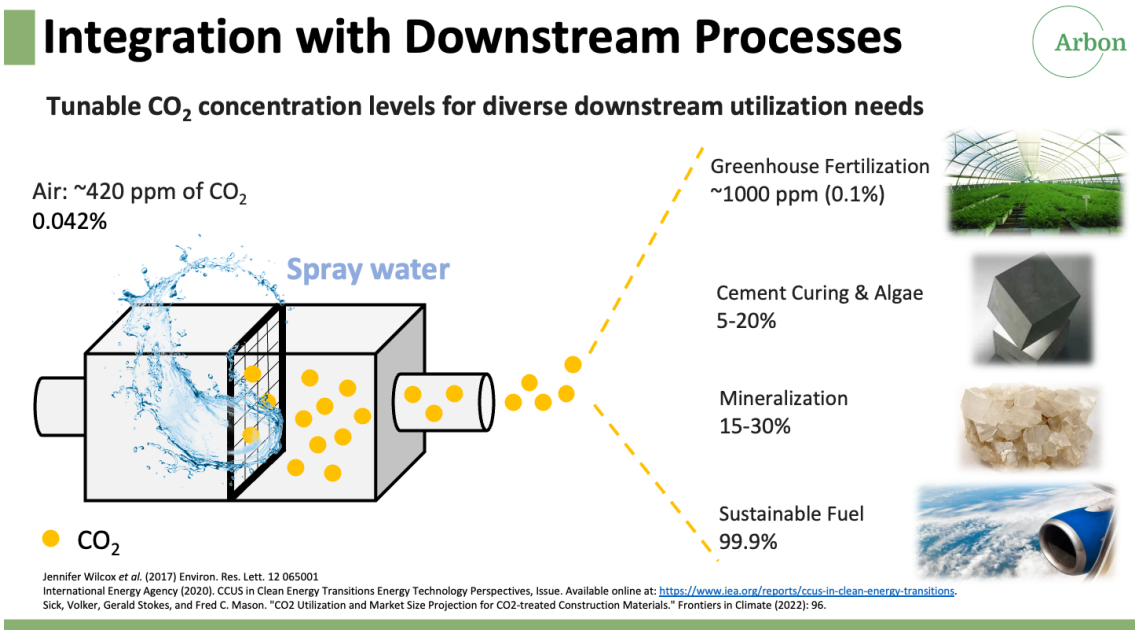
4) low cost (moisture swing CO_2 sorbent only costs water but not heat; the design is simple; the material is stable; the cost can reduce significantly with the massive production of module devices);

5) Fast kinetics (per gram of the sorbent per hour can capture 0.54 mmol of CO_2).



Our co-founder, Dr. Xiaoyang Shi, won Corning Advanced Materials Prize in 2022 based on the new technology of oxide materials (https://labtomarket.columbia.edu/news/dr-xiaoyang-shi-wins-2022-columbia-corning-advanced-materials-prize-50000), which has aroused interests of many Venture Capitals. Arbon has been selected as Activate Fellow in 2023, and a finalist of Breakthrough Energy Fellow.

Our technology has high energy efficiency and stability because we consume water for regeneration instead of heat. Meanwhile, we also plan to integrate the integrated carbon capture and utilization landscape at Arbon. With the input of air, which consists of 420 ppm CO_2, we can have tunable CO_2 concentrations as our output for diverse utilization avenues. Cement curing will be Arbon's first target to store CO_2 permanently.



References:

[1] Arbon's website: https://www.arboncapture.com/

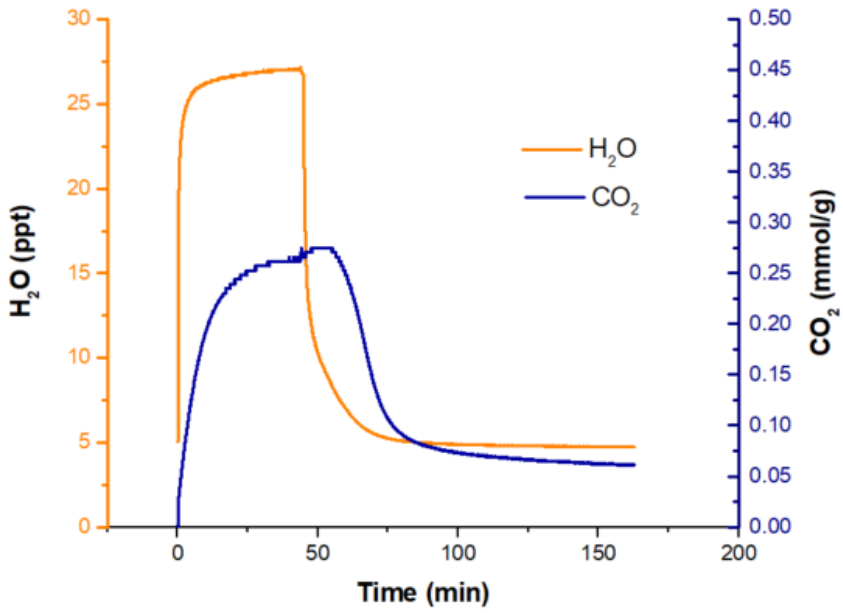
[2] Shi X, Xiao H, Kanamori K, Yonezu A, Lackner KS, Chen X. (2020). Moisture-driven CO2 sorbents. Joule. 4(8), pp. 1823-1837. https://doi.org/10.1016/j.joule.2020.07.005

[3] Shi X, Xiao H, Azarabadi H, Song J, Wu X, Chen X, Lackner KS. (2020). Sorbents for direct capture of CO2 from ambient air. Angewandte Chemie. 59(18), pp. 6984-7006. https://doi.org/10.1002/anie.201906756

[4] Shi X, Xiao H, Lackner KS, Chen X. (2016). Capture CO2 from ambient air using nanoconfined ion hydration. Angewandte Chemie. 55(12): pp. 4026-4029. https://doi.org/10.1002/anie.201507846

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.

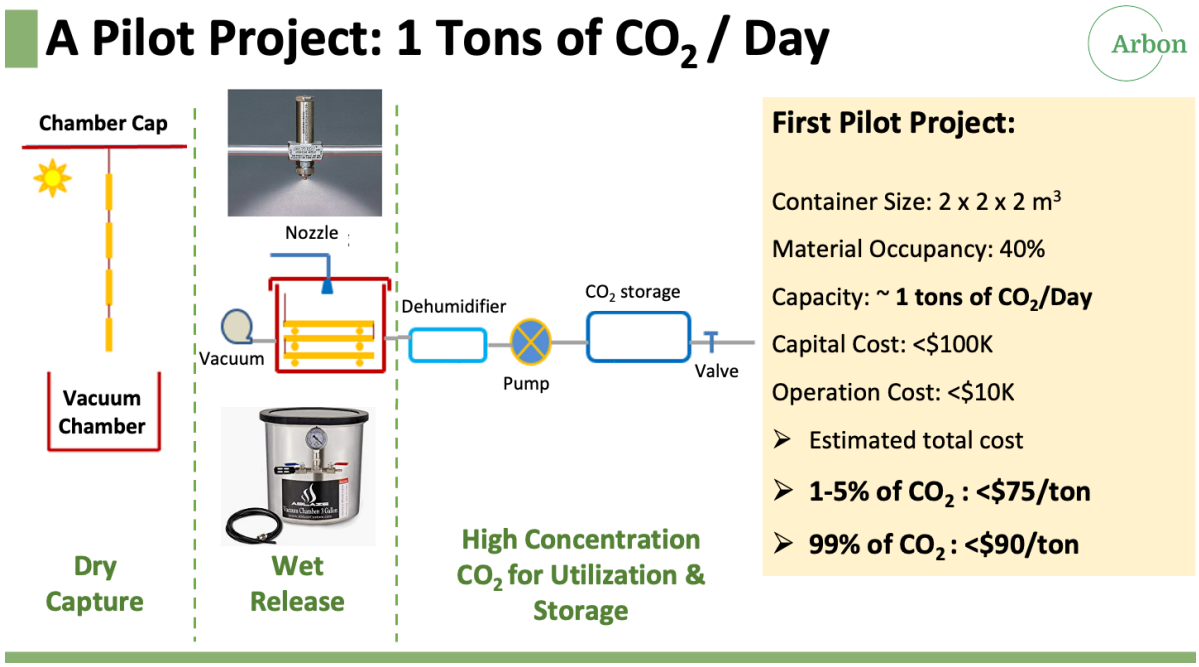
Based on the uptake rate(0.54 mmol of CO_2 per gram and per hr) and density (2600 kg/m^3) of our sorbent material, 1 ton of sorbent can capture 0.3 tons of CO_2 per day. One ton of sorbent needs a total 1.89 cubic meter container if we assume the occupancy of the sorbent is 20% of 1.89 cubic meters.



Arbon's 1-year vision is to build up multiple pilots for CO_2 capture. Each pilot can capture 1 ton of CO_2 per day. Frontier and other companies can buy carbon credits from our captured CO_2. By the end of the 8th month of the project, we plan to build our first pilot. And depending on funding sources, we plan to develop more pilots in the following 4 months. We plan to build up the 1st pilot in New York and sell our 1st ton of CO_2 in 2024.

Total CO_2 emission from human beings is around 40 GtC of CO_2 per year. If we use our device to capture 1 ton of CO_2 per day, then we need 100 million of the device to capture all CO_2 emitted by humans to achieve a carbon-neutral world. If we plan to spend 28 years to 2050 to achieve this goal, we need to produce around 3 million devices annually. If we target 0.5 GtC of CO_2 per year, we need produce 40,000 devices per year.

Even 3 million devices can be produced and processed by human beings. Shanghai Harbor processes 43 million full containers per year, and car and truck production is around 80 million per year.



Our estimated capital cost is around $60/ton of CO_2. Operating cost is around $16/ton of CO_2

Capital cost includes: 1. Container $8000; 2 Sorbent Materials (per ton) $500; 3 Air blower $1000; 4. Vacuum $1000; 5. Humidity Sensor $1000; 6. CO_2 sensor $2000. The detailed cost can be found in the TEA spread sheet.

Our captured CO_2 can be easily measured by Infrared Gas Analyzer in the vacuum tank, also can be quantified by the amount of cured cement.

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.

One of the potential barriers we could face is whether we could directly translate our learnings from academic lab tests to upscaled productions. To that end, the pilot test is a crucial step, and that poses some economic challenges in building these pilots. We consider the initial $100K non-dilutive funding we were awarded from Activate fellowship to be an excellent opportunity to help us de-risk and receive mentorship along the scale-up process. Meanwhile, we are building a more robust and diverse team which is crucial for the future success of our business. We were recently also awarded a $349,779 grant from the Carbontech Development Initiative (CDI) funded by the New York State Energy Research and Development Authority (official news to be

announced in July 2023). Our proposal ranked 1st in all proposals in the Bridge Carbontech track. The CDI funding and connections will help us significantly in the upscaling process.

The stability test will be undergone and continued for years. The moisture-swing sorbent is stable without degradation because the regeneration process doesn't need heat. Only water can drive the chemical reaction. Even though moisture-swing sorbent has outstanding durability, we will look for more robust, low-cost materials for more extended stability.

The cost of the moisture-swing sorbent is lower than other technologies because it has high stability and consumes only water instead of more expensive heat. We will enhance the capacity of moisture-swing sorbent to reduce its cost further. The kinetics of moisture-swing sorbent is also excellent because we are utilizing a porous solid structure that is conducive to gas diffusion compared to liquid-like or gel-like sorbents. We will reduce the particle size and discover new synthesis and assembly technologies to improve the kinetics of CO_2 sorption further.

Risk Identification and Mitigation

Arbon

Technical Risks

Risk	Mitigation
Emergence of new sorbent technologies & Improvement of existing sorbent	Optimize and design the next generation of our moisture swing sorbents
Stability of water supply	Work with multiple water suppliers in industry
Raw materials for sorbent synthesis	Look for multiple sources to provide raw materials in addition to Corning Inc.
Fluctuations of climate conditions	Design devices for the protection of sorbent material, and develop new material resistant to environmental change

Commercialization or CO_2 Reduction Risks

Risk	Mitigation
Regulatory/Policy Risk: The temporary end to government subsidies for carbon dioxide capture technology	Global warming is getting more and more serious and is gaining more and more attention from the whole society. We believe the policy will be more supportive of the technology of CO_2 capture, and the carbon liquidity in the market will increase significantly.
Market Risk: Companies who need to pay carbon tax now will not be required to pay in the future.	
Risk of Supply Chain: The delay of the raw materials for sorbent preparation and CO_2 capture equipment assembly.	At the initial stage of our company, we will use mature and low-cost materials to derisk the supply chain issue of raw materials.

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)*	2777 ton
Delivery window	3 years

(at what point should Frontier consider your contract complete? Should match 2f)	
Levelized Price ($/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	$180/ton, based on the IRA policy.

** 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).*