Anvil Capture Systems LLC

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

Anvil Capture Systems LLC ("Anvil")

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

Anvil is headquartered in New York, with team members in Brooklyn, NY; San Diego, CA; Phoenix, AZ; Las Vegas, NV; and Livermore, CA.

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

James Lawler

Brief company or organization description <20 words

Anvil processes alkaline earth mineral-bearing ore to capture CO2 from the atmosphere in large-scale, low-energy reactors.

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,

[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.

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

Anvil's Direct Air Mineralization process uses a low-cost, low-emissions processing method to optimize alkaline mineral-bearing ore reactivity and increase the ease of material handling. This processing is paired with proprietary, specially-designed, ambient temperature, pressure, and CO_2-concentration reactorsto create ideal conditions for the mineralization reaction.

Our process features measurement-based MRV methodology (supported by high fidelity modeling), low energy usage, and due to the closed nature of our system, negligible impacts on human, agricultural, or natural ecosystems. We have proven our process in the lab on the scale of kilograms of CO_2 removed, and are now optimizing scaling design parameters for our Initial Pilot. Near-term commercial deployments will be sited at existing quarries.

Anvil offers multiple advantages compared to existing Direct Air Capture and Storage (DACS) and / or Enhanced Rock Weathering (ERW) technologies:

1) Cost & economics: Anvil uses a low-cost and readily available feedstock; extraction and feedstock preparation tools that are already deployed at the gigaton scale in the mining industry; a mineralization reaction that occurs quickly under atmospheric temperature, pressure, and CO_2 concentrations without the use of chemicals; and low-cost reactors.

Furthermore, because we take advantage of large-scale, local deposits of feedstock, our process will permit Anvil to be profitable from its first commercial deployment, which will help us attract investment and reach >.5Gt/yr scale quickly, in contrast to other processes which require significant scale to provide a market return. Based on industry-standard engineering handbooks, vendor quotes, and industry studies, we believe we have a clear path to capturing CO2 for <$100/ton.

2) Strong MRV: As CO_2 is thermodynamically stable as solid carbonates at the Earth's surface, its storage is permanent at geologic timescales (i.e., well in excess of 1,000 years). Our storage of mineralized feedstock in engineered disposal sites further ensures that the material is geographically isolated, traceable, and accountable. Post-capture storage requirements are minimal, and well-characterized by existing permitting regimes in the mining industry.

3) Footprint: Our process, inclusive of mining and processing, will use 4-6 ft^2/tCO2-y, or 144–215 square miles per gigaton/y of removal (373-557 square kilometers), with mining operations accounting for 80-90%. Initial deployments will be at or adjacent to quarries in the USA, in locations where permitting concerns have already been addressed, and not near agricultural lands. Because our process is a closed system approach, and does not interact with natural ecosystems, like oceans or streams, or agricultural systems, our path to initial deployment is straightforward, with low risk of later discovery of negative externalities, and no unprecedented permitting issues to overcome to reach gigaton scale.

4) Energy: DACS technologies are, due to the thermodynamics of separation, inherently energy-intensive and will increasingly compete with other uses for green electrons. In contrast to gas separation, the mineralization reaction occurring in Anvil's system is exothermic and spontaneous; in other words, the rocks themselves provide the chemical energy to drive the process. The energy footprint of Anvil's process is associated with accelerating this thermodynamically downhill process.Our process energy requirements are lower than any possible DAC reactor. We estimate Anvil's process will require <500 kWh/tCO2 at FOAK and NOAK deployment.

5) Human & natural ecosystem interactions: Anvil's capture and storage system is segregated from the environment with control of the material at every stage, from feedstock preparation through long-term storage of solid carbonates. This differentiates us from ERW or OAE solutions which will struggle not only to prove the CO2 removal of their methods, but also that their widescale ecosystem intervention has not induced changes to extant carbon stocks or fluxes that counteract their intended CDR. Our process generates negligible emissions (primarily particulate matter) which is controlled via standard environmental engineering controls (i.e., closed comminution circuits with water-based dust suppression), uses no chemicals, and spent feedstock (i.e., inert rock material) may be safely stored at the quarry site following known and already-permitted methods.

7) Versatility: Our process may be used with a variety of mineral feedstocks in later stages of deployment, which we plan to evaluate. Expansion from high grade ores to lower grade ores is how the development of essentially every mining commodity has occurred historically. Expanding feedstocks to other minerals may enable additional integrations with host quarries and mines, and other deployment sites.

Finally, our process addresses the following priority innovation areas described in the RFP:

1. **Leveraging existing industrial assets to scale CDR quickly and at lower cost**: Anvil will site its initial deployments at active quarries and mines. Business model integration potential, the use of additional feedstocks present at the site, and other points of integration are expanded upon in the sections below.

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

What are you trying to build?
Anvil is currently planning our Initial Pilot deployment, capable of 1,931 t/y net CDR at one of several possible active quarries throughout the United States

Current cost breakdown:
Modeled costs of Anvil's Initial Pilot process are as follows.
[All $/t net CDR]
Feedstock preparation: $80
Reactor: $110
Balance of Anvil System: $369
For commercial reasons, we are excluding certain inputs from the public section of this application.

[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."

To reach <$100/ton net CDR and >.5Gt net CDR/yr:
Achieving less than $100/t will require larger-scale deployments at or near sites with sufficient feedstock. At 1Mt/y net CDR at a single location, we expect the following cost breakdown, based on reported mining industry data and Anvil's own cost estimates:

[All $/t net CDR]
Extraction: $16
Comminution: $15
Feedstock preparation: $12
Reactor: $12
Balance of System: $4
Total: $59

High-level assumptions: 30-year life, $/t calculated by simple sum of CAPEX + OPEX over useful life divided by net tons of CDR, extraction and comminution costs based on SME Mining Engineering Handbook and HATCH consulting publications, and the balance based on vendor estimates.

To reach >.5Gt/y CDR for <$100/t, Anvil's process will need to be sited at or near locations with significant feedstock deposits. Making certain reactivity assumptions consistent with our testing and known deposit characteristics, 0.5 Gt/y CDR would require ~1.8 Gt/y of source rock.

Approach to quantifying CO2 removed:
Anvil's measurement-based MRV approach provides a high level of certainty to the market with respect to the tonnage of CO_2 we report from our projects. Anvil is currently optimizing this methodology using our Feedstock Test Reactor.

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

We perceive the following risks for our Initial Pilot project, and later stage systems as indicated:

Technical: (1) The physical behavior of feedstock in our reactors is challenging to simulate in the lab. We are conducting a variety of software-based and physical tests with our bulk solids engineering firm partner, who brings decades of experience in designing systems in the mining and agricultural industries that involve the flow of bulk solids through various physical and chemical conditions. (2) Feedstock purity will vary from site to site. We are currently building a scaled-down version of our reactor system that will allow us to test feedstock performance, both with respect to CO_2-reactivity and physical properties, in advance of any on-site system builds. (3) Energy requirements are purely modeled but, similar to feedstock behavior, they are difficult to simulate in the lab.

Project Execution: (1) Our initial deployments depend on integrations with active quarries and mines. While Anvil's proposition is revenue-generating for our mining partners, it requires these partners, who have limited bandwidth for non-core operations, to work with us on siting our process, providing a feedstock that is currently a waste product (or to expand their extraction of existing rocks suitable for CDR), and adjusting their operations to accommodate an on-site customer.

Ecosystem: Anvil's process is an entirely closed system in which all CO_2 capture and storage is handled by Anvil. As the mineralization reaction is stable under atmospheric conditions, we expect negligible ecosystem risks. Dissolution and transport of reacted carbonates away from the storage site is also prevented by the lined and covered pits used for storage—this is common practice for mining operations in developed countries. **Financial:** Anvil's NOAK TEA has been calculated assuming industry-standard costs for surface mining; reactor estimates are based on similarly complex industrial equipment, adjusted for our process. Anvil's NOAK TEA assumes only a minor change to the energy mix, an electrically-powered comminution circuit, while the extraction process remains diesel-powered. Actual costs of the pilot and NOAK processes could be more expensive than modeled. **Other**: There is a risk of insufficient market demand for high-quality CDR. Anvil is mitigating this risk in 3 ways: 1) While this risk is present for all CDR companies, we believe that we are focused on a process that has the best shot at overcoming this risk, due to our robust MRV process, abundant feedstock, attractive economics at NOAK scale, and negligible impact on natural and agricultural ecosystems. To the extent that there is a market for CDR, it will favor technologies that can satisfy the most stringent MRV requirements, and lowest negative externalities. 2) Anvil believes its process will be useful for small emitters, companies waiting for Class VI storage to become available, and biogenic CO_2streams from biomass. 3) Anvil plans to work with CDR industry groups to advocate for policy that will create additional pathways to monetize CDR, beyond payments for tonnage captured and stored.

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)*	First 357 tons from Initial Pilot reactor deployment
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q1 2026
Levelized cost (\$/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	\$1,180/ton CO_2
Levelized price (\$/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	\$1,400/ton CO_2

[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).