Emissol LLC

Carbon Dioxide Removal Purchase Application

Fall 2022

General Application - Prepurchase

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

Company or organization name

Emissol LLC

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

Mill Creek, WA, USA

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

Ali Bahmanpour, Mansour Masoudi, Ed Tegeler

Brief company or organization description

Emissol exclusively focuses on reducing harmful emissions including CO_2. Our DAC contactor reduces DAC cost by at least 50% [1].

[1] DOE Announces $127 Million For Small Business Research And Development Grants | Department of Energy

1. Project Overview[1]

a. Describe how the proposed technology removes CO_2 from the atmosphere, including as many details as possible. Discuss location(s) and scale. Please include figures and system schematics. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar technology.

TECHNOLOGY.

(a) Background. In this project, the focus is on CO2 removal from air using a capture-and-sequester model. CO2 capture will be performed by Emissol and sequestration by our partner, Carbfix, through their unique and well-documented approach [1-3]. The value proposition is largely based on a novel

[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.

contactor design and optimized operating cycle (process) for using such contactor which, together, results in significant cost reduction in the DAC process. Our techno-economic analysis indicates this achieves a DAC cost reduction of at least 50% when compared to currently operating DAC systems [4].

(b) How It Works. Our innovative, patent-pending contactor, designed specifically for highly efficient DAC, incorporates proprietary spiral channels, replacing straight channels commonly used in mainstream contactors [5]. Generating a strong and stable secondary flow across a wide range of flow rates [6,7], it transforms diffusive CO2 transport with the much-stronger convective transport, accelerating CO2 mass transfer from the gas phase (contactor channels) to the solid sorbent phase (coated on the contactor walls), with concomitant shortening of the contactor length making available both sorbent saving and lower pressure drop. The performance of our contactor compared to a conventional straight channel contactor can be seen in Fig. 1 [8].

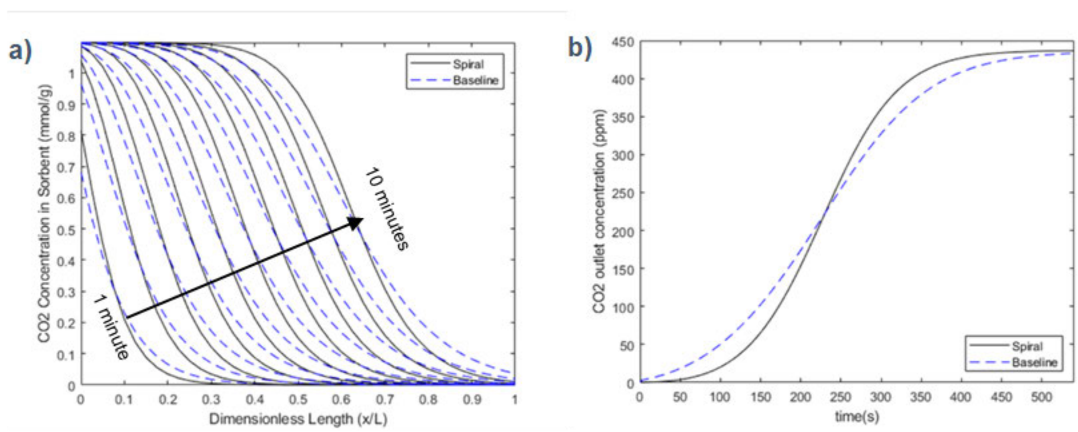


Figure 1. a) CO2 site coverage for straight and helical channels vs length at different times b) CO2 concentration at the channel outlet. Both a) and b) point to a 35% contactor surface area reduction, hence sorbent reduction (see next page), extendible to 50-80% when synergized with process optimization (ibid).

As shown in Figure 1, CO2 capture rate with our contactor having spiral channels outperforms that in the straight channels: It adsorbs more CO2 in the first half of the channel due to its advective secondary flow, allowing shortening the channels, and therefore needing less sorbent, to capture the same target CO2. Based on the techno-economic analysis done by the National Academy of Sciences, sorbent cost is often one of the most expensive components of the overall DAC cost [9]. Therefore, we can save on sorbent capital expenditure, enabling marked cost savings [10].

Experimental analyses of our prototype contactors have confirmed the validity of our model predictions. Figure 2 shows such validation through comparing CO2 concentration at the channel outlet between model and experimental data, for straight channel and our spiral-channel contactor prototype.

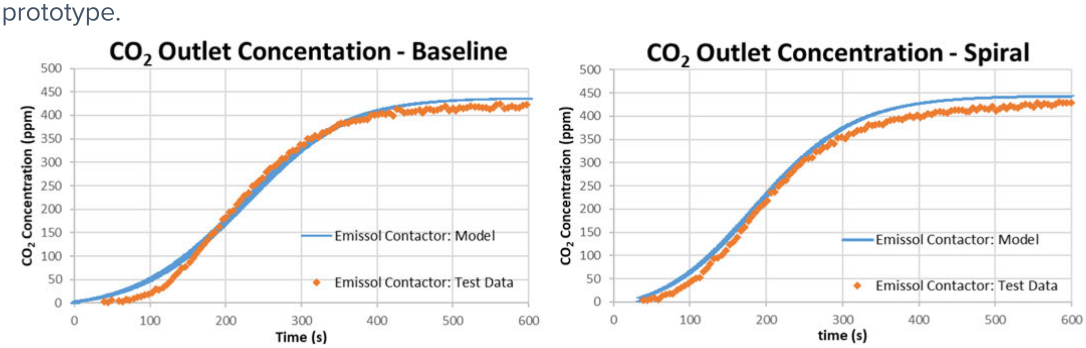


Figure 2. Comparing model and experimental data: (Left) Baseline (straight channel) vs. (Right) spiral channel contactor.

Expanding on geometry-based cost savings, we have next optimized our capture *process* (flow rate, channel hydraulic diameter, channel length, and sorbent layer thickness), while synergized with our novel contactor, to minimize the overall DAC cost. Relying on cost components in the techno-economic analysis by the National Academy of Sciences [9], various scenarios were studied via assigning different weight factors to each cost component [11], simulating multiple distributions of capital and operating expenses (see addendum for details). Using reliable data in the literature as the baseline case [5], our fully optimized contactor-process synergy yields significant DAC cost reduction, ranging from 50% to 80%, shown in Fig. 3 [4].

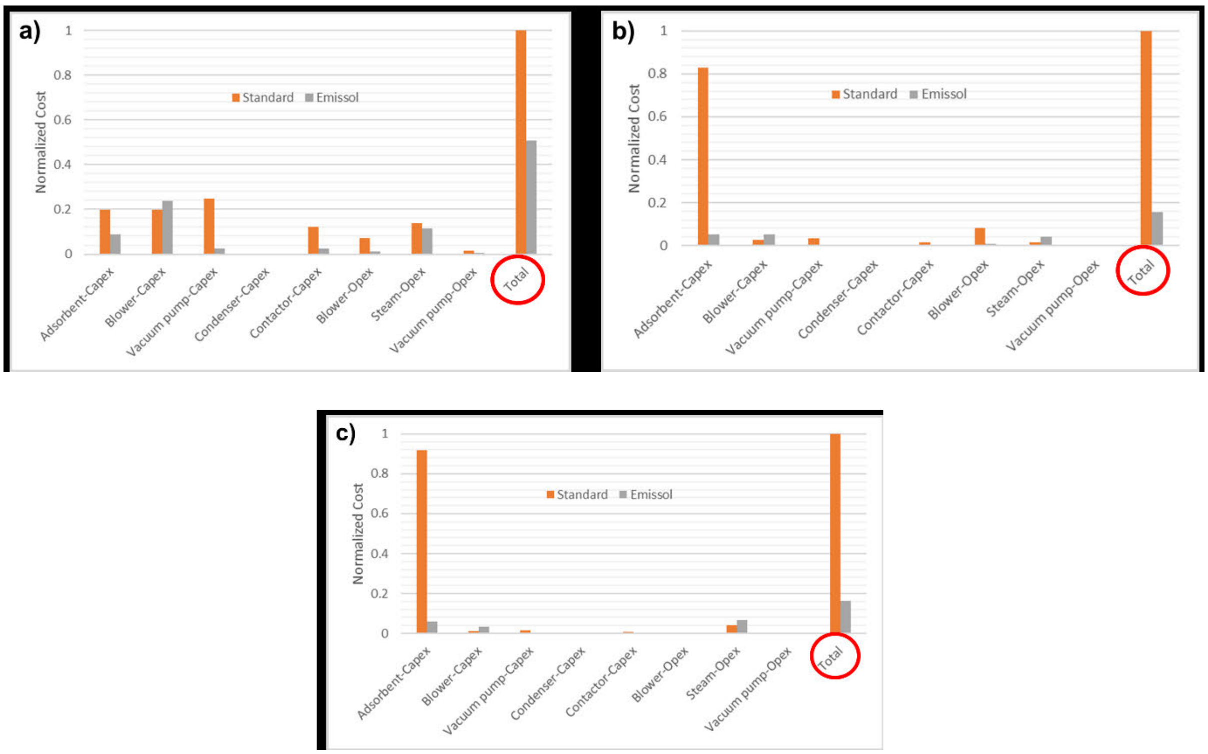


Figure 3. Comparison of (a) best case, (b) middle case, and (c) worst case cost scenarios [4]. 'Best', 'middle' and 'worst' cost scenarios are as prescribed in Ref. [9].

As in any DAC operation, sorbent forms a significant component of our overall system and its associated DAC cost. Emissol therefore maintains relationships with centers of competence on sorbent developments including Center for Negative Carbon Emissions (CNCE), Arizona State University, Research Triangle Institute (RTI) and several national labs (esp. ORNL, PNNL and NETL), amongst others, staying abreast of the latest developments in DAC sorbent technologies. Additionally, our team is working on developing two novel sorbents: one for high humidity and another for dry climates, to be used in conjunction with our contactor. The goal is to choose a sorbent most suitable to our application: One with highest durability, longer lifetime with low-to-reasonable cost [12] yielding most optimal cost saving for our DAC CapEx and OpEx.

MODEL FOR FRONTIER PRE-PURCHASE.

Our approach includes three stages:

-- In the first stage (target completion: Q2-2023, we will design and manufacture a fully functional DAC module, incorporating our very low pressure drop (5-10 Pa) proprietary contactor and low loading of sorbent (50% reduction compared to mainstream) capturing 5 kg CO2/day (1.5 tonnes/yr). A contractor has already been identified to manufacture this module (see Addendum). For this module, the sorbent is polypropylenimine (PPI), a highly durable amine-based sorbent [13] loaded on high-porosity alumina contactors as the support. This stage has already started and the module design and manufacturing is currently in its alpha phase.

-- In stage 2 (target completion: Q4,2023), we will build at least 6 of the same modules targeting 30 kg/day (10 tonnes/year) of CO2 capture. While the exact location is in discussions with Carbfix and is to be agreed upon, the modules will be installed either at the Carbfix facility in Reykjavik, Iceland or at a mutually agreed upon location in the US[2] where the captured CO2 will be permanently sequestered using their state-of-the-art sequestration technology.

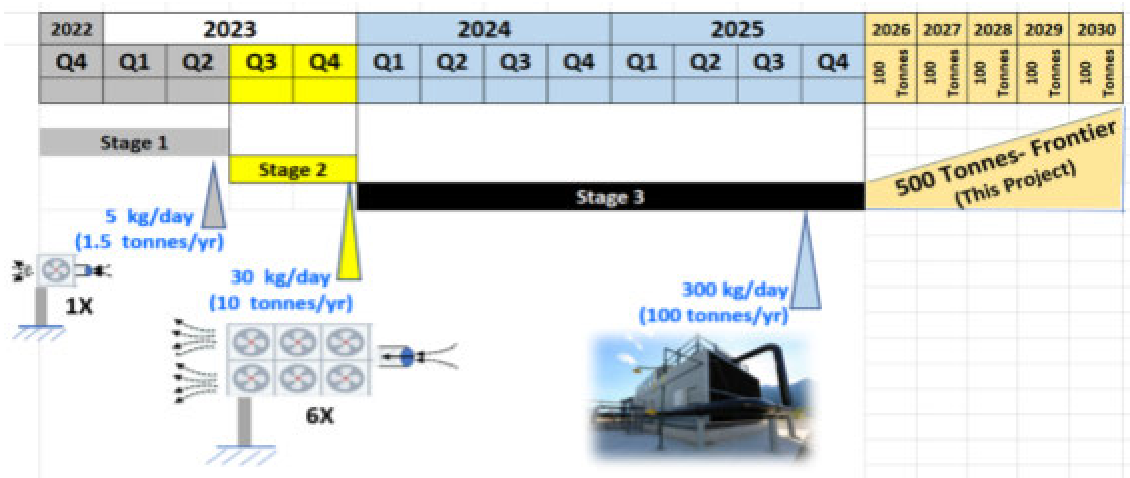


*Figure SEQ Figure * ARABIC 4. Gantt chart (timeline) for the 3 stages of scaling from 1.5 to 100 tonnes/year. (Stage 1 is already in progress.)*

-- In stage 3 (Q1,2024 toQ3/4,2025), we plan to expand the early-stage modular setup into a pilot plant with its capacity to capture and sequester 300 kg/day or ~ 100 tonnes/year. In a joint, three-party effort led by Emissol, B&V will implement the stage 3 scale-up while Carbfix will execute the sequestration once the plant is operational. This is the plant that will deliver Frontier's pre-purchased CO2 between 2026 and 2030.

These 3 stages are depicted in Figure 4. The lifetime of the plant built in stage 3 is estimated to be 15 years [14], with its first 5 years (2026-2030) dedicated to this Frontier project, delivering at a rate of 100 tonnes/year or a total of 500 tonnes by 2030.

Any additional capture capacity (in considerations), i.e. beyond that of delivery to Frontier, will be integrated into our commercialization strategy toward the 2050 goal.

[1] Snæbjörnsdóttir, S.Ó., Sigfússon, B., Marieni, C., Goldberg, D., Gislason, S.R. and Oelkers, E.H. (2020). "Carbon dioxide storage through mineral carbonation." Nature Reviews Earth & Environment, 1, 90-102.

[2] Sigfússon, B., Gíslason, S.R., Matter, J.M., Stute, M., Gunnlaugsson, E., Gunnarsson, I., et al. (2015). "Solving the carbon-dioxide buoyancy challenge: The design and field testing of a dissolved CO2 injection system." International Journal of Greenhouse Gas Control, 37, 213–219.

[2] Carbfix currently is in search of a suitable location to establish operations in the US. Once their US location is known, we will examine the locality of our capture plant in concert with Carbfix, upon which the exact location of our Stage-3 plant will be determined.

[3] Matter, J.M., Stute, M., Snæbjörnsdóttir, S.Ó., Oelkers, E.H., Gíslason, S.R., Aradóttir, E.S., et al. (2016). "Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions." Science, 352, 1312-1314.

[4] M. Masoudi, E. Tegeler, T. Colbert, A. Bahmanpour, V. Balakotaiah, "Optimized Techno Economics for Future DAC Plants, NETL Project Review Meeting," 2022, Pittsburgh, USA.

[5] A. Sinha, L.A. Darunte , C.W. Jones, M.J. Realff, and Y. Kawajiri, "Systems Design and Economic Analysis of Direct Air Capture of CO_2 through Temperature Vacuum Swing Adsorption Using MIL-101(Cr)-PEI-800 and mmen-Mg_2(dobpdc) MOF Adsorbents." Industrial & Engineering Chemistry Research 56, no. 3 (2017): 750 764.

[6] S. Berger, L. Talbot, LS. Yao, "Flow in Curved Pipes", Ann. Rev. Fluid Mech. 15. 461-512. (1983)

[7] Dean, W,R. "Fluid Motion in a Curved Channel." Proc. Roy. Soc. London, Series A. (1928).

[8] E. Tegeler, T. Colbert, M. Masoudi, A. Bahmanpour, "Novel and Efficient Contactor Design to Reduce the Cost of Direct Air Capture of CO_2," In preparation. To be submitted to Applied Energy.

[9] National Academies of Sciences, Engineering and Medicine, "Negative Emissions Technologies and Reliable Sequestration: A Research Agenda," The National Academies Press, Washington, DC, 2019. https://nap.nationalacademies.org/read/25259/chapter/1#v

[10] M. Fasihi, O. Efimova, C. Breyer. "Techno-Economic Assessment of CO2 Direct Air Capture Plants." J. Cleaner Production. 224 (2019). 957-980.

[11] Private Communication with Burk Technoeconomic consultant Mr. Chris Burk (2021-2022)

[12] Azarabadi, H., and Lackner, K.S., "A sorbent-focused techno-economic analysis of direct air capture". Applied Energy, 250, p. 959-975. (2019).

[13] S.H. Pang, L.C. Lee, M.A. Sakwa-Novak, R.P. Lively, C.W. Jones, "Design of Aminopolymer Structure to Enhance Performance and Stability of CO_2 Sorbents: Poly(propylenimine) vs Poly(ethylenimine)," Journal of the American Chemical Society, 2017, 139, 10, 3627–3630.

[14] C. Beuttler, L. Charles, J. Wurzbacher, (2019) "The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions". Front. Clim. 1:10. doi: 10.3389/fclim.2019.00010

b. What is the current technology readiness level (TRL)? Please include performance and stability data that you've already generated (including at what scale) to substantiate the status of your tech.

We have completed constructing a fully functional DAC predictive model [1] in a contactor built on first principles of convective-diffusive transport in channel scale and diffusive transport in sorbent pores, chemisorption kinetics and thermal regeneration. Model contactor prototypes have been constructed, coated, tested and their data has been compared with our model, displaying good agreement with model predictions (see Fig. 5). Our contactor technology is currently at TRL 4 as defined in the TEA spreadsheet.

Fig. 5A-E compares our experimental and modeling data on CO2 concentrations at the contactor outlet for Emissol novel contactors., consistently displaying satisfactory agreement between the two. Figure 5F shows a reliable reproducibility in our test results.

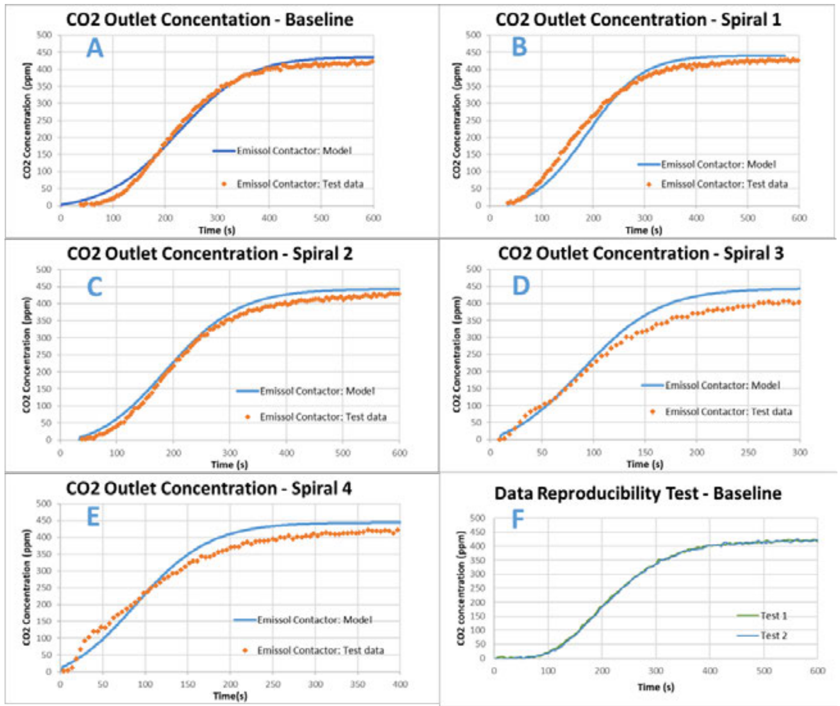


Figure 5. Reasonable-to-good agreement seen between our model and experimental data for CO2 concentration at the contactor outlet. 'A' is baseline (straight channel, conventional contactor); 'B' through 'E' are Emissol proprietary contactor utilizing spiral channels: 'F' displays reliable data reproducibility in our experiments.

Fig. 6 demonstrates our novel contactors and a sample sorbent (PEI) coating in the spiral channels of the contactors. X-ray images of internal coating thickness (Fig. 6E and F), display successful coating of the channels. It can be noted that the contactors are uniformly coated which requires a technique development due to the spiral shape of the channels. This was done with high precision to add durability to our contactors.

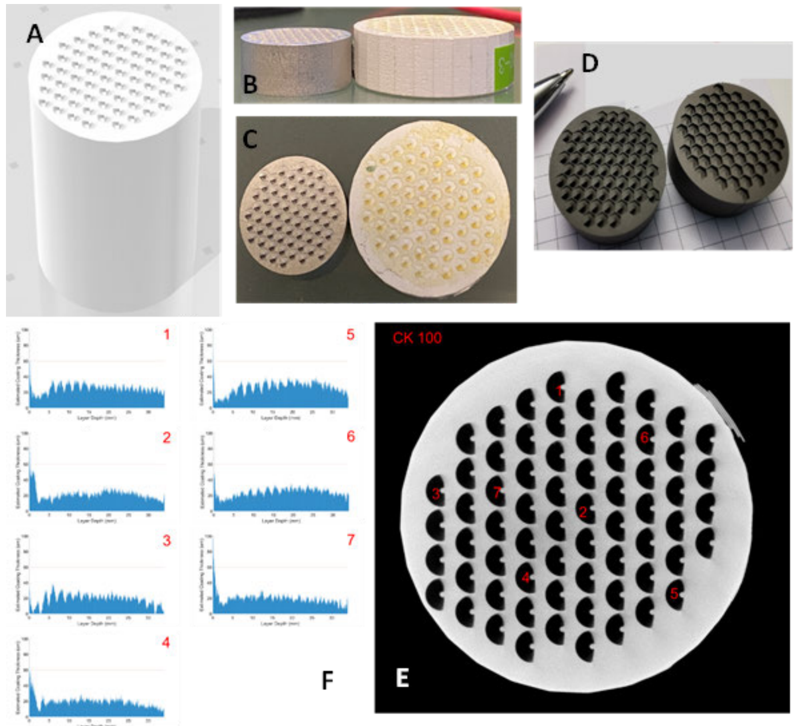


Figure 6. A-D: Sample prototypes of uncoated, Emissol proprietary DAC contactor. E: a coated sample (top view).
F1 to F7: X-ray CT images of the thickness of the sorbent coating in several (7) contactor channels, displaying successfully coating them reasonably 'uniformly' throughout (i.e., from channel inlet to channel exit).

Given our clear laboratory success in demonstrating our contactor technology and its potential for marked DAC cost reduction, we are now incorporating our contactor into a stand-alone, fully operational DAC unit for a full CO2 capture process, advancing it to TRL 5 by Q4-2022/Q1-2023. Our newly optimized contactor will be tested in the full unit in a field test to gain more data on adsorption-desorption process and on contactor-sorbent system durability.

[1] E. Tegeler, T. Colbert, M. Masoudi, A. Bahmanpour, "Novel and Efficient Contactor Design to Reduce the Cost of Direct Air Capture of CO_2," In preparation. To be submitted to Applied Energy.

c. What are the key performance parameters that differentiate your technology (e.g. energy intensity, reaction kinetics, cycle time, volume per X, quality of Y output)? What is your current measured value and what value are you assuming in your nth-of-a-kind (NOAK) TEA?

Key performance parameter	Current observed value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
Sorbent Cost	50% reduction (our contactor is sorbent-agnostic)	50-80% reduction	Novel designs are being tested which reduce the sorbent cost more than current design, based on our models
Pressure Drop	5-10 Pa	5-10 Pa	Pressure drop calculated for our contactor is in good agreement with

			our data
Vessel volume	15% reduction	15% reduction	The vessel volume reduces by 15% in our tests since less contactor volume is needed in our setups.

d. Who are the key people at your company who will be working on this? What experience do they have with relevant technology and project development? What skills do you not yet have on the team today that you are most urgently looking to recruit?

Key people: Our team includes an inner Emissol core and a large, extended network of DAC experts.

Dr. Ali Bahmanpour is a Chemical Engineer with strong background in material synthesis, catalyst/sorbent design, and process intensification. He has been working on CO2 adsorption/reaction and valorization through his PhD studies and post-PhD research. He has developed new processes for CO/CO2 valorization through hydrogenation to fuels and chemicals as well as novel sorbents for Direct Air Capture (provisional patents). His works on CO/CO2 hydrogenation reactions, H2 production, and process intensification has been published in prestigious journals with 970 citations and h-index of 19. He has contributed to research funds on CO2 mitigation and valorization for up to $300k in his roles as a researcher in Australia and Switzerland. He continues to serve as a reviewer for prestigious journals such as Nature Communications and ASC Catalysis.

Dr. Mansour Masoudi is experienced in heat and mass transfer enhancement. He has more than 20 years of academic and industrial R&D experience. The inventor of spiral-channel contactor delivering superior mass transfer making it ideal for low-cost carbon capture, his work in heterogenous reactions has resulted in 10 filed patents (issued or pending), two R&D-100 Award recognitions and ~800 citations. He is the co-Founder and Editor-In-Chief of the international journal Emission Control Science and Technology by Springer Nature, exceeding 43,000 annual downloads (2021). Together with Dr. Ali Bahmanpour, Dr Masoudi is further establishing a new, archival, peer-reviewed, authoritative journal in CCUS involving world's best CCUS scientists in its editorial board.

Lead R&D Engineer at Emissol, Mr. Ed Tegeler is a Chemical Engineer versed in mathematical modeling, techno-economic analysis, and process simulations. He has designed novel contactor geometries, new processes for CDR (patent pending) and modeled complex flow and sorbent behavior including their pressure drop, secondary flows, complex kinetics, heat and mass transfer processes and diffusion transport in pore structures. He has prior industrial experience in equipment and process designs from his prior work with GE in the US and in Australia. He has multiple patent applications and publications on contactor modeling and design.

e. Are there other organizations you're partnering with on this project (or need to partner with in order to be successful)? If so, list who they are, what their role in the project is, and their level of commitment (e.g., confirmed project partner, discussing potential collaboration, yet to be approached, etc.).

Partner	**Role in the Project**	**Level of Commitment**
Carbfix	Sequestration	Discussing potential collaboration
Black and Veatch (B&V)	Scale-up	Confirmed project partner

Saint-Gobain	Large-scale air contactor production	Discussing potential collaboration
Research Triangle Institute (RTI)	Sorbent Expertise, Exploration	Confirmed project partner
Carbon Solutions LLC	Support LCA, TEA, Env. Justice, others	Confirmed project partner

f. What is the total timeline of your proposal from start of development to end of CDR delivery? If you're building a facility that will be decommissioned, when will that happen?

Pilot plant start delivering 100 tonnes of CO2/year to Frontier will be operational by 2025. Total 'Frontier project' timeline delivering 500 tonnes of CO2 in 5 years is thus 2026-2030.

g. When will CDR occur (start and end dates)? If CDR does not occur uniformly over that time period, describe the distribution of CDR over time. Please include the academic publications, field trial data, or other materials you use to substantiate this distribution.

As described in section 1.a (page 4), our technology scaling will reach the maturity to deliver 100 tonnes per year by 2025 and the full 500-tonne prepurchase by 2030. The promise of our technology, soon to be submitted for peer-reviewed publication, is described in section 1.a.

h. Please estimate your gross CDR capacity over the coming years (your total capacity, not just for this proposal).

Year	Estimated gross CDR capacity (tonnes)[3]
2023	1.8
2024	10.9
2025	109.5
2026	350.0
2027	900.0

[3] We believe transitioning from 20,000 tonnes/year to half a gigaton in 20 years (2030-2050), i.e., by four orders of magnitude, is feasible. Existing models, such as that of Climeworks, scale by one order of magnitude every three years. This, along with expectedly rapid advances in DAC technologies in the coming years, will be great enablers, providing potentials to scale up to 0.5 G tonnes/yr by 2050.

2028	2,700.0
2029	8,000.0
2030	20,000.0

i. List and describe at least three key milestones for this project (including prior to when CDR starts), that are needed to achieve the amount of CDR over the proposed timeline.

	Milestone description	**Target completion date** (eg Q4 2024)
1	Field testing of our first module equipped with our proprietary contactor (1.8 t/y)	Q1 2023
2	Multi-module, mini-pilot plant will capture CO2 and sequester it (via Carbfix) in Iceland (10.9 t/y)	Q4 2023
3	Pilot plant: Scaling up the mini-pilot plant (109.5 t/y)	Q3/4 2025

j. What is your IP strategy? Please link to relevant patents, pending or granted, that are available publicly (if applicable).

Our proprietary Direct Air Capture contactor based on which, the above-discussed results are generated, and its variation are patent-pending. See in the links below,

i) US20210349065A1 - Direct capture substrate, device and method - Google Patents (patent pending)
ii) We have also filed more than two provisional patents, on DAC contactor variations, on sorbent formulation and on process / cycles concept best suited to our contactor.

We also voluntarily share parallel patents (fully issued) of a similar monolith developed by this team for automotive emission control, having marked similarity in performance and advantages to the DAC contactor discussed here. (Note both belong to the heterogenous reactions regime.)

US10815856B2 - Catalytic converters having non-linear flow channels - Google Patents
US10598068B2 - Catalytic converters having non-linear flow channels - Google Patents

Our IP strategy is to continue to file newer patents (mostly international) so to maintain and increase our gap with our competition. The inventions could include newer generations and variations of our contactor, sorbent synthesis and particularities of our capture process.

k. How are you going to finance this project?

Financing the project is through various sources, including:
1) investments from external stakeholders (names could be shared once we observe indications of strong prospects with Frontier) with Frontier).
2) Non-dilutive governmental funding particularly sequential funding for continued R&D and commercialization (~$2 M so far received from Department of Energy (DOE) while more funding

applications to the DOE and the National Science Foundation NSF) are in the making. Examples include Phase IIB of our current SBIR funded project ($1.65M) and its potential Phase III where private investment is matched by a government funding agency (in this case DOE) dollar-to-dollar making such investment opportunities markedly appealing to the private sector. 3) Prepurchase funding from Frontier While we do not yet have exact numbers to share on these revenue streams, we will continue to monitor the market development closely and update our funding strategy.

l. Do you have other CDR buyers for this project? If so, please describe the anticipated purchase volume and level of commitment (e.g., contract signed, in active discussions, to be approached, etc.).

There are several corporations (buyers) in our target portfolio having displayed their dedication to the new, evolving CDR market segment, amongst which we can name Microsoft (to be approached), Boeing (to be approached), Amazon (to be approached), Stripe (to be approached) and others. Note, several of these major corporations interested in CDR purchase are, just like Emissol, based in the State of Washington. 'Buy local' strategy may strike a chord with them, as well as other synergistic benefits such as state tax credit, business locality, or 'good-neighbor' stewardship. We will study and refine our sales strategy carefully in the coming phases and adapt to market conditions as the CDR market evolves.

m. What other revenue streams are you expecting from this project (if applicable)? Include the source of revenue and anticipated amount. Examples could include tax credits and co-products.

Projecting to ~ 2030, except for the sale of captured CO2 beyond that purchased by Frontier, no additional revenue streams are anticipated for this project. Tax-credits will not be pursued to avoid double counting of sequestered CO2. Since we will produce more than Frontier will buy (see 1.h above), additional revenue streams will be revisited.

n. Identify risks for this project and how you will mitigate them. Include technical, project execution, ecosystem, financial, and any other risks.

Risk	Mitigation Strategy
Project execution – Plant venue	The plant venue will be to be either in the US or in Iceland, pending further discussion with our partners and specially with Carbfix. Carbfix is looking for new sequestration locations in the US. Washington State is known to be geologically a suitable location. Thus, in the interim, we are having discussions with local authorities in Washington State to better understand the landscape and its suitability for our project.

	Regarding the plant construction (2025+), given its reputation and track record, we believe B&V is well capable of a low-risk execution.
Financial – Unsuccessful investment/grant applications	We will increase our chances by applying for multiple funding opportunities. Based on the newly announced IRA, about $1B USD is dedicated to low carbon emission and CO2 mitigation strategies. We will use this opportunity to seek, both via DOE and NSF, non-dilutive funding. (Note we have a strong track record in this regard, having received $4+ M in 5 years from the DOE and NSF, with $2 M exclusively for CDR R&D.) We are also currently in active discussions with investors and VCs.
Technical – Sorbent deactivation.	Sorbent is an important part of our CDR operation. While monitoring the sorbent development field, and we are also developing two new sets of proprietary, cost-effective and highly durable sorbents, to be used in humid and dry conditions.
Technical – Low sorbent value development	One of our contactor's key value propositions is that it needs markedly less sorbent, saving substantial sorbent cost. As the sorbent cost will likely be on a downtrend, our contactor's lower-cost advantage may be reduced, (but will never disappear since competing contactors will continue to need more sorbent than ours, regardless of the sorbent cost). That being said, its pressure drop of 5-10 Pa will continue to remain highly competitive, adding to its appeal in face of competition. To this, we add its lower thermal mass requiring lower thermal energy during regeneration (unloading), expanding on its value proposition.
Technical – Low availability of PPI	PPI has been shown to perform better compared to PEI both in terms of longevity and CO2 capture rate (ref 13, section 1.a.). However, our understanding is that PPI is not commercially available in large scale as opposed to PEI. We consider PPI to be our first choice of sorbent. However, in the event PPI availability becomes scarce, we could reasonably shift to using PEI instead (highly durable PEI patented by/available via RTI); this could add a cooling step to our process design to avoid PEI oxidation (since PEI oxidizes at lower temperatures compared to PPI). While we are aware of these challenges, to the best one can see, we do not observe an insurmountable obstacle hindering our progress, further attested by various TEAs we have performed to date (see section 1.a).

2. Durability

a. Describe how your approach results in permanent CDR (> 1,000 years). Include citations to scientific/technical literature supporting your argument. What are the upper and lower bounds on your durability estimate?

The durability of solid carbonate minerals, once precipitated, exceeds 1000 years with no definitive

upper limit [1].

[1] Snæbjörnsdóttir, S.Ó., Sigfússon, B., Marieni, C., Goldberg, D., Gislason, S.R. and Oelkers, E.H. (2020). Carbon dioxide storage through mineral carbonation. Nature Reviews Earth & Environment, 1, 90-102.

b. What durability risks does your project face? Are there physical risks (e.g. leakage, decomposition and decay, damage, etc.)? Are there socioeconomic risks (e.g. mismanagement of storage, decision to consume or combust derived products, etc.)? What fundamental uncertainties exist about the underlying technological or biological process?

Carbfix injection achieves instant solubility trapping, the second most durable form of geological carbon storage [1,2]. This has been confirmed by downhole camera imaging (no bubbles were observed) and flux measurements at well-head [3].

Innovative approaches have also been developed to monitor the fate of the injected gas mixture confirming the rapid mineralization process [4,5]. This involves regular sampling and tracer tests using adjacent monitoring wells, a combination of chemical and tracer analyses, geochemical calculations, isotope analyses and physical evidence, showing that the injected CO2 are fixed as predominantly calcite minerals within a few months to two years from injection, depending on the temperature of the storage formation.

The durability of the solid carbonates is generally understood to exceed 1000 years. Carbfix is effectively removing CO2 from the short carbon cycle and placing it in the long carbon-cycle. Most of carbon on Earth is fixed in rocks with an average residence time of thousands to millions of years [2].

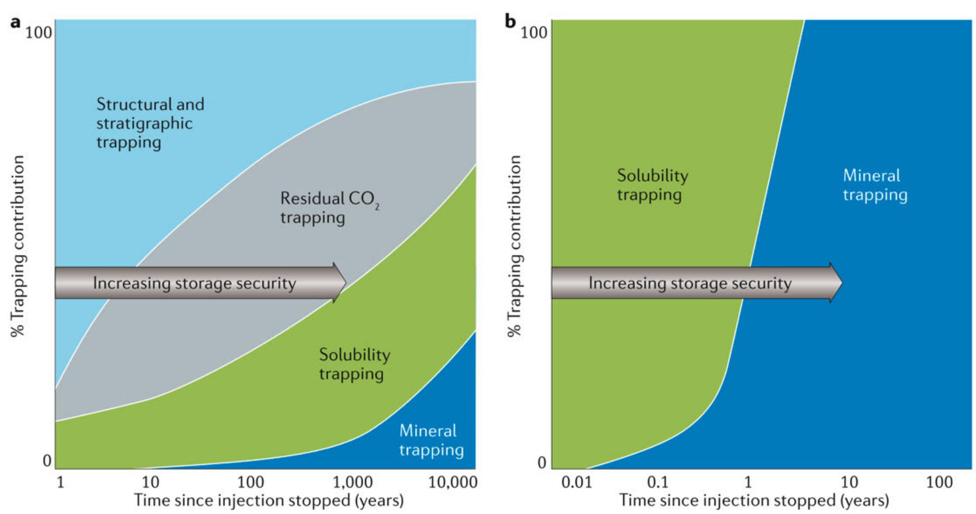


Figure 7. Comparing CO2 -trapping mechanisms and storage security for supercritical and dissolved CO2 injections (adopted from [2] and references therein).

[1] Benson, S. et al. in IPCC Special Report on Carbon Dioxide Capture and Storage, Ch. 5 (Cambridge Univ. Press, 2005). 8.

[2] Snæbjörnsdóttir, S.Ó., Sigfússon, B., Marieni, C., Goldberg, D., Gislason, S.R. and Oelkers, E.H. (2020). Carbon dioxide storage through mineral carbonation. Nature Reviews Earth & Environment, 1, 90-102.

[3] Sigfússon, B., Gíslason, S.R., Matter, J.M., Stute, M., Gunnlaugsson, E., Gunnarsson, I., et al. (2015). Solving the carbon-dioxide buoyancy challenge: The design and field testing of a dissolved CO2 injection system. International Journal of Greenhouse Gas Control, 37, 213–219.

[4] Matter, J.M., Stute, M., Snæbjörnsdóttir, S.Ó., Oelkers, E.H., Gíslason, S.R., Aradóttir, E.S., et al. (2016). Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. Science, 352, 1312-1314.

[5] Pogge von Strandmann, P.A.E., Burton, K.W., Snæbjörnsdóttir, S.Ó., Sigfússon, B., Aradóttir, E.S., Gunnarsson, I., et al. (2019). Rapid CO2 mineralisation into calcite at the CarbFix storage site quantified using calcium isotopes. Nature Communications, 10, 1983.

3. Gross Removal & Life Cycle Analysis (LCA)

a. How much GROSS CDR will occur over this project's timeline? All tonnage should be described in **metric tonnes** of CO_2 here and throughout the application. Tell us how you calculated this value (i.e., show your work). If you have uncertainties in the amount of gross CDR, tell us where they come from.

Gross tonnes of CDR over project lifetime	500 tonnes
Describe how you calculated that value	Utilizing our proprietary contactor, a fully functional DAC module is being designed and developed by Emissol in collaboration with a contractor (see its identity in the Addendum). Our model prediction shows about 5 kg of CO2/day (1.8 tonne/year) of capture is feasible. (Calculations are presented in the confidential addendum.) Successful deployment of this module concludes our Stage 1 (projected Q1-2023) In stage 2, we are gathering funding to build 6 modules for capture with the capacity of 30 kg/day. At this stage, capture will be locally connected with sequestration. This will be happening either in the Carbfix facility in Iceland if the facility is ready to use, or in the US based on Carbfix's interest in the US market. In stage 3, in collaboration with Carbfix as well as Black and Veatch (B&V), we are planning to scale up to x10 (by Q3/4 2025). This will result in ~100 tonnes/year of CO2 capture and sequestration and will be the beginning of "this project" for Frontier. The estimated overall CO2 capture and sequestered in the lifetime of the plant is ~1500 tonnes. Considering our cost calculated based on our TEA ($858/tonne) and including the price margin and the uncertainty discount (see sections 4.c. and 5.a.), the final cost is estimated to be $1272/tonne CO2. The prepurchase funding available is $500,000 and the calculation shows that a gross CDR for the lifetime of this project will be ~500 tonnes.

b. How many tonnes of CO_2 have you captured and stored to date? If relevant to your technology (e.g., DAC), please list captured and stored tons separately.

Capture: 0.5 g (from our lab-scale development, a module is being designed for field testing)

Sequestration: 0

c. If applicable, list any avoided emissions that result from your project. For carbon mineralization in concrete production, for example, removal would be the CO_2 utilized in concrete production and avoided emissions would be the emissions reductions associated with traditional concrete production. Do not include this number in your gross or net CDR calculations; it's just to help us understand potential co-benefits of your approach.

Using our proprietary contactor results in 15% reduction in overall contactor casing size. This results in less stainless-steel usage which, in turn, results in less CO2 emissions associated with the steel production process.

d. How many GROSS EMISSIONS will occur over the project lifetime? Divide that value by the gross CDR to get the emissions / removal ratio. Subtract it from the gross CDR to get the net CDR for this project.

Gross project emissions over the project timeline *(should correspond to the boundary conditions described below this table)*	37 tonnes of CO2
Emissions / removal ratio *(gross project emissions / gross CDR–must be less than one for net-negative CDR systems)*	0.07
Net CDR over the project timeline *(gross CDR - gross project emissions)*	463 tonnes of CO2

e. Provide a process flow diagram (PFD) for your CDR solution, visualizing the project emissions numbers above. This diagram provides the basis for your life cycle analysis (LCA). Some notes:

- The LCA scope should be cradle-to-grave
- For each step in the PFD, include all Scope 1-3 greenhouse gas emissions on a CO_2 equivalent basis
- Do not include CDR claimed by another entity (no double counting)
- For assistance, please:
    - Review the diagram below from the CDR Primer, Charm's application from 2020 for a simple example, or CarbonCure's for a more complex example
    - See University of Michigan's Global CO_2 Initiative resource guide
- If you've had a third-party LCA performed, please link to it.

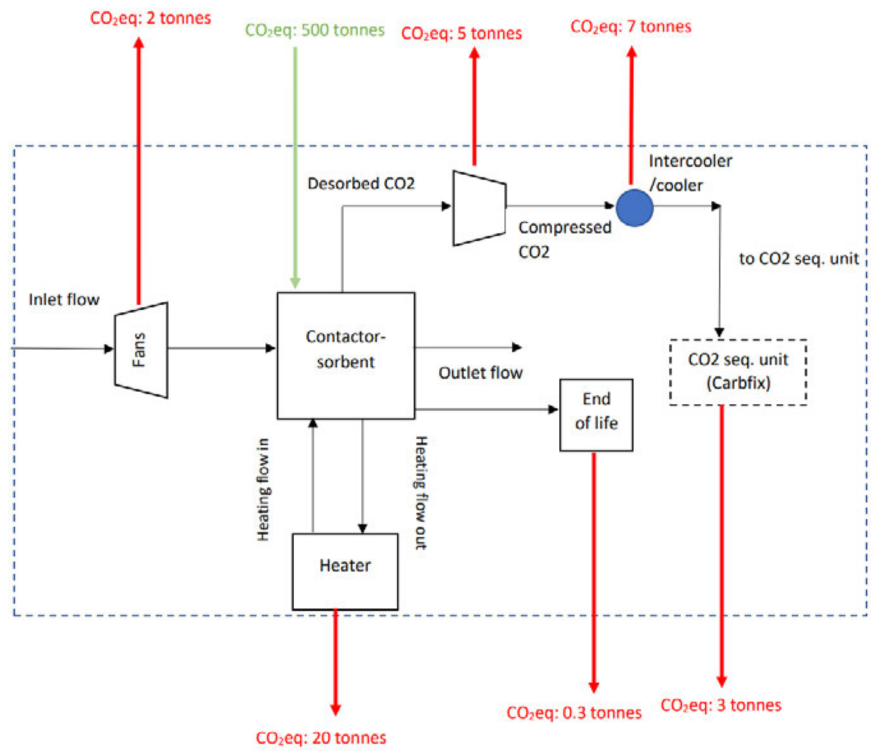


Figure 8. CO2 eq calculations done based on 5 years of project lifetime. Details of the calcultions are given in a supplimentary document as a confidential addendum.

f. Please articulate and justify the boundary conditions you assumed above: why do your calculations and diagram include or exclude different components of your system?

> The presented LCA considers both capture and sequestration. We did not include transportation since the capture plant is planned to be adjacent to the sequestration facility. The details of the LCA and assumptions made are presented in the confidential addendum. A more thorough LCA will be done before the start of the project. CO2 eq. were calculated based on GREET LCA model.

g. Please justify all numbers used to assign emissions to each process step depicted in your diagram above. Are they solely modeled or have you measured them directly? Have they been independently measured? Your answers can include references to peer-reviewed publications, e.g. Climeworks' LCA paper.

Process Step	CO_2(eq) emissions over the project lifetime (metric tonnes)	Describe how you calculated that number. Include references where appropriate.
Fan	2	Calculated based on our model (publication submitted) using the calculated pressure drop and needed flow rate.
Heater	20	Calculated based on our process simulation program (COCO simulator) based on the requirements provided

		through a publication by National Energy Technology Laboratory (NETL) [1].
Compressor	5	Calculated based on the energy requirements for pressurizing CO2 for sequestration. While the presented value for pressure is low for supercritical CO2 injection, it is still sufficient for Carbfix technology since Carbfix uses CO2-water mixture. Outlet pressure requirements are set by Carbfix.
Cooler	7	Calculated based on the energy requirements for reducing CO2 temperature for sequestration. Outlet temperature requirements are set by Carbfix.
Amine end of lifetime	0.3	For sorbent lifetime, the techno-economic analysis published by National Academy of Sciences is considered. Various scenarios are presented in this study. The "mid-case" is chosen for sorbent lifetime and emissions [2].
Sequestration	3	The CO2 emission value is 0.5kg to 14 kg CO2 for each tonne sequestered based on Carbfix, depending on operating and environmental conditions. In this LCA, an average value of 7 kg per tonne of sequestered CO2 is chosen.

[1] J. Valentine, A. Zoelle, Direct Air Capture Case Studies: Sorbent System. NETL, July 2022 DOE/NETL-2021/2865

[2] National Academies of Sciences Engineering, Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, The National Academies Press, Washington, DC, 2019.

4. Measurement, Reporting, and Verification (MRV)

Section 3 above captures a project's lifecycle emissions, which is one of a number of MRV considerations. In this section, we are looking for additional details on your MRV approach, with a particular focus on the ongoing quantification of carbon removal outcomes and associated uncertainties.

a. Describe your ongoing approach to quantifying the CDR of your project, including methodology, what data is measured vs modeled, monitoring frequency, and key assumptions. If you plan to use an existing protocol, please link to it. Please see Charm's bio-oil sequestration protocol for reference, though note we do not expect proposals to have a protocol at this depth at the prepurchase stage.

> To consider all potential losses, the measured amount of CO2 sequestered will be counted as the net amount of CDR. This is done through regular sampling and tracer tests using adjacent monitoring wells, a combination of chemical and tracer analyses, geochemical calculations, isotope analyses and physical evidence, showing that the injected CO2 are fixed as predominantly calcite minerals within a few months to two years from injection, depending on the temperature of the storage formation. In particular, one of our measurement methods is to use calcium (Ca) isotopes in both pre- and post-CO2 injection waters to quantify the amount of carbonate precipitated, and hence CO2 stored.

b. How will you quantify the durability of the carbon sequestered by your project discussed in 2(b)? If direct measurement is difficult or impossible, how will you rely on models or assumptions, and how will you validate those assumptions? *(E.g. monitoring of injection sites, tracking biomass state and location, estimating decay rates, etc.)*

> The primary method of verification and quantification will be in the form of tracer tests, in which non-reactive, and sometimes reactive, chemical tracers are co-injected with the CO2 and nearby monitoring wells regularly sampled. Coupled with mass-balance calculations based on a transport model, the mineralization, and rates, can be quantified [1-4].
>
> The monitoring will be based on the Carbfix methodology which has been certified by DNV in compliance with the ISO 14064-2 Standard (https://carbfix.cdn.prismic.io/carbfix/038e79da-eb75-4379-9892-77c964dac751_Methdology+Carbfix_V1_2022_validated.pdf).
>
> ---
>
> [1] Matter, J.M., Stute, M., Hall, J., Mesfin, K., Snæbjörnsdóttir, S.Ó., Gíslason, S.R., et al. (2014). Monitoring permanent CO2 storage by in situ mineral carbonation using a reactive tracer technique. Energy Procedia, 63, 4180-4185.
>
> [2] Matter, J.M., Stute, M., Snæbjörnsdóttir, S.Ó., Oelkers, E.H., Gíslason, S.R., Aradóttir, E.S., et al. (2016). Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. Science, 352, 1312-1314.
>
> [3] Snæbjörnsdóttir, S.Ó., Oelkers, E.H., Mesfin, K., Aradóttir, E.S., Dideriksen, K., Gunnarsson, I., et al. (2017). The chemistry and saturation states of subsurface fluids during the in situ mineralisation of CO2 and H2S at the CarbFix site in SW-Iceland. International Journal of Greenhouse Gas Control, 58, 87-102.
>
> [4] Clark, D.E., Oelkers, E.H., Gunnarsson, I., Sigfússon, B., Snæbjörnsdóttir, S.Ó., Aradóttir, E.A., Gíslason, S.R. (2020). CarbFix2: CO2 and H2S mineralization during 3.5 years of continuous injection into basaltic rocks at more than 250 °C. Geochimica et Cosmochimica Acta, 279, 45-66.

c. This tool diagrams components that we anticipate should be measured or modeled to quantify CDR and durability outcomes, along with high-level characterizations of the uncertainty type and magnitude for each element. We are asking the net CDR volume to be discounted in order to account for uncertainty and reflect the actual net CDR as accurately as possible. Please complete the table below. Some notes:

- In the first column, list the quantification components from the Quantification Tool relevant to your project (e.g., risk of secondary mineral formation for enhanced weathering, uncertainty in the mass of kelp grown, variability in air-sea gas exchange efficiency for ocean alkalinity enhancement, etc.).
- In the second column, please discuss the magnitude of this uncertainty related to your project and what percentage of the net CDR should be discounted to appropriately reflect these uncertainties. Your estimates should be based on field measurements, modeling, or scientific literature. The magnitude for some of these factors relies on your operational choices (i.e., methodology, deployment site), while others stem from broader field questions, and in some cases, may not be well constrained. We are not looking for precise figures at this stage, but rather to understand how your project is thinking about these questions.
- See this post for details on Frontier's MRV approach and a sample uncertainty discount calculation and this Supplier Measurement & Verification Q&A document for additional guidance.

Quantification component Include each component from the Quantification Tool relevant to your project	**Discuss the uncertainty impact related to your project** Estimate the impact of this component as a percentage of net CDR. Include assumptions and scientific references if possible.
Storage	5%: based on published experimental methodology. Rapid CO2 mineralisation into calcite at the CarbFix storage

	site quantified using calcium isotopes | Nature Communications
Leakage	1%: To ensure the safety of the injection system, any leak detection from surface installations and wellheads are closely examined. CO2 gas detectors are placed at strategic locations around the premises. In addition, all wellhead buildings are equipped with CO2 sensors and visually inspected for gas leaks. (https://www.carbfix.com/proven/)
Materials and Energy	2%: LCA considers details for emissions from materials and energy, considers various scenarios, lowering the uncertainty level. (While exact percentage is not known, it is calculated by doubling the percentage used by highly developed plant in the case study to include uncertainties)
Secondary impact of energy demand	6% waste heat and geothermal hot water are used for the project due to the low energy demand for material regeneration. (While exact percentage is not known, it is calculated by doubling the percentage used by highly developed plant in the case study to include uncertainties)
Storage monitoring and maintenance (not included in accounting of CO2 captured)	5% based on published experimental. Rapid CO2 mineralisation into calcite at the CarbFix storage site quantified using calcium isotopes | Nature Communications

d. Based on your responses to 4(c), what percentage of the net CDR do you think should be discounted for each of these factors above and in aggregate to appropriately reflect these uncertainties?

> Storage 5%, Leakage 1%, Materials and Energy 2%, Secondary impact of energy demand 6%. Overall 14%

e. Will this project help advance quantification approaches or reduce uncertainty for this CDR pathway? If yes, describe what new tools, models or approaches you are developing, what new data will be generated, etc.?

> At stages 1 and 2, previously developed technologies for CO2 quantification will be used. At stage 3 which is “this project”, however, part of our research and development will be pointed towards lowering the uncertainties on quantification of captured and sequestered CO2 through using more advanced methods for CO2 quantification and leakage detection.

f. Describe your intended plan and partners for verifying delivery and registering credits, if known. If a protocol doesn’t yet exist for your technology, who will develop it? Will there be a third party auditor to verify delivery against that protocol or the protocol discussed in 4(a)?

Emissol will be partnering with Anew Climate (https://anewclimate.com/) for this matter. Anew Climate and its network will verify our storage volume, identify potential leakage, monitor CO2 retention during and post injection, and monitor the gas volumes, energy consumptions, as well as venting events. Registration will be done by a third party.

5. Cost

We are open to purchasing high-cost CDR today with the expectation the cost per tonne will rapidly decline over time. The questions below are meant to capture some of the key numbers and assumptions that you are entering into the separate techno-economic analysis (TEA) spreadsheet (see step 4 in Applicant Instructions). There are no right or wrong answers, but we would prefer high and conservative estimates to low and optimistic. If we select you for purchase, we'll work with you to understand your milestones and their verification in more depth.

a. What is the levelized price per net metric tonne of CO_2 removed for the project you're proposing Frontier purchase from? 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), but we will be using the data in that spreadsheet to consider your offer. Please specify whether the price per tonne below includes the uncertainty discount in the net removal volume proposed in response to question 4(d).

$1272/tonne CO_2 (including uncertainty discount)

b. Please break out the components of this levelized price per metric tonne.

Component	Levelized price of net CDR for this project ($/tonne)
Capex	583
Opex (excluding measurement)	647
Quantification of net removal (field measurements, modeling, etc.)[4]	30
Third party verification and registry fees (if applicable)	12
Total	1272

c. Describe the parameters that have the greatest sensitivity to cost (e.g., manufacturing efficiencies, material cost, material lifetime, etc.). For each parameter you identify, tell us what the current value is, and what value you are assuming for your NOAK commercial-scale TEA. If this includes parameters you already identified in 1(c), please repeat them here (if applicable). Broadly, what would need to be true for your approach to achieve a cost of $100/tonne?

[4] This and the following line item is not included in the TEA spreadsheet because we want to consider MRV and registry costs separately from traditional capex and opex.

Parameter with high impact on cost	Current value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
Contactor Cost	\$15/L	\$5/L	The current cost is based on a cost estimate for additive manufacturing of the contactor. NOAK cost reflects moving to a technique more suited for high volume production (e.g., stamping or extrusion). Assumed installation factor of 6 for contactor is also expected to drop to 4 as technology matures. As sorbent technology improves (i.e., as capacity and uptake rate increase), the volume of contactor needed to capture a unit amount of CO2 per time will also decrease.
Vessel Cost	\$44/tonne CO2 capture	\$1/tonne CO2 captured	Vessel cost is currently estimated as a pressure vessel, which scales with capacity raised to a power of 0.52. The NOAK value uses the top of the cost correlation range (1000 m3/vessel), making use of economies of scale. As described in the next section, there is uncertainty around this method of estimation. The same impact of improvement in sorbent technology also applies to vessel volume. That is, as sorbent becomes faster and volumetric capacity increases, the volume of process vessels should decrease.
Sorbent cost	\$70/kg	\$10/kg	The sorbent chosen for this project, PPI, is not widely available commercially. As such, we expect the cost drop-off from this project to NOAK to be steep.

d. What aspects of your cost analysis are you least confident in?

We have lower confidence in operational real estate costs, insurance/taxes/fees, and other fixed operating costs (rows 37-39 in the TEA spreadsheet input tabs), due to a relative lack of maturity in DAC technologies, as reflected in the DAC TEA literature. In the coming stages, we will consult proper expertise and update said parameters accordingly.

The vessel cost estimation, currently based on a standard pressure vessel, is likely lower than the number used here, due to reduced durability requirements in a DAC environment.

e. How do the CDR costs calculated in the TEA spreadsheet compare with your own models? If there are large differences, please describe why that might be (e.g., you're assuming different learning rates, different multipliers to get from Bare Erected Cost to Total Overnight Cost, favorable contract terms, etc.).

> Our cost analysis/TEA shows our contactor reduces the levelized cost of net CO2 removal by 50-80% relative to a baseline contactor (see Fig. 3). This relative reduction is still seen when we compare the baseline case to our own using the Frontier TEA spreadsheet. However, the baseline cost of net CO2 removal using this method is more than $3000/tonne, while our case is $858/tonne of CO2 captured. This may indicate that we are overestimating equipment costs in our own analysis. Therefore, DAC cost using our technology could be lower than the cost projected in this proposals TEA. If, during this project, we discover such lower costs, we will keep Frontier apprised of the development and strive to remove additional CO2 in compensation.

f. What is one thing that doesn't exist today that would make it easier for you to commercialize your technology? (e.g., improved sensing technologies, increased access to X, etc.)

> A more rewarding tax credit for CO2 removal; also combined with a mandate to purchase CO2 removal to stay below a cap.

6. Public Engagement

In alignment with Frontier's Safety & Legality criteria, Frontier requires projects to consider and address potential social, political, and ecosystem risks associated with their deployments. Projects with effective public engagement tend to:

- Identify key stakeholders in the area they'll be deploying
- Have mechanisms in place to engage and gather opinions from those stakeholders, take those opinions seriously, and develop active partnerships, iterating the project as necessary

The following questions help us gain an understanding of your public engagement strategy and how your project is working to follow best practices for responsible CDR project development. We recognize that, for early projects, this work may be quite nascent, but we are looking to understand your early approach.

a. Who have you identified as relevant external stakeholders, where are they located, and what process did you use to identify them? Please include discussion of the communities potentially engaging in or impacted by your project's deployment.

> Washington State has high potentials for CDR and sequestration. The City of Seattle and King County, Washington have both been active, dynamic voices in the climate and decarbonization technology space through development of the city's Climate Action Strategy, and the King County Climate Action Plan; many environmental, climate, and social justice organizations were critical to these efforts. At a broader scale, the State of Washington Department of Natural Resources (DNR) has also prepared significant analysis to showcase the role that CCUS technologies could have in the state journey towards decarbonization, including identification of suitable geologic sequestration. To ensure that deployment engages community, our team would seek to connect with grass-top organizations working in the climate decarbonization space in Seattle who also already have trusted relationships

with community members in the area. Example groups include the King County Climate Equity Community Task Force, Front and Centered, Cascadia Climate Action, Sovereign Power, the Clean Energy Transition Institute, 350 Seattle, the Energy Facility Site Evaluation Council, NW Energy Coalition, and Renewable Northwest.

Stakeholders and organizations were identified largely based on prior engagement with local and regional climate action planning processes, cognizant that local municipalities put in a lot of work to ensure that the voices crafting the climate action plans were representative of the diverse communities in and around Seattle. To expand the list of organizations, our team would connect with local municipalities to understand other stakeholder and community organizations working directly on climate, energy, and equity. This is further important because direct air capture and carbon geologic sequestration technologies are so nascent, there are no local organizations dedicated specifically to them. Fortunately, there are inherent synergies, but as engagement is undertaken, the group of stakeholders and organizations should be considered fluid and will necessarily evolve to meet the needs of community conversations.

b. If applicable, how have you engaged with these stakeholders and communities? Has this work been performed in-house, with external consultants, or with independent advisors? If you do have any reports on public engagement that your team has prepared, please provide. *See Project Vesta's community engagement and governance approach as an example and Arnestein's Ladder of Citizen Participation for a framework on community input.*

We have participated in broader conversations, such as with the State of Washington Department of Natural Resources, and understand through published planning documents, for example, that the state and many local municipalities, including Seattle, are interested in understanding how decarbonization technologies can serve them in achieving longer-term goals for greenhouse gas emission reductions. Despite not having conducted engagement to date, our team has defined a strong ethos around what community and stakeholder engagement should look like for this process. Without authentic community and stakeholder engagement, the project team wholly recognizes that the project cannot be deployed equitably, and could, in fact, have negative, long-term consequences to scale deployment down the road. As with many decarbonization technologies, our team understands that suitability for deployment will vary from community to community. In this way, having honest, authentic conversations upfront about the potential benefits of the technology, as well as any potential risks or disbenefits, is essential to providing communities with accurate information for decision-making on whether the proposed technology truly can serve them or not. With the initial plant, this may take the form of focus groups, ideally facilitated through a local partner, and grounded in an understanding that deployment of DAC technologies must advance and support broader goals of equitable decarbonization and social justice. Referencing Arnstein's Ladder of Citizen Participation, or the more widely utilized IAP2 Spectrum of Public Participation, we would aim to devise a stakeholder process within the realms of collaboration and empowerment (or in Arnstein's terms, between Partnership and Delegated Power). Engagement would also recognize the unfair burden often placed on communities identified as vulnerable to participate (or serve as tokens) in public engagement spaces, particularly when outcomes of engagement are not directly shaped by their involvement. Our approach of starting with organizations already connected to community helps alleviate some of this inequity.

c. If applicable, what have you learned from these engagements? What modifications have you already made to your project based on this feedback, if any?

Though not yet applicable, as noted above, our engagement process would be structured with inherent evolution in mind. As we hear from community organizations, we will amend the process to recognize the feedback received. Further, because this is a pilot (with the capacity to sequester 100 tonnes per year), there is a lot within subsequent phases of development yet undefined. In this way, community conversations in the initial phases have tremendous opportunity to influence and determine what shape subsequent deployment should take. This will be particularly pertinent as the project looks to various geographies, within the US or in Iceland, to replicate engagement in other local geographies.

d. Going forward, do you have changes to your processes for (a) and (b) planned that you have not yet implemented? How do you envision your public engagement strategy at the megaton or gigaton scale?

Engagement will need to change quite a bit between the pilot stage (in Washington State), to the megaton/gigaton scale. This is due partially to the expansion of geography. The process described above is tailored to one local context. Any future engagement at other project development sites will necessarily need to be refined cognizant of local context. Depending on project size, partners may look different, with additional emphasis added for state or federal/national insights. Similarly, the state of Washington is heavily reliant on carbon-free hydropower for electricity; deployment elsewhere may require more in-depth conversations about supplementary renewable energy generation capacity for the project's electricity needs.

7. Environmental Justice[5]

As a part of Frontier's Safety & Legality criteria, Frontier seeks projects that proactively integrate environmental and social justice considerations into their deployment strategy and decision-making on an ongoing basis.

a. What are the potential environmental justice considerations, if any, that you have identified associated with your project? Who are the key stakeholders? Consider supply chain impacts, worker compensation and safety, plant siting, distribution of impacts, restorative justice/activities, job creation in marginalized communities, etc.

As with development of any decarbonization technology, there are inherent environmental justice concerns. The legacy of energy development done throughout the United States at the expense of vulnerable, primarily communities of Black, Indigenous, and People of Color (BIPOC) folks, still informs the lived experience of many today in the form of proximity to legacy pollution, poor air and water quality, and even less directly through less-walkable communities, and less green space (and the associated health implications). Proposing new development or technology innovation necessitates significant work to interrogate what impacts the technology will have on communities, and due diligence required to ensure that benefits are directed towards communities who a) want the technology developed, and b) have the greatest opportunity to benefit from it. This is particularly true in the United States, but also elsewhere. That understood, CDR and sequestration technology is extremely nascent; the greatest opportunity to recognize EJ in the project development is with siting. In other parts of the world, DAC facilities have been characterized by largely industrial development patterns. Understanding where historically vulnerable communities are can help characterize where

[5] For helpful content regarding environmental justice and CDR, please see these resources: C180 and XPRIZE's Environmental Justice Reading Materials, AirMiners Environmental and Social Justice Resource Repository, and the Foundation for Climate Restoration's Resource Database

infrastructure should likely not be located. However, the ultimate decisions on where infrastructure should be deployed should be informed by community input.

b. How do you intend to address any identified environmental justice concerns and / or take advantage of opportunities for positive impact?

In the U.S., we can look to local land use and zoning plans to help determine where it would be most advantageous to site DAC facilities. To the extent possible, the project team would seek to collaborate with local green job and technology training programs to provide opportunity for hands-on skills development. Yet again, the benefits important to community invariably need to be defined by community, insights which the project team will hope to generate through the engagement described above.

At the same time, and as with all decarbonization technologies, global scales of equity and justice are also at play. It's well understood that a handful of countries are disproportionately responsible for a significant amount of total greenhouse gas emissions. Nations across the world who are most likely to experience the debilitating impacts of climate change are also least likely to have been responsible for contributing to it. The United Nations, along with other publications like the 2022 IPCC report, have repeatedly confirmed that CCUS is a key strategy among many in efforts to ensure that global temperature increases stay below the 2 °C threshold (ideally 1.5 °C degree threshold) outlined in the 2015 Paris Targets. In this way, U.S. leadership around CDR technologies plays in role in recognizing the legacy of contribution to global GHG levels. Similarly, though not a country with a legacy of significant emissions, Iceland has a wealth of carbon-free energy in the form of geothermal and hydro, allowing for significant CDR and DAC expansion with limited externalities in the form of electricity emissions. As the technology scales to higher capture thresholds of a megaton/gigaton, this strategic deployment will have broad-reaching, positive impact for the countries experiencing the greatest impacts of climate change, without allocating any additional burden.

8. Legal and Regulatory Compliance

a. What legal opinions, if any, have you received regarding deployment of your solution?

At present, the project team has not received any legal opinions regarding deployment of our CDR technology.

b. What permits or other forms of formal permission do you require, if any, to engage in the research or deployment of your project? What else might be required in the future as you scale? Please clearly differentiate between what you have already obtained, what you are currently in the process of obtaining, and what you know you'll need to obtain in the future but have not yet begun the process to do so.

To site a facility capable of 100+ tonnes capture per year will require local site permits, and may also include broader permitting. If the facility will be in the United States, this will need to be done through authorities such as the National Environmental Protection Act or state-specific regulatory requirements. Construction permit from the municipality needs to be obtained. If in Iceland, injection permit from the Environmental Agency will be needed, which is subjected to Environmental Impact Assessment if injection exceeds 100,000 tCO_2. The injection permit is based on the requirements of EU's CCS directive (2009/31/EC). An EIA for large-scale injection in this site is currently underway with Icelandic authorities, but no work has been done to procure any longer-term siting or regulatory permits in the US at the moment.

c. Is your solution potentially subject to regulation under any international legal regimes? If yes, please specify. Have you engaged with these regimes to date?

The only way in which CDR may come under regulation of international legal regimes is not to do with the technology itself, but rather through potential emissions (carbon credit) trading systems. Neither the U.S., nor Iceland, are new to the carbon capture credit market. The United Nations outlines carbon credits as a commodity under the allocated mechanisms defined through the Kyoto Protocol. While the United States dropped from the list of countries who have ratified the Kyoto Protocol as of 2001, Iceland is a party to both the United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol.

d. In what areas are you uncertain about the legal or regulatory frameworks you'll need to comply with? This could include anything from local governance to international treaties. For some types of projects, we recognize that clear regulatory guidance may not yet exist.

The only uncertainties exist around final location of scaled project deployment. Depending on where the pilot plant with the 100+ CR capacity will be deployed, for example in the state of Washington, or elsewhere in the U.S., regulatory uncertainties will arise. While there is precedent for DAC facility in the U.S. (in Wyoming), there is no precedent in Washington, which would require some work to coordinate with regulatory authorities to ensure siting compliance, or work with partners to help establish regulatory precedence for CDR technologies in the geography.

e. Do you intend to receive any tax credits during the proposed delivery window for Frontier's purchase? If so, please explain how you will avoid double counting.

The team does not intend to receive any tax credits *during* the proposed delivery window for Frontier's purchase. No course of action to avoid double counting is necessary.

9. Offer to Frontier

This table constitutes your **offer to Frontier**, and will form the basis of contract discussions if you are selected for purchase.

Proposed CDR over the project lifetime (tonnes) *(should be net volume after taking into account the uncertainty discount proposed in 4(c))*	393 tonnes of CO2
Delivery window *(at what point should Frontier consider your contract complete? Should match 1(f))*	Start 2026 – End 2030

Levelized Price (\$/metric tonne CO_2) *(This is the price per tonne of your offer to us for the tonnage described above)*	\$1272/ tonnes of CO2

Frontier

Application Supplement: DAC

(Only fill out this supplement if it applies to you)

Note: these questions are with regards only to air capture: e.g. your air contactors, sorbents or solvents, etc. Separately, there exist Geologic Injection and CO_2 Utilization supplements. We anticipate that most companies filling out this DAC supplement should ALSO fill out one of those supplements to describe their use of the CO_2 stream that's an output of the capture system detailed here.

Physical Footprint

1. What is the physical land footprint of this project, and how do you anticipate this will change over the next few years? This should include your entire physical footprint, i.e., how much land is not available for other use because your project exists. Also, what is the estimated footprint if this approach was removing 100 million tons of CO_2 per year?

Land footprint of this project (km^2)	0.01 (extrapolated from current Climeworks ORCA plant size)
Land footprint of this tech if scaled to 100 million tons of CO_2 removed per year (km^2)	17 (extrapolated from NETL Direct Air Capture Case Studies: Sorbent System [1])

[1] J. Valentine, A. Zoelle, Direct Air Capture Case Studies: Sorbent System. NETL, July 2022 DOE/NETL-2021/2865

Capture Materials and Processes

1. What material(s) is/are you using to remove CO_2?

Amine-based sorbents are used for CO2 capture. They are supported on alumina.

2. How do you source your material(s)? Discuss how this sourcing strategy might change as your solution scales. Note any externalities associated with the sourcing or manufacture of it (e.g., hazardous wastes, mining, etc.). You should have already included the associated carbon intensities in your LCA in Section 3.

The sorbent material will be purchased from commercially available products. The sorbent support will be purchased from Sasol. The amine-based sorbent (PPI) will be purchased from Alfa Aesar. If, due to availability issue, we would need to shift to PEI as the active ingredient for CO2 capture, we will source it commercially from Merck but, at the same time, we collaborate with RTI to scale PPI sorbent synthesis. For the contactor, we are partnering with Saint-Gobain for commercial production of our contactors. No new methodology for contactor-sorbent system with potentially hazardous waste or mining will be considered. Our sorbent exploration (provisional patent filed) will parallelly proceed with this application. For this method, no new hazardous waste or mining is needed based on our proposed synthesis methods.

3. How much energy is required for your process to remove 1 net tonne of CO_2 right now (in GJ/tonne)? Break that down into thermal and electrical energy, if applicable. What energy intensity are you assuming for your NOAK TEA?

~2.7GJ/tonne which is all geothermal electricity. We expect little to no change in energy intensity in the NOAK case, barring a change in sorbent used.

4. What is your proposed source of energy for this project? What is its assumed carbon intensity? How will this change over the duration of your project? (You should have already included the associated carbon intensities in your LCA in Section 3).

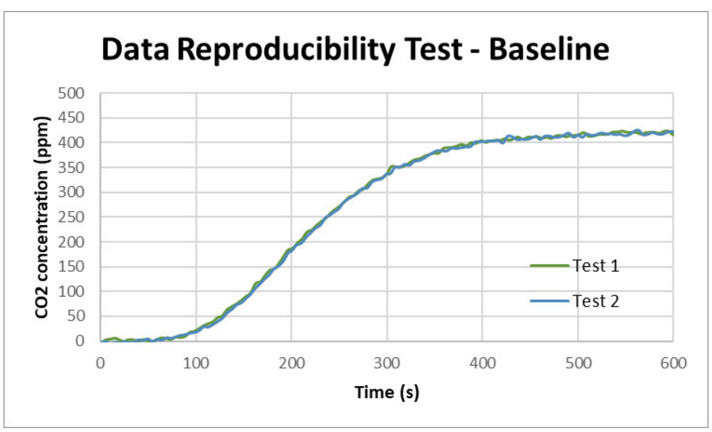
Geothermal electricity will be used for this project for which, 25.28 g CO_2 /MJ electricity is considered. This is not to change through the duration of this project.

5. Besides energy, what other resources do you require (if any, such as water)? Where and how are you sourcing these resources, and what happens to them after they pass through your system? (You should have already included the associated carbon intensities in your LCA in Section 3).

If our stage 3 occurs in Iceland, a combination of renewable electricity and geothermal hot water will be used. If this stage occurs in the US, only geothermal electricity will be used.

6. Do you have experimental data describing how your system's CDR performance changes over time? If so, please include that data here and specify whether it's based on the number of cycles or calendar life.

Currently, we have experimental data for two cycles (which were originally done to ensure data reproducibility).



The second cycle shows no degradation, but we will generate more data on longevity and durability of our cycles in our stage 1 (using the full module in our field testing).

7. What happens to your capture medium at end-of-life? Please note if it is hazardous or requires some special disposal, and how you ensure end-of-life safety.

> The capture medium is composed of contactor and sorbent. The contactor is reusable. The sorbent will be off loaded from the contactors and the contactors will be reloaded with new sorbents. The support of the sorbent (alumina) is also reusable. It will not be off loaded but impregnated with new amine-based sorbents. The amine-based sorbent, however, will be off loaded. Depending on the availability and costs, it will be either co-combusted in coal burners or used as NOx scrubbing agent in incinerators [1].

[1] J N Yin, C J An, K Zhao, Y K An, S Young, Handling of Amine-Based Wastewater Produced During Carbon Capture, Journal of Environmental Informatics Letters (2) 57-69 (2019)

8. Several direct air technologies are currently being deployed around the world. Why does your DAC technology have a better chance to scale and reach low cost than the state of the art?

> Our technology uses a novel contactor which considerably maximizes the sorbent capacity, resulting in significant reduction in sorbent need and, as a result, in sorbent cost. Our contactor also maximizes mass transfer while reducing pressure drop. Through optimizing the operating conditions associated with our process, our TEA shows an overall cost reduction of between 50-80%. We are also exploring novel sorbents tailored for various climates to be coupled with our contactor. Using our novel sorbet-contactor system will highly affect the total cost as well as the longevity of the DAC system.

Application Supplement: Geologic Injection

(Only fill out this supplement if it applies to you)

Feedstock and Use Case

1. What are you injecting? Gas? Supercritical gas? An aqueous solution? What compounds other than C exist in your injected material?

> Aqueous solution. Injected mixture consists of fresh water and CO2 - No other compounds present in the mixture.

2. Do you facilitate enhanced oil recovery (EOR), either in this project or elsewhere in your operations? If so, please briefly describe.

> No

Throughput and Monitoring

3. Describe the geologic setting to be used for your project. What is the trapping mechanism, and what infrastructure is required to facilitate carbon storage? How will you monitor that your durability matches what you described in Section 2 of the General Application?

> The trapping mechanism is solubility trapping (short term) and mineral strapping (long-term). The CO_2 is stored in form of solid carbonate minerals (such as calcite, aragonite, siderite, magnesite, etc.) formed through CO_2-water-rock reactions in the subsurface reservoir. The precipitation of these minerals from water-dissolved CO_2 takes place rapidly within months, as broadly demonstrated by Carbfix. These minerals are stable over geological timescales so that after the verification of mineralization in a monitoring program, no active management or intervention is necessary. This rapid mineralization distinguishes the Carbfix method from conventional CO_2 sequestration processes, drastically improving the long-term storage reliability. The infrastructure required are injection and monitoring wells, as well as pumps, pipelines, well casings and compressors.
>
> In addition to subsurface MMV campaigns, the following parameters are monitored at the surface:
> **The accurate amount of CO_2 received from the DAC system and injected via the injection system** will be monitored for accurate book-keeping of the transported and injected CO_2 and to ensure no fugitive emissions from surface installations and wellheads. Flows, temperatures, and pressures will be monitored continuously. Mass balance calculations allow quantification of any fugitive losses until the wellheads.
>
> **Detection of leakages from surface installations and wellheads,** which would affect the overall efficiency of the project. Fugitive CO_2 emissions from surface pipes will be monitored to ensure efficient operation. CO_2 gas detectors will ensure the immediate detection of malfunction of the injection system.
> **Ensuring the chemistry of the gaseous CO_2 and the water for injection adheres to quality** requirements set out by the project and contamination levels are below those set by operational licenses. Sampling valves will enable manual sampling by third parties for verification that impurities do

not exceed maximum allowed concentrations. The temperature, pressure and conductivity of injected water will be monitored continuously but its chemical composition will be determined from samples collected manually.

Ensuring optimal injection conditions: The optimal injection conditions will be maintained by monitoring physical parameters of the CO_2 gas and water flowing to the injection wells. A CO_2 and water flow meter will be installed at the wellhead. Pressure sensors in the CO_2 gas pipe at the wellhead as well as pressure sensors in the annulus at the wellhead will confirm optimal injection conditions. Any formation of bubbles will cause a deviation in water flow and irregularities in pressure.

Optimization of injection: The data on the chemical composition and physical parameters of injected gaseous CO_2 and water together with the injectivity of the injection well lay the foundations of the injection system setup such as the mixing depth and setting the ratio of water to CO_2 being injected.

4. For projects in the United States, for which UIC well class is a permit being sought (e.g. Class II, Class VI, etc.)?

Class VI

5. At what rate will you be injecting your feedstock?

The only feedstock needed for a Carbfix injection system is water, which is co-injected with the CO_2. The water is sourced from the storage formation. The mass flow ratio of water to CO_2 in the injection system at the DAC innovation park will be 25:1. Thus, for a DAC facility with 1000 t CO_2 capacity per year, 25.000 t of water will be required. This translates to an average mass flow rate of 32 g/s CO_2 co-injected with 0,8 kg/s of water.

Environmental Hazards

6. What are the potential environmental impacts associated with this injection project, what specific actions or innovations will you implement to mitigate those impacts? How will they be monitored moving forward?

An Environmental impact assessment for large-scale injection in this site is currently underway with Icelandic authorities. The EIA will specify in detail potential impacts associated with the project along with mitigation measures. A license to operate will be provided by the Environmental Agency fulfilling a detailed monitoring plan, based on the requirements of EU's CCS directive (2009/31/EC).

7. What are the key uncertainties to using and scaling this injection method?

By mixing CO_2 with water for injection, solubility trapping occurs immediately, thus improving storage security significantly. This requires approximately 25 tons of water for every ton of gas injected [1]. Although Iceland's freshwater supply is abundant, this is not the case in many countries which are experiencing increased water scarcity. Carbfix has developed the scientific basis for using seawater to dissolve CO_2, prior to injection, thus expanding the applicability of the technology to water scarce regions, coastal and offshore areas. Reaction path modelling and laboratory studies have quantified the chemical interactions between emission-charged seawater and basalt and indicate that >80% of injected CO_2 dissolved in seawater causes carbonate mineralization at temperatures ≤170°C [2,3]. A field site demonstration of mineral storage using seawater is currently ongoing.

[1] Snæbjörnsdóttir, S.Ó., Oelkers, E.H., Mesfin, K., Aradóttir, E.S., Dideriksen, K., Gunnarsson, I., et al. (2017). The chemistry and saturation states of subsurface fluids during the in situ mineralisation of CO2 and H2S at the CarbFix site in SW-Iceland. International Journal of Greenhouse Gas Control, 58, 87-102.

[2] Marieni, C., Voigt, M., Clark, D.E., Gíslason, S.R., Oelkers, E.H. (2021). Mineralization potential of water-dissolved CO2 and H2S injected into basalts as function of temperature: Freshwater versus Seawater. International Journal of Greenhouse Gas Control, 109, 103357.

[3] Voigt, M., Marieni, C., Baldermann, A., Galeczka, I.M., Wolff–Boenisch, D., Oelkers, E.H., & Gislason, S.R. (2021). An experimental study of basalt–seawater– CO2 interaction at 130 °C. Geochimica et Cosmochimica Acta.