NeoCarbon GmbH

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

NeoCarbon GmbH

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

Berlin, Germany

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

René Haas (Co-Founder & CEO of NeoCarbon)

Brief company or organization description <20 words

NeoCarbon captures CO2 at low cost and at scale by leveraging waste heat, existing infrastructure, and its novel reactor.

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

a. **Description of the CDR approach:** Describe how the proposed technology removes CO_2 from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If your project addresses any of the priority innovation areas identified in the RFP, tell us how. Please include figures and system schematics and be specific, but concise. 1000-1500 words

Summary

NeoCarbon captures CO2 at low cost and at scale by leveraging waste heat and existing

[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.

infrastructure, as well as its novel monolithic reactor. Specifically, the company was founded to overcome the three primary obstacles hindering the scalability of Direct Air Capture (DAC): elevated costs, substantial electrical energy requirements, and slow scaling due to greenfield operations.

We developed a breakthrough monolithic reactor based on hollow fibers to decrease the electrical energy and costs of Direct Air Capture. Compared to a packed bed design, the monolithic reactor requires 23% less electricity and 19.4% lower thermal demand. This is mainly driven by the fact that we can distribute the heat extremely locally, compared to heating the complete reactor needed in a packed bed design.

In addition, utilizing pre-existing infrastructure allows us to substantially reduce capital expenditures, eliminating the need for ground work (e.g. constructing roads, electricity and water lines), and other facilities to deploy our modular Direct Air Capture units. Additionally, harnessing the low-grade waste heat generated by industries lowers the electrical demand for our process by up to 93.5%, enhancing scalability and overall cost-effectiveness, with no impact on the industries' operations.

Combined, by leveraging existing infrastructure, waste heat, and our hollow fiber reactor, we are able to capture 1.3 Gigaton of CO_2 per year with a cost per ton of $82. We have already built two autonomous carbon capture modules, and an offtake from Frontier will kickstart our first carbon removal plant with first deliveries in 2025.

Best in class DAC: low electrical energy requirement of 0.21 MWh/t due to hollow fiber reactor and waste heat integration

Due to leveraging waste heat at over 95 °C, the electrical energy constitutes only 6.5% of the total energy demand, indicating highly efficient use of waste heat. This reduces our reliance on renewable energy sources, setting us apart from most DAC companies for example those using electrochemical processes, and results in an electrical energy need of 0.21 MWh/t in 2030.
The low electrical energy need is primarily driven by our monolithic reactor and has several clear advantages. First of all, it leads to better heat management: the heating and cooling liquid can be distributed extremely locally which results in lower heat loss and faster heat transfer, significantly lowering both the duration of the transition steps of the cycle (heating & cooling phases, during which neither adsorption or desorption happen) and limiting sorbent degradation over time. Furthermore, the design is modular and therefore easily scalable.
As mentioned, the waste heat provides most of the energy needed, but the electrical demand is driven by the fan for adsorption (56%), vacuum pump (23%), chiller (18%), and fan during cooling (3%). Given that access to renewable energy will become highly competitive in the near future, our process is optimized to minimize electrical energy consumption. Since low-grade waste heat is abundantly available and there are no other viable recovery techniques suitable for the low temperature range that NeoCarbon operates at, an information that has been substantiated by waste heat research institutes during discussions, the thermal demand does not pose a bottleneck for our approach.

Best in class DAC: Capture potential of 1.3 Gigaton of CO_2 per year by leveraging low-grade waste heat

Our market analysis shows that by leveraging waste heat that is not being used for anything else in the low-grade temperature range we target, we have the opportunity to capture 1.3 billion tons of CO_2 removed per year. Here, we specifically leverage low-degree waste heat (35-200°C) which is not being used for anything else, as it is for example quite difficult to use for producing electricity. Waste heat with a temperature between 35-200°C can be found in almost all industries, for example in cement production, iron and steel, pulp and paper, chemicals, etc.

Besides the overall potential of waste heat, we also validated the potential on specific sites. By leveraging the sites of our pilot customer only in their home market of Japan, we have identified 340 sites where each has a capture potential of >10,000 t/y (overall removal potential of 144M t/y). At the site of a German cement plant, we can capture 350,833 tons per year by leveraging their waste heat at 130°C. Additionally, a US cement plant produces up to four times more cement than German plants. This significant production volume translates to a potential capture capacity of over 1 million tons of CO_2 per year when leveraging the waste heat of a single site. Therefore, waste heat does not limit us in the overall removal potential, nor in the removal potential per individual industrial site.

Best in class DAC: Already two autonomous carbon capture modules in operation and validated technology

Earlier this year, we installed our pilot module at the site of our pilot customer in western Germany. With a nominal capacity of 10 tons per year, it has already completed multiple autonomous cycles, validating the technical feasibility of integrating waste heat from a normally operating industrial site in real-life conditions.
Previously, in Q2 2023, we completed our second product iteration, the NeoBox, with scalable engineering and autonomous operation. This brought NeoCarbon to the kilogram-scale of CO2 captured and liquefied already over a year ago. This differentiates us also significantly from many other Direct Air Capture companies that are still focusing on lab-scale operations.

In addition, we also performed an extensive technical due diligence with Fraunhofer IPT, who primarily focuses on predictability of new technologies. The main conclusions of the report state explicitly the following: “NeoCarbon’s reactors operate with lower OPEX compared to their competitors by reducing the required external energy input”, “Differs significantly from the status quo”, and “The capturing volume can have the same scale as a centralized approach”.

Hollow fiber and temperature vacuum swing proven approaches for DAC

The hollow fiber reactor makes NeoCarbon clearly significantly different and substantially more performant than other DAC companies.

First of all, temperature vacuum swings are a very mature technology, and thus can benefit from much faster deployment, scaling, and iterative learning, a much needed benefit in the current climate situation. Specifically about using hollow fibers, maturity and supply chain are also no concern, considering that the technology has already been used at scale in industrial applications for decades, also within potentially very aggressive environments, like point-source capture or waste water purification.

Secondly, alternative promising approaches such as electrochemical companies are only valuable if they can leverage a very high amount of renewable energy - which will be in short supply for the next decade at least, effectively displacing dirtier energy to other uses. Finally, electrochemical approaches still suffer from large challenges that have not been resolved, and which would make them lose their energy edge at industrial scale (e.g. cooling needs, water consumption, bubble formation, cleaning of electrodes …). This lower maturity is also explicitly stated in BCG’s research: “Shifting the Direct Air Capture Paradigm”.

Storage secured through a MoU with Carbonaide and connection to CO2 pipeline infrastructure

Our Direct Air Captured CO2 will be stored by Carbonaide, with whom we signed an MoU. Due to this partnership, we secured an alternative for geological storage for sequestration in the upcoming years. In addition, at scale, the cement plants from which we leverage the waste heat will be attached to the German CO2 pipeline network, thus enabling us to secure the complete value chain of our captured CO2 for early installations and at complete capacity. Specifically, Germany is planning to construct 4,800 kilometers of pipelines to link high-emission industries (which generate significant waste heat, even after decarbonization pathways) to designated offshore storage sites in the North Sea.

Innovation areas addressed: DAC Innovation, Industrial Integration, Additional Revenue Sources, Environmental/Economic Co-Benefits

Due to our approach and partnerships, we align to many innovation areas, specifically:

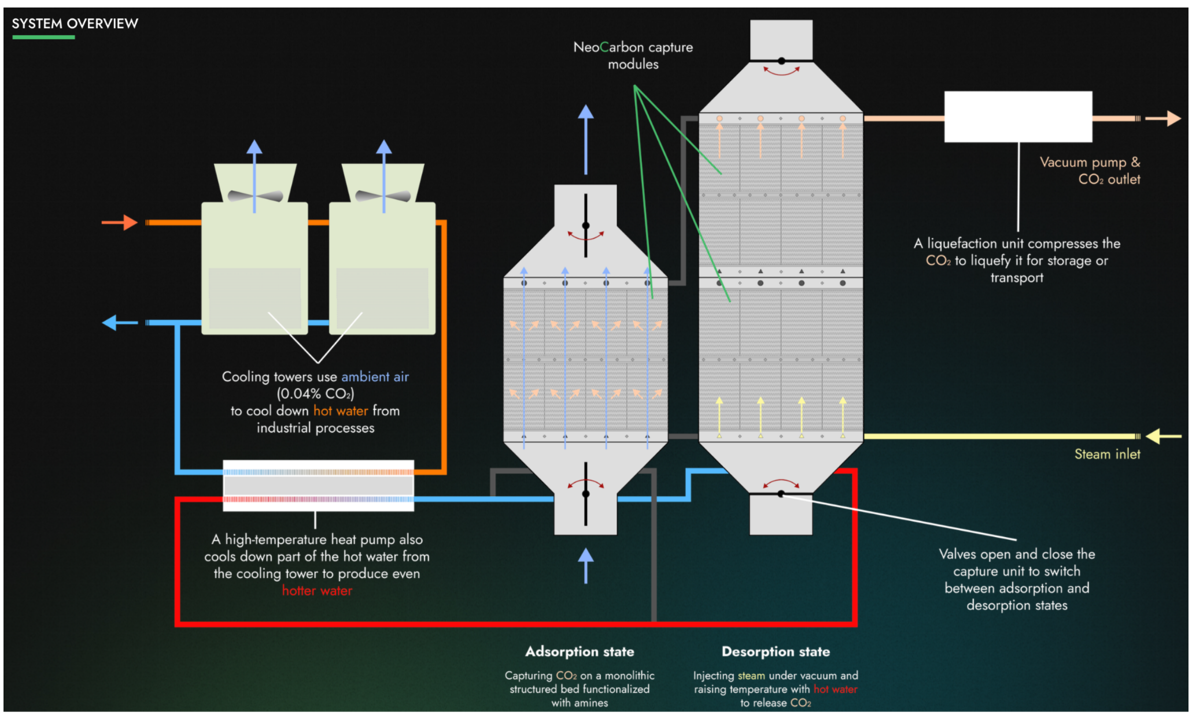
- DAC Innovation: By developing our monolithic reactor design with our approach, we fundamentally innovate on the core process of Direct Air Capture, which is protected via our patent strategy.
- Industrial Integration: By leveraging waste heat and operating on existing industrial sites, we can achieve cost-efficient and rapidly scalable Direct Air Capture. This also differentiates us significantly from other Direct Air Capture companies that do greenfield operations.
- Additional Revenue Sources: By storing CO2 in concrete, we create a valuable product that generates alternative revenue, thus decreasing our dependence on generating all revenue

via carbon removal credits.

- Environmental/Economic Co-Benefits: Another benefit of storing CO2 in concrete is the reduced need for cement in the process. Consequently, this also reduces emissions on top of the CO2 that is permanently stored in the concrete. Specifically, for each ton of Direct Air Captured CO2 utilized in concrete, we avoid another 0.18-0.6 ton of CO2 emitted. Additionally, by sharing revenue with large industrial players, we incentivize them to participate in carbon removal early on and make the decarbonisation journey more attractive to them.

Schematics and figures

The figure below illustrates how waste heat is utilized by a liquid-to-liquid high-temperature heat pump. It's important to note that a heat pump is necessary only when the waste heat temperature is significantly below 95°C. In many instances, such as in cement production, we have validated that waste heat of 130°C is commonly available. This eliminates the need for a heat pump, which consequently significantly reduces the electrical energy required for our process. Specifically, when utilizing heat at 45°C, the electrical demand is 1.28 MWh/t for our at-scale installation. However, when utilizing heat at >95°C, this demand decreases to 0.21 MWh/t. It is still notable that we have developed our process to be able to work with waste heat temperature this low, making it extremely flexible and reducing barriers to reaching large scale removal.



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

[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

First removal project at a cement plant

Our first carbon removal project will be installed while leveraging waste heat of a German cement plant. Here, we will install our 62.5 t/y module in Q1 2025, before installing our 500 t/y plant in H2 2025. In 2026, we will further upscale the capture capacity to 1,500 t/y. Due to our modular system design and significant availability of waste heat, we can reach this capture capacity on the same site. When leveraging all the waste heat of 130 °C of the German cement plant, we can capture 350,833 tons per year, marking the significant capture potential on one site. One particular German cement plant is at the forefront of our discussions. However, we are actively engaged with nearly all the major German cement companies and have received positive feedback from most of them.

Objective carbon removal by measuring and externally validating the complete value chain

One of the main advantages of Direct Air Capture is the precise measurement of captured CO2. We use low- and high-concentration CO2 sensors at both the inlet and outlet to measure the captured CO2 down to the gram at any given moment. Once captured, the CO2 is stored by our partner Carbonaide. Carbonaide already stores CO2 on an industrial scale. Storing CO2 into concrete has been experimentally and scientifically validated as permanent removal, aligning to Frontier's criteria of storing the CO2 for over 1000 years.
Additionally, the entire process will be validated by Puro, particularly in alignment with the Carbonated Materials methodology. This comprehensive validation ensures the highest quality of carbon removal credits and enhances the objectivity of our measurements, consequently leading to delivering the highest quality of carbon removal credits available.

Current cost breakdown & factors influencing price decrease to $82/t

Currently, our capture price is $1,840/t. This is mainly driven by the capture capacity of 10 tons of our carbon capture modules, meaning the CAPEX is relatively high compared to the amount of CO2 captured annually.

From a cost perspective, the following factors primarily drive the cost reduction when transitioning from a standalone pilot-size module with a packed bed design to a 10K t/y plant with a monolithic reactor design: 39.53% is attributed to the implementation of the monolithic reactor (mainly due to OPEX savings), 18.37% to waste heat integration, 7.87% to the novel sorbent, and 18.01% to external improvements such as economies of scale and enhancements in heat pump efficiency.

As a result, the TEA indicates that we will achieve a carbon removal cost of $82 per ton. This price includes a revenue share with the industries from which we leverage the waste heat, as well as a storage cost of $16 per ton.

Pathway to remove 1.3 Gt per year

Scaling

By retrofitting industrial waste heat below 200 °C, and only retrofitting the part that is presently unutilized, we have the potential to capture 1.3 Gigatons of CO2 per year. The main industries for waste heat are chemical manufacturing (22%), iron & steel (22%), non-metallic minerals (e.g. cement) (14%), pulp and paper (13%), food and tobacco (9%), textile and leather (2%), wood and wood products (2%), waste-water treatment (1%), plastic & rubber (1%).

Furthermore, we evaluated the potential at existing locations:

- Utilizing the infrastructure of our pilot partner, only in their home market of Japan, we can capture up to 144 million tons of CO2 per year. Over 340 Japanese sites from just this partner each have the potential to capture more than 10,000 tons annually.
- By harnessing the waste heat from a single German cement plant, we can capture 350,833 tons of CO2 per year.
- Similarly, by leveraging the waste heat from a German data center, we can capture 200,000

removal of hundreds of millions of tons, are otherwise compelling enough to be part of the global portfolio of climate solutions.

tons of CO_2 annually.

Concluding, there is significant potential to remove a vast amount of CO_2 while leveraging waste heat.

Transforming complete industrial sites to Net-Negativity

Another interesting consequence of leveraging existing industrial sites is the opportunity to turn complete industrial sites into carbon sinks. We validated that, by combining point-source carbon capture, and leveraging waste heat for Direct Air Capture, we can capture more CO_2 than what is emitted overall. This approach has been validated using an existing industrial site emitting 1,084,000 tons per year. By installing point-source technology, it is possible to economically capture up to 74%, totaling a maximum of 800,000 tons per year. However, by also leveraging the site's waste heat, currently unused, we can capture an additional 32%, or 350,833 tons yearly. In total, this results in capturing 1,150,833 tons annually while emitting 1,084,000 tons, effectively transforming the entire factory into a carbon sink. To deploy our modules effectively, we signed a MoU with Cool Planet Technologies, who have started installing a point-source installation at Holcim's site, and have further agreements with large industrials like Carmeuse.

Offtake by Frontier unlocks first removal project

Currently, we operate two autonomous carbon capture modules. Our module 'NeoDuo' is integrated at a partner's industrial site, while the other module 'NeoBox' has been operating at our facility for over a year. The fact that we are already working with customers, including two projects creating revenue demonstrates significant industrial interest in our technology. However, to further advance our development and kickstart our carbon removal efforts, securing an offtake agreement with Frontier will incentivize our industrial partners to install the first carbon removal plant on their site. In addition, many carbon removal buyers rely on the thorough and expert due diligence of Frontier to gain the confidence to purchase carbon removal credits of NeoCarbon. Given the potential on one site and the similarity of industrial sites in terms of waste heat characteristics, we anticipate that this initial deployment will enable large-scale carbon removal projects in the EU and US, transform entire factories into carbon sinks, and address the climate crisis at the necessary scale.

Conclusion

This first carbon removal facility could become a game-changer for industrial sites worldwide, facilitating large-scale and cost-effective carbon removal. Specifically, we have the opportunity to capture 1.3 Gigaton of CO_2 per year at a cost of $82/t, while delivering the highest quality of carbon removal credits available. An offtake agreement with Frontier would kickstart this first carbon removal plant.

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

Technical

1. Risk: monolithic reactor design at scale performance. The monolithic reactor is being empirically tested on a small scale and shows promising results, primarily in terms of decreased electrical energy need and sturdiness. However, this reactor design will be implemented in a full-size module in Q4 2024/Q1 2025, meaning the validation on a larger scale will happen soon.
    a. Risk mitigation: We have performed extensive testing to mitigate the risk of underperformance at a larger scale. In addition, we develop this monolithic reactor in collaboration with a leading research institute, who is also experienced in upscaling

this kind of membrane from small-scale testing to full-scale industrial size.

2. Risk: Technological upscaling of the modules. We plan to increase the capacity of our modules by a factor of 6 compared to current operations in Q4 2024/Q1 2025, and further upscale by a factor of 50 in H2 2025, compared to the size of our current module. Depending on the speed of learning there is a risk of not moving fast enough or not achieving the learning curve we want.
    a. Risk Mitigation: We currently operate two modules, which have provided valuable insights into autonomous operation in real-world environments. For instance, we discovered how to mitigate the impact of debris and other impurities in the air channel (e.g. mosquitoes), ensuring the modules run smoothly. Such practical challenges can only be identified through real-life operation, not in a lab setting. Additionally, we utilize our strong advisor network to address these issues proactively, and we already have discussions with manufacturing partners to produce our modules at scale.

Project execution:

3. Risk: convincing large industrial players. We are currently in discussions with various German cement plants to utilize their waste heat. Our business model involves revenue sharing with the companies whose waste heat we leverage. However, we have encountered some hesitation from these companies due to the absence of an offtaker for the project.
    a. Risk Mitigation: We clearly outline the capture potential and corresponding revenue share to persuade buyers to participate now. We are also actively engaging with various offtakers to secure the first agreement, which will convince large industrial players. Given the substantial quantities of waste heat per site and the large number of sites with waste heat, we are confident that this business model can be replicated extensively.

Financing:

4. Risk: Debt Financing with Favorable Conditions for Large-Scale Installations. We recognize that Direct Air Capture is a capital-intensive technology. Debt financing is essential for scaling up installations, and high interest rates or failure to secure the necessary funds could limit our growth.
    a. Risk Mitigation: To address this risk, we have several strategies in place. First, we are in discussions with major industrial partners to license our technology, with one letter of intent already signed. This would allow the industrial partner to use our modules under a white-label agreement. Second, we are exploring forming joint ventures with some large industrial players, which would improve our position of securing favorable lending terms. Third, even if NeoCarbon is solely responsible for financing the machines, we are in early discussions with various debt financing institutions to understand the key performance indicators (KPIs) needed to secure over $100M for our large-scale installations. This involves demonstrating technological validity and securing customer commitments for project offtake.

Concluding

As we are scaling a hardware solution, we acknowledge the risks associated with our project. However, we are committed to transparency and proactive risk management. We are confident that none of the aforementioned risks will prevent NeoCarbon from performing Direct Air Capture at scale, and an offtake agreement will kickstart the next phase of our development.

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*	833

uncertainty discount proposed in 5c)	
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	H1 2027
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	$496
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	$600

[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).