Frontier

Kairos Carbon Limited

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

Kairos Carbon Limited (fka Exocarbon)

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

United Kingdom

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

Megha Raghavan

Brief company or organization description <20 words

Kairos uses supercritical water oxidation to convert wet biomass into CO2 for permanent geological storage

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

Technologies aimed at permanent atmospheric carbon removal must strike a careful balance between multiple criteria: high permanence (>1,000 years), easy and precise measurement and verification, low (or no) energy input requirement, scalability, cost, and co-benefits to the environment and society. Kairos's novel biomass pathway can be best-in-class across all these criteria and enable rapid deployment of CDR at low cost, reaching Mt scale by the early 2030s.

Furthermore, our technology addresses several of the priority areas identified in Frontier's RFP. First,

[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.

we are focused on addressing contaminated and unused waste biomass, with a focus on sewage waste and unutilized animal slurries, as well as municipal solid waste, at scale. Second, we aim to recover nutrients from our wastes for reuse in e.g. agriculture, thereby preventing nutrient depletion. Third, this enables us to offer low-cost carbon removal by providing an additional revenue source from the sale of these materials. Fourth, our project has multiple environmental co-benefits: by preventing these wastes from being landfilled / spread, we can prevent the runoff of harmful leachates into the environment. In fact, our technology is one of a very small number of technologies that can destroy robust pollutants contained in sewage and other similar wastes. Finally we can also prevent air quality problems that arise from landfilling and spreading these wastes or leaving them in "lagoons", as well as pre-empt them from emitting methane and potentially NOx.

Within the biomass space, our project is notable for its high yield of carbon from feedstocks (targeting >90-95% yield) as well as for capitalizing on an abundant and novel set of waste streams (those that are wet and contaminated). Finally, we aim to integrate with industrial facilities such as sewage treatment plants, feedlots, and MSW sorting facilities to enable cost-effective and rapid scaling.

Kairos uses supercritical water oxidation (SCWO), a hydrothermal process, to break down organic wastes – particularly those that are wet or contaminated – into CO_2 gas, inorganic materials, and clean water. In doing so, we can transform a problematic waste feedstock into multiple useful products and corresponding sources of revenue. Carbon is captured from the atmosphere through photosynthesis – leveraging the sun's energy to do the hard work of removing carbon from low atmospheric concentrations – and is incorporated to the cells and tissues of plants throughout terrestrial and ocean ecosystems. These plants are then used by humans and animals, with billions of tonnes of plant matter ending up in sewage sludge, animal manure, municipal solid waste, and other waste products each year. Absent any human intervention, the carbon in these wastes is emitted back into the atmosphere in a short time frame. In fact, these wastes emit not only CO_2, but also methane – a far more potent greenhouse gas, particularly in the short term. Kairos aims to step in at this point, processing these wastes to capture the carbon dioxide as CO_2 gas, while also recovering the minerals and clean water in those wastes for use in agriculture and industry. Our technology is capable of processing a wide range of feedstocks, but is particularly suited to these wet and contaminated wastes which others struggle to address.

Using SCWO has several benefits. First, it takes advantage of photosynthesis and the sun's energy to capture carbon, rather than putting additional strain on grid energy. Second, the reaction runs within a "closed system," i.e. one where the volume of carbon captured can be precisely measured, enabling high precision and verifiability of removal volumes. The CO_2 can then be pumped underground – into basalt formations or other geological formations – where they can be monitored for long-term storage for >1,000 years using existing and established techniques. Finally, SCWO is relatively feedstock-agnostic, which means that we can focus on wet, contaminated, or otherwise "difficult" forms of waste biomass (and destroy robust organic pollutants like PFAS and microplastics in the process). This is a critical part of our value proposition: rather than competing for a limited pool of feedstocks suitable for multiple use cases, we will focus on the wastes that few others can use. Over time, the best feedstocks for our process may evolve as patterns of waste production change, alternate technologies for waste processing develop, and markets and regulations evolve. By using a feedstock-agnostic process, we will be able to adapt and fill whatever gaps remain for disposing of organic wastes, and in particular, provide a safe disposal route for wastes polluted with contaminants.

The carbon removal potential from using SCWO is enormous. Estimates show that there are >10 Gt (dry tonnes equivalent) of organic waste that would be suitable for SCWO, corresponding to about 10 Gt of CO_2 removal potential when considering the %C in these materials as well as stoichiometric ratios. While some of these wastes might be better diverted to other uses – including energy and materials production – the majority are unsuitable for these use cases, leading to them being landfilled or incinerated. These disposal routes represent a massive loss of resources, as carbon (as CO_2 and CH_4) is emitted back into the atmosphere while water and nutrients run off and are lost to the environment. Kairos aims to unlock gigatonnes of carbon removal by targeting this vast pool of previously unsuitable biomass feedstock, while also preventing nutrient and water loss. Additionally, because we focus on wastes with high methanogenesis potential, we believe that we can have an impact far beyond the volume of CO_2 that we capture. This is particularly important when considering the short-term warming potential of methane and the urgency of reducing near-term warming.

This approach has several environmental co-benefits: by preventing these wastes from being landfilled, we can prevent nutrient runoff and eutrophication. We can also prevent more dangerous compounds – such as PFAS, microplastics, and antibiotics – from leaching into the environment. This is particularly important for the types of waste that we will focus on, i.e. those that are highly contaminated. SCWO has been used as one of the few reliable methods for reliably destroying these harmful compounds Some of our target wastes can also be detrimental to air quality when landfilled, spread, or left in slurry lagoons, causing everything from odors to asthma in nearby communities.

Additionally, nutrient and mineral depletion is a major concern and has been identified by the UN as a critical problem facing global food security. The wastes that we look to process contain a variety of valuable nutrients and minerals – which are typically lost to the ecosystem in other disposal routes. Kairos is unique in that we capture those valuable materials so they can be recycled, displacing the need for virgin materials, which has three benefits. First, many inorganic mineral reserves are depleted, with already past peak production. This poses a threat to global food security. Second, mineral mining is detrimental to the environment. By displacing it we can prevent environmental damage. Lastly, nutrient runoff has led to eutrophication and other problems, which we can prevent by collecting, separating, and properly deploying it where it is needed.

In order for carbon removal to scale, we believe that it is critical to unlock new sources of scale potential. RMI's CDR roadmap and the BICRS roadmap highlight the scaling constraints on various CDR pathways including biomass-based pathways, and demonstrate a need for new pathways that can scale rapidly. In particular, biomass-based pathways are primarily constrained by the availability of suitable sustainable biomass. For this reason, we believe that converting wet contaminated wastes, of which there are several gigatonnes, can be a critical lever to reaching scale for carbon removal.

Relative to other technologies which seek to address these types of wastes, we believe that we have two advantages. First, other technologies typically cannot recover minerals or nutrients in a usable form. Some hydrothermal processes recover them in a form that can be reused for road aggregate or other low-value purposes, but these do not address the global issue of nutrient depletion. Secondly, our process can drastically reduce transportation costs and therefore address a much wider range of feedstocks in more diverse geographical areas. This is because it strips out the water content from the incoming feedstocks – typically >80% of the total volume – leaving only a much smaller volume of CO_2 and minerals to transport to storage sites or other destinations.

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

We are building facilities which can receive organic wastes (such as sewage sludge, animal manures, and MSW); process it using SCWO; and recover the CO_2 at a pressure and purity level suitable for geological storage. We will also recover clean water and inorganic minerals. In particular, we are currently looking to build a small pilot facility capable of removing 25 kg / hour of CO_2 when accounting for downtime This would be housed at Cranfield University's dedicated pilot testing facilities. These facilities are approved for testing high-pressure and high-temperature processes, and are often used by industry to trial, develop, and validate advanced processes. Because of this, Cranfield has health and safety protocols in place, as well as highly experienced and skilled staff to support testing. Similarly, Cranfield brings all relevant permitting and protocols for working with

[2] We're looking for approaches that can reach climate-relevant scale (about 0.5 Gt CDR/year at $100/ton). We will consider approaches that don't quite meet this bar if they perform well against our other criteria, can enable the removal of hundreds of millions of tons, are otherwise compelling enough to be part of the global portfolio of climate solutions.

organic wastes, as well as an onsite sewage sludge and relationships with relevant waste producing industries. Working with Cranfield staff will also provide a degree of external validation for Kairos. All the required analytical facilities are also based onsite.

We plan to work with a third party for geological storage of the CO2 we produce, and are in discussions with a few prospective partners.

Our estimated costs at this stage are high – in the low thousands of dollars per net tonne – with the vast majority of that corresponding to capex depreciation. Given the (very) small size of this facility, we would expect these costs to be far lower as we scale up. Based on our conversations with fabricators, this is a natural benefit of scale that will be realized as we deploy larger facilities. Reducing our cost of capex / tonne is the most significant lever to reduce our cost of delivery.

Similarly, we are expecting to need far more staff per tonne delivered at this scale than we will in the future. In fact, we expect that a facility ~40x the size would only need 2-3x the number of staff, and potentially less over time as automation increases.

Finally, we will ideally optimize our facility to be completely energy-neutral rather than purchasing electricity.

These cost savings alone would be enough to offer $<100/t credits, but there are further optimizations that would enable even lower carbon removal costs.

First, we can optimize our economics by increasing the revenue we earn from selling inorganic materials. For simplicity, our early development work is focused on recovering phosphoric acid (valued at $1300/t H3PO4). However, there are numerous other inorganic materials – silicates, calcium, and possibly even lithium – which could be recovered from the wastes that we are targeting. Over time, we will seek to maximize value recovery from these other sources to further reduce the price per tonne of CO2 and enable more circular reuse.

Our early TEA work assumes low transportation costs. This is because we have identified 100's of kilotonnes of removal potential that would not require much transport; i.e. where feedstocks and injection sites are already colocated. As such, we have begun discussions with relevant feedstock providers and injection site operators at these sites, and have received LOIs from several already. Our aim will be to target this type of site first, and minimize the need for any transportation in the next 5-7 years.

Over time, our ambition is to scale this pathway to well over 0.5 Gt of scale, which will require us to transport materials from source to facility to injection site. While there are several gigatonnes of suitable material available, not all of it is colocated with existing (or even suitable potential) injection sites. Based on our conversations with injection site operators, we will aim to develop a "hub and spoke" model which minimizes the emissions and costs associated with transportation. Crucially, the SCWO process results in a ~5x volume reduction from feedstock to CO2, primarily due to the removal of water from the feedstock. As such, we can minimize transport costs by aiming to site processing facilities as close as possible to feedstocks, and transport the output CO2 for longer distances if needed. Our analysis of the transport costs for doing this, assuming a combination of rail and truck transport, indicates that we should be able to profitably access feedstock across both the US and Europe as needed. If additional rail or pipeline infrastructure is made available this would further reduce costs. We will also leverage existing DAC protocols for MRV for the sake of consistency and simplicity.

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: Historically SCWO processes have suffered from corrosion and plugging due to the inorganic salts formed during the reaction. We are mitigating this through our novel reactor design

that prevents residues from attaching to reactor walls and reduces corrosion. This also helps to protect downstream equipment by separating out inorganics in the reactor itself. We have conducted sensitivity analyses to better understand the impacts of high corrosion rates and are confident that our process can still deliver <$100 credits even in the worst case scenario. Technical: We are aiming to reduce energy requirements of the system but have not yet proven the extent to which this is possible. Even in our worst case scenario, the system energy requirement is low enough that it should not significantly harm our TEA or LCA. MRV: As this is a new pathway for CDR, we will need to develop a custom methodology for MRV. To mitigate this, we have begun to engage with standards bodies and registries already. These conversations have confirmed that the MRV for our system should be relatively straightforward and can borrow from e.g. DAC storage protocols to simplify methodology development Permitting: Our process relies on geological storage, for which permitting can be complex to navigate. We are in conversation with operators who own existing permitted sites to avoid taking on this risk ourselves. We are also in discussions NGOs in the CDR space in US and Europe who can help to understand and influence the regulations surrounding permitting for carbon storage. Ecosystem: high pressure / temperature processes require specialized fabricators and knowledge to design and produce reactor vessels to the right standards. We have already identified a shortlist of highly specialized fabricators in the UK who are capable of producing equipment to code, and can work with the materials we require. Feedstock availability: Reaching >0.5 Gt of carbon removal will require us to secure access to vast quantities of organic materials. Additionally, similar to DAC, we will ideally need to be sited near geological injection sites. To plan for this, we have carried out an initial mapping exercise with Innovate UK and Isle Utilities to identify key producers of organic wastes overlaid with geological storage potential. From this, we have identified areas where Mts of material are produced in proximity with suitable storage locations, and will focus on these as our initial targets over the next 5-10 years as we scale. In the short term, we have received LOIs from companies producing 100s of kt of waste, enough to sell out our capacity for at least 5 years.

d. **Proposed offer to Frontier:** Please list proposed CDR volume, delivery timeline and price below. If you are selected for a Frontier prepurchase, this table will form the basis of contract discussions.

Proposed CDR over the project lifetime (tons) *(should be net volume after taking into account the uncertainty discount proposed in 5c)*	150 t CO2
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q1 2027- Q1 2028
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	$3162
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	$3000

[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).