Frontier

CarbonRun

Carbon Dioxide Removal Prepurchase Application

Summer 2023

General Application

Public section

The content in this section (answers to questions 1(a) - (d)) will be made public on the [Frontier GitHub repository](#) after the conclusion of the 2023 summer purchase cycle. Include as much detail as possible but omit sensitive proprietary information.

Company or organization name

CarbonRun Carbon Dioxide Removal Ltd.

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

Halifax, Nova Scotia, Canada.

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

Dr. Shannon Sterling

Brief company or organization description <20 words

CarbonRun amplifies geochemical reactions in rivers to permanently, safely and verifiably sequester carbon dioxide and deliver socio-environmental benefits.

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

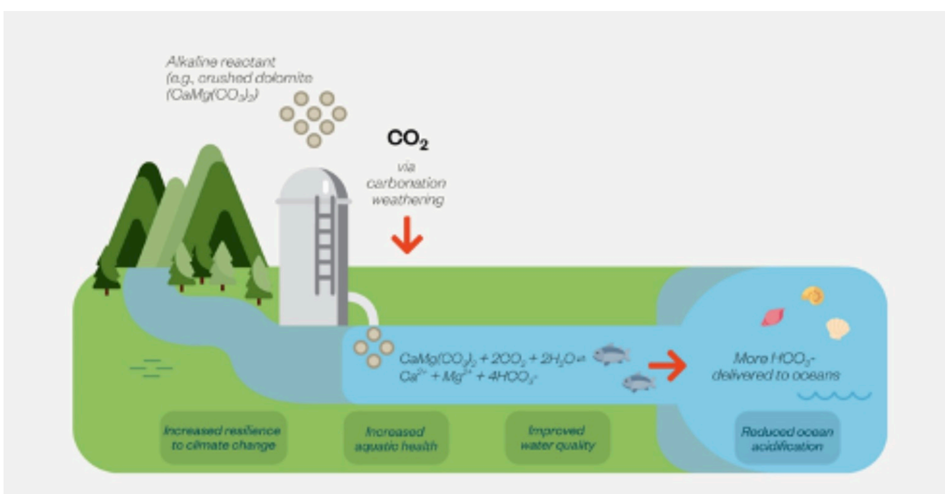
a. **Description of the CDR approach:** Describe how the proposed technology removes CO_2 from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If your 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. Aim for 1000-1500 words.

The CDR Approach. Based in Nova Scotia, Canada, CarbonRun has developed an innovative method called river alkalinity enhancement (RAE) to effectively draw down CO_2 (Sterling et al., 2023a). By introducing alkaline materials into rivers, RAE converts the abundant CO_2 into stable HCO^{3-} and securely transports it to the ocean where it is stored for over 1,000 years (Figure 1.1). CarbonRun offers a fresh approach to carbon removal, diversifying our options and addressing challenges faced by existing methods. With dedication and ingenuity, CarbonRun is leading the way toward a sustainable future, contributing to the well-being of our planet and future generations. Together, we can make a tangible difference and create a more environmentally balanced world.

Figure 1.1 Mechanisms of carbon dioxide drawdown (CDR) from addition of alkalinity to rivers (red arrows), and co-benefits (round rectangles). The lighter blue area represents the treated water plume in the river and ocean (from Sterling et al., 2023a).

Our technology removes CO_2 from the atmosphere by adding safe alkaline materials to rivers where they dissolve in carbonation weathering processes, e.g., for dolomite (Equation 1). We strategically add alkalinity in the final reaches of the land-to-ocean carbon cycle, unlocking numerous environmental co-benefits (Figure 1.1).

$$CaMg(CO_3)_2 + 2H_2O + 2CO_2 \rightarrow 4HCO_3^- + Ca^{2+} + Mg^{2+} \quad (1)$$



[1] We use "project" throughout this template, but note that term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

Best-in-class. Our system is best in class because:

- It's **simple MRV process** uses the natural land-to-ocean continuum that concentrates element exports to the ocean via river networks.
- It is **safe.** This process is well-understood having decades of long-term studies and delivers important environmental co-benefits to river and estuarine systems. If undesirable consequences are found, it can be decommissioned quickly without long-lasting effects to the ecosystem.
- It has a clear path to become **affordable** at scale. It uses the energy of rivers to do much of the dissolution and transportation work, and it employs safe and relatively inexpensive sources of alkaline feedstock.
- It uses the network of rivers and their renewable sources of water to create a **path to scaling** up within safe levels of alkalinity enhancement to 0.5 Gt CO_2/yr, thus providing a diverse and meaningful part of carbon removal portfolios.
- It is **fast**; rivers are dilute and promote chemical disequilibrium at point inputs of alkaline material through continuous refreshing via advective transport.
- It has a **small physical footprint** (< 45 m^2).
- Its location on rivers provides an easily accessible place-based center for learning, training and **community engagement**; as we have learned, demonstration of instantaneous chemical changes in the river make for a great engagement tool with the community.

Differentiation. CarbonRun differentiates from other organizations because we are the first company to use rivers as the primary medium for CDR reactions. We have developed a CDR pathway that creates and quantifies river-based carbon dioxide removal, setting us apart from traditional methods such as enhanced terrestrial weathering and ocean alkalinity.

Rivers, and their efficient mixing dynamics, lead to exceptional energy efficiency, MRV certainty, and environmental co-benefits. Inland waterways not only provide an abundant source of pCO_2 but also efficiently transport their contents to a well-defined terminus at the head of tide. These unique characteristics of rivers set us apart from other CDR technologies that rely on costly and energy-intensive processes, such as accelerating reaction kinetics in industrial settings or underground CO_2 pumping systems (DAC).

CarbonRun further differentiates itself from other CDR companies with its team that has a combined 30 years of experience deploying alkalinity enhancement projects to restore watersheds and designing monitoring programs to measure the impacts. At

Our project addresses the following **Priority Innovation Areas** listed in the 2023 RFP, offering innovation in both ocean-based and geochemical CDR pathways:

- *Novel approaches.* Our project will be the first commercial RAE project in the world, thus delivering considerable advancements to the suite of CDR options (Sterling et al., 2023). Our project is novel in its use of carbonate minerals as alkaline feedstock in an open system and in its deployment in river waters that are dilute with high pCO_2.

- *Cross-cutting technologies.* Our technology directly tackles measurement, durability, and MRV challenges faced by enhanced terrestrial weathering (ERW) and ocean alkalinity enhancement (OAE) by using rivers to measure element exports at-a-point. In doing so, CarbonRun connects these two crucial areas of CDR and fills critical data gaps for these technologies.

- *Ocean-based CDR innovation.* We have developed an ISO 14064-2 compliant RAE MRV methodology. Our RAE MRV advances quantification methods of OAE by adapting simple hydrological paired catchment approaches (e.g., Taylor et al., 2021) to quantify gross CDR and provide robust baseline estimations, and that reduces assumptions necessary in the quantification (see section 5). Our quantification method uses at-a-point river flux estimations that integrate all upstream carbonate alkalinity inputs and outputs such as photosynthesis, precipitation, and other unanticipated gains and losses (Figure 1, section 5, below), as rivers transport dissolved and suspended constituents from the watershed to a single outlet point.

- *Geochemical CDR innovation.* RAE advances geochemical methods by developing a new approach to accelerate weathering rates by locating weathering reactions in river media which is dilute, has high carbonate acidity, and has a maintained chemical disequilibrium through river hydraulic processes. Our observations show that dolomite dissolves in rivers in the right conditions in a matter of minutes. This kinetic enhancement comes with limited penalty to overall net-negativity. This methodology reduces assumptions as we directly observe RAE impact downstream from our project sites.

- *Assessment of potential associated ecosystem effects.* RAE draws upon a long-history of ecosystem-effects monitoring (Sterling et al., 2023a), and our data-driven approach and data-driven models will increase global capacity to monitor ecosystem effects of CDR.

Project objectives: What are you trying to build? Discuss location(s) and scale. What is the current cost breakdown, and what needs to happen for your CDR solution to approach Frontier's $100/t and 0.5Gt targets? What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

Our [redacted] River Alkalinity Enhancement (RAE) Project for Carbon Dioxide Removal (CDR), would be the first commercial trial of RAE in the world. The objective of this project is to develop and implement a RAE CDR [redacted] that captures and permanently removes carbon dioxide while helping restore river and estuarine ecosystems for fish and wildlife.

Additional project objectives include expanding our understanding of how RAE technology can benefit freshwater and marine life and ecosystems, increasing efficiency and cost-effectiveness of the RAE CDR to inform scaling up of the technology, and mobilizing and empowering stakeholders to understand, engage and promote the project and its benefits.

Locations and Initial Scale. The project will take place [redacted] in [redacted] Nova Scotia (NS)[redacted]. This area has been impacted by coal mining and by a pulp mill that was closed in 2020. The project location is [redacted] located in a [redacted] rural NS area, and will be run in a close partnership with government, local groups and Indigenous communities.

The dosing infrastructure is designed to adapt existing lime-dosing technology from lime dosers such as those found in Scandinavia and parts of NS to increase carbon capture efficiency, and has a small footprint > 45 m^2 on the edge of the river (Figure 1.2). As it is designed to be deployed carefully in suitable locations, our project will also deliver important ecosystem co-benefits and opportunities for community and rural development engagement and actions.

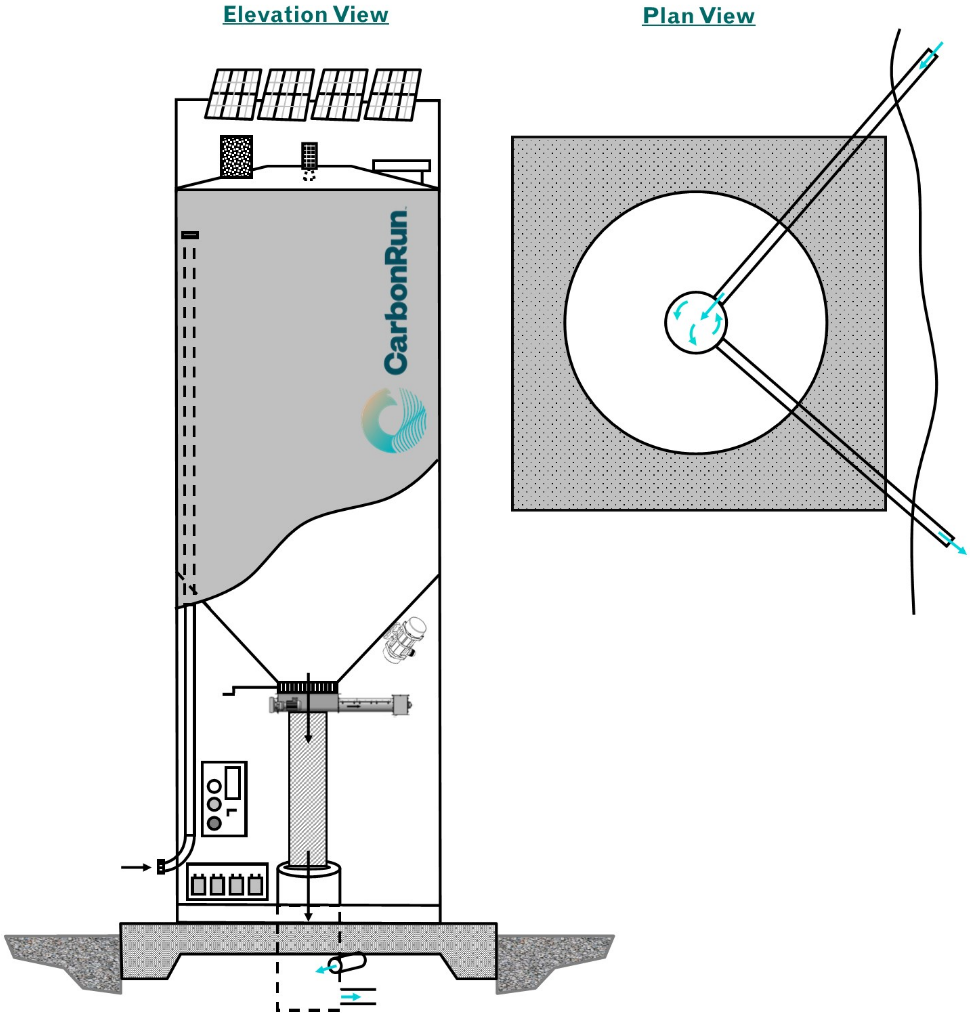


Figure 1.2 Schematic design of a passive intake alkalinity doser. Here, water flows into a mixing well beneath the doser via passive hydraulic flow, typically using 1-2% sloping pipe. Limestone power is dropped into the turbulent mixing well and the limestone + water solution flows back to the river passively.

Scaling up. This project will be the first in a network of point-additions (dosers) of alkalinity to rivers. To approach Frontier's 0.5 Gt CO_2 yr^{-1}, RAE dosing sites must be expanded to river sites across the globe (Figure 1.3). One of our modeling scenarios shows that by deploying in low-alkalinity rivers, and raising the alkalinity to 0.6 mmol L^{-1}, CDR capture can reach 100s of millions of tons CO_2 per year, and can be increased by deploying in moderate-level alkalinity rivers.

Figure 1.3. Amount of CDR increase (Mt CO_2e yr^{-1}) by raising low alkalinity watersheds (< 0.6 mmol L^{-1}) to threshold of 0.06 mmol L^{-1} (from Sterling et al, 2023a).

Timing. Our CDR demonstration project will start delivering 3rd party verified carbon credits by mid 2024 and continue over a twenty-year period. These initial locations have a potential range of annual carbon dioxide removal of 200-1000 tCO_2 yr^{-1}.

Costs. The current cost breakdown can be simply demonstrated as our adaptive technology redeploys existing technology and hardware in a novel fashion. Our costs are well known and clearly defined and are based on real-world costs and existing mine-to-market models.

The largest costs associated with our technology are related to our 'alkalinity dosing' hardware and costs for sourcing and transporting alkaline material to application sites. Application and MRV sites are automated and reduce overall costs substantially.

For our solution to approach $100/t and 0.5 Gt targets, the following needs to happen:

1. Feedstock prices must come down. To achieve this CarbonRun is working with Industry partners to identify actual production costs and use these figures to forecast our future procurement costs based on higher volume and industry participation.
2. Application sites must be placed in close proximity to feedstock sources. For large projects application sites would need to be in close proximity to feedstock which reduces transport costs and energy intensity impacts.
3. Waste is the future. Mines that produce milled and cut alkaline stone produce dust and other fines that are a waste product that would be well suited for CarbonRun's application process. Relationships are currently being developed with industry stakeholders to secure access to these materials.

RAE offers 0.5 Gt/year potential by 2050 if fully optimized and scaled. In order for this to happen alkaline feedstock production would need to increase 1 Gt per year, and global cooperation and project development would be required.

Our approach to quantifying the carbon removed is to employ standardized hydrology techniques to quantify the increase in HCO_3^- delivered to the ocean from rivers, from comparison of the treated river to a baseline condition derived from continuous monitoring of neighboring control sites. Field observations can be supplemented by reactive transport hydrological modeling to provide an independent estimate of carbon drawdown and storage. The rapid speed of the dissolution reactions that convert CO_2 to HCO_3^- allow us to monitor carbon drawdown and delivery to oceans in real-time.

c. **Risks:** What are the biggest risks and how will you mitigate those? Include technical, project execution, measurement, reporting and verification (MRV), ecosystem, financial, and any other risks. Aim for 500-1000 words.

Risks associated with the proposed RAE project include the following:

SOCIAL

Humans are strongly tied to rivers; therefore, local communities must be fully engaged with the goals of RAE, methods, safety and benefits. Communities need to be given adequate opportunity for information sharing, to ask questions and provide input before giving prior and informed consent to the project. **There is a risk of community opposition to the project, biased decision-making, and unfair distribution of impacts and benefits.** We will need to demonstrate that we have sufficiently liaised with community groups and first nations. In most of our projects we will form collaborative agreements where we co-develop, collaboratively operate and share the proceeds of projects. The CarbonRun CDR technology make it economically advantageous for the local communities to have RAE projects

PROGRESS: Mitigating this risk will require ongoing engagement and communication. CarbonRun has grown from community-led science and conservation and is therefore well positioned to make genuine collaborations and ensure that projects reflect the values and views of the communities around project sites. As discussed in section 6 and 7, we have chosen a site that has low negative impacts to the community. We have designed a community engagement model that involves active communication and education. We have partnered with and are actively engaging an Indigenous community to have a more fulsome understanding of the cultural impact of RAE.

REGULATORY

Jurisdictional rules regarding working with freshwater bodies vary by region. Extensive monitoring and advanced analysis is required to ensure regulatory requirements are satisfied. **The risk here is that a failure to adequately navigate the regulatory landscape would lead to delays in project development**.

[redacted]

NATURAL

Working in rivers always presents a challenge. **Risks to the project include extreme weather and the unforgiving nature of moving water** that necessitate careful planning. Flooding has the potential to damage infrastructure and monitoring equipment or pose danger to staff working alongside the river. Natural disasters such as hurricanes, storms and wildfire could impact operations - all of which are expected to be more prevalent with a changing climate.

PROGRESS: This risk will never be fully mitigated; however, careful site selection, appropriate design of infrastructure and careful training of staff will ensure that the impacts of extreme weather are minimal. We have built-in redundancy in our hardware (e.g., multiple sensors, spare parts, etc.), and we have back-up energy sources when the normally-reliable solar systems fail. Existing doser infrastructure in Nova Scotia has weathered nearly two decades of extreme weather, including four hurricanes.

Careful site selection entails modeling floodplain dynamics and flood risks. Further, investment in proper construction of facilities, such as overflows, drainage and naturalized swales will allow our structures to fit within the river landscape. Preparedness and contingency planning also all factor into mitigating this risk.

TIME & EXPEDIENCY

CarbonRun is a start-up with novel IP (US provisional patent); therefore, we must secure our market position rapidly to avoid well resourced second movers infringing upon the marketspace. One of Carbon Run's core principles is that we want our proprietary process to make a meaningful contribution in the fight against climate change. In that respect, we need to scale as rapidly as possible. **A risk to the project is delays to deployment if we were faced with technical and innovation hurdles.**

PROGRESS: We are currently the only company conducting CDR in freshwater. We aim to be the best and are 'all hands on deck' to achieve our climate objectives. Any risk associated with technical challenges has been reduced due to our deliberate leveraging of decades of river dosing technology. Our team is a select few globally with experience in this field.

LOGISTICAL

The CarbonRun RAE process requires the deployment of capital infrastructure and hardware to add alkaline materials autonomously and continuously to strategic river locations. **Logistical risks include delays in fabrication or other components of the supply chain will affect the lead time to bring projects online.** Once operational, the project must be maintained and the constant supply of carbonate mineral powder is essential.

PROGRESS: A major milestone in mitigating supply chain challenges is establishing strong relationships with vendors. To that end, we have established an important partnership with a global leader in the cement industry, to supply feedstock, to upcycle equipment for construction of our doser, and to share other project costs. We are working with a global leading cement producer to fortify the supply chain and ensure access to an inexpensive and abundant supply chain of alkaline material feedstock. This relationship will also increase purchasing power to reduce capital infrastructure costs.

As we scale, we will look to acquire our own quarries, low-energy milling facilities and trucking infrastructure.

Proper maintenance schedules, redundancy design and warehousing of commonly used components will help ensure that breakdowns do not occur.

FINANCIAL

A financial risk is not having the capital to deploy the projects. We require a conservative amount of upfront capital to bring projects online. This infrastructure is durable, serviceable and uses widely available components, so we are well able to forecast these costs and avoid cost overruns. Early investment of capital will also permit the operation of our core, R & D and business development staff.

PROGRESS: We are mitigating this risk by keeping infrastructure costs low, engaging with high quality customers (thank you Frontier!), diversifying our customer portfolio, following a sound and disciplined financial plan and maintaining strong internal governance with experienced advisors. Finally, we have capitalized on many kinds of non-investment support, such as mentoring, coaching and networking. Groups like Airminers, the MaRS incubator, individual industry leaders and non-climate industry moguls have generously offered advice and support, believing in our mission and our simple yet impactful technology.

MRV

Risks that could impact the quality of our MRV include inadequate baseline estimations or low signal-to-noise ratio between treatment and baseline scenarios.

PROGRESS:

To mitigate the risk of inadequate baseline estimations our project is designed to have one year of pre-treatment data collection to establish robust models to project baseline conditions from future observations at control sites. We have selected our project site to have a high signal-to-noise ratio between control and treatment scenarios. As we scale up in future projects we will refine reactive transport models that will supplement our baseline estimations in sites with lower signal-to-noise ratios. By design, we avoid the need to quantify all inputs and outputs to CAlk (e.g., evasion of gas, incorporation of DIC into sediment, losses to organic carbon) which would influence estimates of CO_2 drawdown, as identified (#2-6) in the Quantification tool (section 5).

POLITICAL

The introduction of a novel CDR approach into a CDR market that is nascent necessitates political education and lobbying. All levels of government will have touch points to our projects; therefore, political acceptance and the generation of political capital will help ensure that we are successful. **The risk is that political complacency, or worse opposition, will slow our progress,** such has happened during the development of policies around the use of government-owned lands (e.g., Canadian Crown Lands, State or Federal lands, etc.).

PROGRESS: We have been communicating our work with all levels of government, with indigenous governing bodies and community champions. We are also supporting and receiving support from CDR ecosystem organizations and policy initiatives such as Carbon Removal Canada (Na'im Merchant), MaRs(cleantech accelerator), and AirMiners which will foster a political culture for carbon removal in Canada and abroad. Developing genuine interest and clearly defining the potential of this work is creating a significant ground swell in the region of our first projects.

In Nova Scotia, we have developed a good understanding and relationship with politicians and their senior bureaucrats based on a demonstrated public benefit.

d. **Proposed offer to Frontier:** Please list proposed CDR volume, delivery timeline and price below. If you are selected for a Frontier pre-purchase, 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)*	20 year project potential: 6530 tCO_2 **Volume offered to Frontier: 1300 tCO_2*CR**
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Project lifespan will surpass the delivery window. Our contract with Frontier will be considered complete June 2029 (5 years from project launch). **260 tCO_2 / year will be offered to Frontier.**
Levelized Price (\$/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	**\$387 / tCO_2**

*[CR] Please note that the data and estimates presented in this proposal pertain solely to CarbonRun's initial project site, the 'First Nations River Alkalinity Enhancement Project for Carbon Dioxide Removal' site. CarbonRun is committed to building and operating multiple project sites simultaneously, which will result in more CO_2 removal than this initial site. If Frontier is interested in extending the purchase beyond the initial site, we would be more than willing to discuss the possibilities and provide detailed projections for the expanded scope.

** 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).*