



# [Brineworks]

## 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

Brineworks B.V.

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

Amsterdam, Netherlands

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

Joseph T. Perryman  
Gudfinnur Sveinsson

Brief company or organization description <20 words

Brineworks is driving down the cost of electrochemical marine CDR with our low-cost electrolysis system that co-generates H<sub>2</sub>.

### 1. Public summary of proposed project<sup>1</sup> to Frontier

- a. **Description of the CDR approach:** Describe how the proposed technology removes CO<sub>2</sub> 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

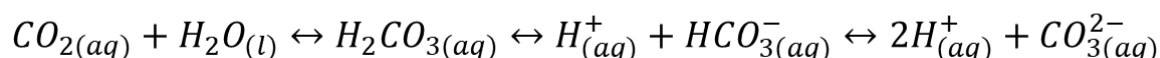
**Introduction to Brineworks:** Brineworks has developed a world-class hybrid electrolysis system that uniquely leverages the benefits of high-current water electrolysis for hydrogen production, as well as

<sup>1</sup> 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.

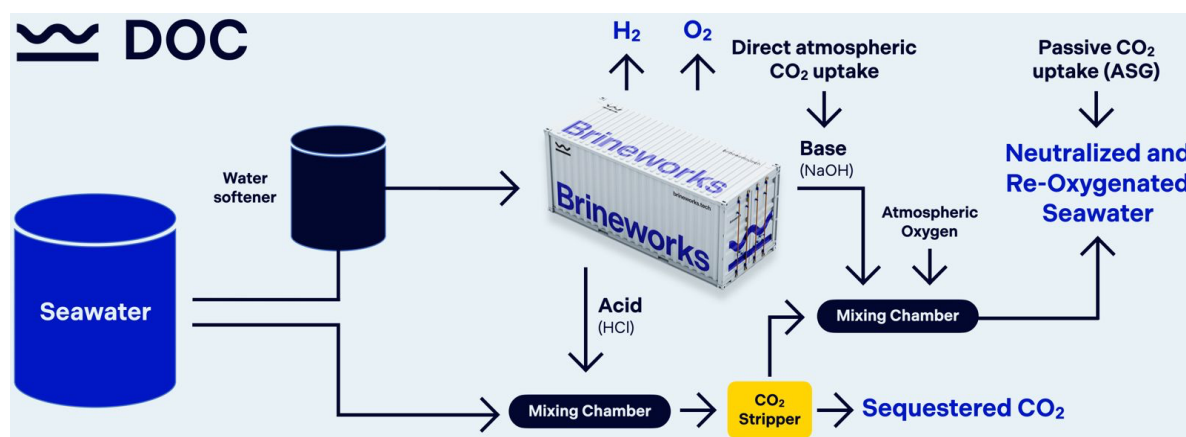
the benefits of low-energy electrodialysis for acid/base production. As a result, **our system can power high-performance, pH-swing marine carbon dioxide removal (mCDR) while offering green hydrogen at scale as a co-product**. Our approach to scaling mCDR is unique in that we can, with our hybrid electrolysis technology, power direct ocean capture (DOC) and/or ocean alkalinity enhancement (OAE) to achieve Gt/yr scale removal, while always producing green hydrogen as a co-product.

The flexibility of our electrolysis platform to generate acid and base quickly and cost effectively allows us to take advantage of and scale alongside incremental advances in monitoring, reporting, and verification (MRV) within the mCDR space. We can deploy in the short-to-medium term with lower-risk direct ocean capture (DOC) where ecosystem impacts are significantly lower or entirely avoidable. As ecosystem impact questions are answered and MRV protocols are refined for ocean alkalinity enhancement (OAE), our electrolyzer allows us to also quickly deploy electrochemical OAE in the long term, with a clear path to achieving <\$100/ton CDR at scale.

**How our technology removes CO<sub>2</sub>:** In the DOC process scheme, our electrolyzer technology unlocks cost-effective and scalable mCDR by leveraging the bicarbonate equilibrium of the sea, given by



to draw down gigatons of atmospheric CO<sub>2</sub> and permanently store it as bicarbonate (HCO<sub>3</sub><sup>-</sup>) and carbonate (CO<sub>3</sub><sup>2-</sup>) ions. With the acidic stream from our electrolyzer, we first shift the bicarbonate equilibrium to ensure all dissolved inorganic carbon (DIC) exists as dissolved CO<sub>2</sub> gas, which is then stripped out of solution under mild vacuum with a commercialized gas transfer membrane. After being stripped from solution, high-purity (>90-95%) CO<sub>2</sub> gas can be utilized or permanently sequestered in geologic formations with a durability of >10,000 years and minimal risk of reversal. The alkaline stream from our electrolyzer is then re-introduced, **either with or without some degree of “direct atmospheric CO<sub>2</sub> uptake” with air contactors**, to the acidic seawater stream for neutralization for safe discharge as seawater with slightly elevated pH owing to the partial or complete removal of dissolved CO<sub>2</sub>. Air-sea gas exchange (ASG) then ensures that the remaining CO<sub>2</sub> is introduced back into the partially or completely CO<sub>2</sub>-depleted outfall. These restoration steps take advantage of Henry’s law which dictates that dissolved CO<sub>2</sub> concentration must be proportional to the atmospheric CO<sub>2</sub> partial pressure. Hence DOC provides a low energy barrier to the actual CO<sub>2</sub> drawdown process by leveraging thermodynamics and the vast capacity of the world’s oceans to naturally and permanently store dissolved CO<sub>2</sub>.



**Benefits of our technology compared to state-of-the-art:** Brineworks’ proprietary electrolyzer enables more rapid generation of acid and base as compared to electrodialysis, which is the technology ubiquitously used in current DOC and OAE approaches. Moreover, our proprietary design and the mechanism by which it achieves rapid acid/base production also results in 1:2:2 (H<sub>2</sub>:NaOH:HCl) co-production of green hydrogen—unlocking a significant additional revenue stream unavailable when

utilizing competitive technologies. c

*Other DOC (and OAE) systems* can incur significantly higher CDR costs owing to reliance on traditional electrodialysis (ED) systems. They can also carry substantially higher environmental impact risks (e.g. related to pH increases and full DIC depletion) that are as-of-yet unaddressed and poorly understood and therefore **pose a larger hurdle to receiving favorable legislation and social acceptance. This hinders their ability to quickly and safely scale up to Gt/y CDR.** Lastly, time and resource-intensive MRV protocols are currently commonplace for DOC (and OAE) deployers owing to the general nature of ASG-reliant approaches. The Brineworks technology addresses all three of these concerns through our process organization and deployment strategy, as discussed in subsequent sections.

**Our ability to scale:** Our approach is uniquely capable of reaching the gigaton/year scale compared to non-marine approaches because:

- 1) It is not limited by land-use requirements like many biogenic approaches, as most of Earth's surface consists of seawater which can support our CDR system, and we can operate either at coastlines or on offshore platforms.
- 2) It is not limited by the dilute CO<sub>2</sub> concentration of the atmosphere like direct air capture (DAC), as seawater has on average ~125x more extractable CO<sub>2</sub> (as dissolved inorganic carbon) than air.
- 3) It takes advantage of the fact that oceans currently contain >30,000 Gt CO<sub>2</sub> which can be stripped at any given time, and would allow for a close to 1:1 reduction in atmospheric CO<sub>2</sub> tonnage for every ton of CO<sub>2</sub> stripped from the ocean.

We believe that our approach is also more likely to scale safely, even compared to other mCDR pathways such as micro/macroalgae cultivation, artificial up/downwelling, and mineral-based alkalinity enhancement. These alternative pathways carry significant environmental concerns owing to their imminent and often immediately predictable changes to ocean biogeochemistry. Our approach has the potential to mitigate environmental concerns in the short term because we can perform mCDR in a semi-closed fashion wherein our output stream is almost chemically identical to our input stream. We have already shown in our first pilot that our output stream can be re-oxygenated and re-carbonated (via atmospheric draw-down using the alkaline stream of our electrolyzer prior to neutralization) prior to discharge, mitigating any negative large-scale ecosystem impacts. Regardless, we are moving forward with independent third parties such as Hourglass Climate to perform robust ecosystem impact assessments and to develop short-, medium-, and long-term monitoring plans considering the most likely scenario where, at large scale, we also completely leverage air-sea gas exchange to re-carbonate seawater. In doing so, we will save on the capital cost of purpose-built air contactors.

**Our pathway to affordable CDR:** Our path to achieving <\$100/ton is clear. It's currently projected that electrolysis contributes to 50%-70% of CDR cost (DOC-OAE, respectively), with the next highest contributor being water pumping at 20% of CDR cost. **Hence, our electrolysis technology takes direct aim at the major cost driver of electrochemical mCDR.** The key innovation of our approach is our hybrid electrolysis system which can drive significantly higher rates of acid and base production than traditional ED technologies generally employed for both DOC and electrochemical OAE. This innovation allows for dramatic cost reduction (~\$50 per ton) by reducing CapEx in comparison to commercial ED-driven systems. Secondly, our system is energy competitive with ED, but with the added production of sellable quantities of green hydrogen. Finally, our system utilizes Earth-abundant electrode materials which lowers material cost, reduces the number of membranes necessary to drive acid/base production which further lowers material cost, and minimizes levelized energy consumption through co-production of H<sub>2</sub> which can be used as an energy vector if not directly sold. In the short-medium term where DOC is positioned to be the early mover in mCDR, we project costs approaching \$100/ton, but at the Mt/y and Gt/y scales where our electrolysis technology is positioned to support OAE scale up, removal costs are projected at significantly under \$100/ton.

**How we address priority areas of innovation:** In both the long and the short term, our electrolysis solution immediately benefits from integration with existing industries such as desalination and aquaculture where massive volumes of water are already being pumped, saving what can amount to ~20% of our total CDR cost for DOC. Appending our technology to these infrastructures also allows industrial partners to support positive environmental impacts by repurposing their waste streams that could otherwise be damaging. By stripping CO<sub>2</sub> from e.g. desalination brines, we can provide environmental co-benefits by:

1) helping to regulate aragonite supersaturation ( $\Omega_{\text{aragonite}}$ ) to safe levels near plant outfalls. We will ensure high enough  $\Omega_{\text{aragonite}}$  to support healthy marine life and coral reefs while preventing such high  $\Omega_{\text{aragonite}}$  that algal blooms or invasive calcifiers start to cause ecological imbalances.

and

2) deploying our proprietary re-oxygenation system to mitigate formation of transient hypoxic or anoxic zones during outfall mixing—further preserving aquatic ecosystems.

Economic co-benefits naturally arise from the development of scaled CDR with our technology, as we expect significant job growth, particularly in coastal communities which are most likely to be adversely affected by increasing global temperatures and rising sea-levels. Perhaps the most important economic co-benefit of our process is the generation of carbon-negative  $\text{H}_2$  that our electrolysis technology enables, which can be sold without purification other than drying and represents a significant additional revenue stream. Worth noting, as our electrolysis system is deployed into OAE processes, the neutralization of HCl with alkaline minerals like white olivine will lead to the production of  $\text{MgCl}_2/\text{MgCO}_3/\text{SiO}_2/\text{H}_2\text{O}$  mixtures that can be sold to end-users in the construction sector.

- 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?<sup>2</sup> What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. 1000-1500 words

**Our current project details:** We are working to build a 240 t/y capacity DOC pilot in Iceland in collaboration with the Breid Innovation Center in Akranes in Q4 2024. This location was selected because Iceland provides access to affordable (~\$70-80/MWh) and extremely low-carbon (~28g  $\text{CO}_2/\text{kWh}$ ) electricity from the Icelandic grid that is a mix of 68% hydroelectric and 32% geothermal energy.

We have also secured two LOIs with well-established sequestration partners, one of which is on the island performing deep-injection to permanently mineralize stripped  $\text{CO}_2$  from our process, and the other who is mineralizing  $\text{CO}_2$  for permanent sequestration in construction materials. We therefore have strong flexibility in how our  $\text{CO}_2$  will be sequestered for this project and will explore the economic and logistical viability of both options, in case it is advantageous to develop multiple pathways for sequestration in parallel.

Our aim is to operate this pilot for 3 years for this project to deliver up to 400 tons to Frontier by 2027. We will continue operating the system indefinitely as a test bed for improving our process design, for testing new iterations of our proprietary electrolysis system, and for advancing critically needed environmental impact assessment work through an existing third party collaboration that we will make

<sup>2</sup> 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.

readily available to the mCDR community.

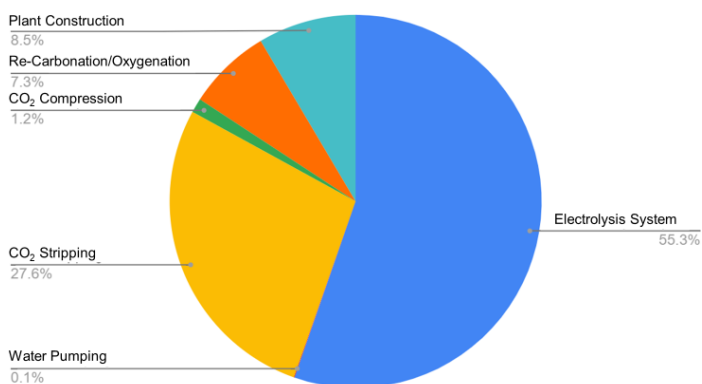
**Our cost breakdown:** Full engineering documentation for the plant has been prepared in collaboration with an independent engineering firm based in the EU that specializes in water treatment plant design, and have started the process of equipment procurement and are in the early stages of finalizing actual purchase prices. A Class III cost estimate was performed, with the ratiometric cost breakdown given in the accompanying pie chart based on our conservative estimate of final capital costs.

**How we get to scale:** In order for our core electrolysis technology to scale, in the short term (<2030) we must:

1) Improve our cost-advantage over traditional electrodialysis by leveraging our competitive energy spend, favorable system CapEx, and co-production of sellable  $H_2$  to drive down levelized CDR cost.

2) Show that both mitigation of environmental risk associated with electrochemical ocean interventions and reduction of MRV capital and operational cost are achievable in the short term, which will reduce the two largest barriers to acceptance of mCDR pathways like DOC and OAE.

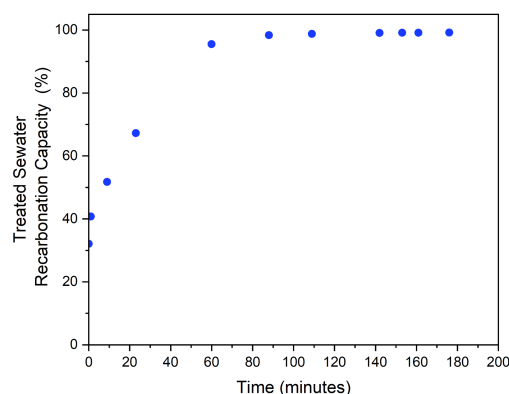
DOC Pilot Capital Cost Breakdown (Conservative Price Estimates)



To this second point, we will operate in a slightly less cost-effective manner in the short term by directly restoring  $O_2$  and (at least partially)  $CO_2$  levels to our process feed prior to discharge to sea. This will alleviate the financial burdens that come with existing MRV requirements and with CapEx for monitoring equipment. However, advances over the next several years in DOC/OAE MRV protocols based on reliable modeling, as well as establishment of robust ecosystem impact assessments, will both facilitate future large-scale deployments of DOC and OAE which directly leverage natural ASG to draw down atmospheric  $CO_2$ . By this period which we expect to be in the medium (2030-2040) term, direct discharge we will see a dramatic reduction in overall cost per ton CDR for both DOC and OAE, with OAE (with natural ASG) projecting to reach below \$100/t and DOC projecting to reach around \$120/t at scale. By this time, we will have been operating at the kt/year scale and we expect that our technology will be well-known and optimized enough to quickly scale to Mt/y removal capacity. By transitioning in the long term to OAE with natural ASG, which utilizes our same core technology, achieving our projected cost per ton <\$100 will unlock scaling to 0.5-2.0 Gt/y CDR.

**Our approach to quantifying  $CO_2$  removed:** Considering the nature of our process which will involve re-introduction of significant atmospheric  $CO_2$  to feed prior to discharge, we directly measure the mass of  $CO_2$  removed from seawater, as well as calculate the mass of  $CO_2$  re-introduced to the seawater (measured as DIC). With forced carbonation prior to discharge, our approach to quantification is simplified to a simple gravimetric analysis which comprises three parts.

- 1) Directly Verified Removal:  $CDR_M = \text{kg } CO_2 \text{ re-introduced to the outfall}$



$CDR_M$  refers to the mass of  $CO_2$  that has already been reintroduced from the atmosphere prior to discharge. In other words, it is the  $CO_2$  that we can observably re-introduce to our alkaline stream or our outfall with air contactors. This is distinct from the mass of  $CO_2$  that has been physically stripped from seawater, and is calculated from DIC measurements using the equation:

$$g\ CO_2 = DIC \left( \frac{\mu mol\ C}{kg\ seawater} \right) \times \left( \left( \overset{\text{CO}_2 \text{ Equivalents Present as CO}_2}{0.005} \left( \frac{\mu mol\ CO_2}{\mu mol\ C} \right) \right) + \left( \overset{\text{CO}_2 \text{ Equivalents Present as HCO}_3^-}{0.915} \left( \frac{\mu mol\ CO_2}{\mu mol\ C} \right) \right) + \left( \overset{\text{CO}_2 \text{ Equivalents Present as CO}_3^{2-}}{0.08} \left( \frac{\mu mol\ CO_2}{\mu mol\ C} \right) \right) \right) \times kg\ Seawater \times \frac{44.01\ g\ CO_2}{1.0 \times 10^6\ \mu mol\ C}$$

The colored fractional values above represent the distribution of each species at a relevant pH which will be actively monitored at all times for our outfall. We also note that for this example outfall pH of 8.2,  $H_2CO_3$  has been omitted from the calculation owing to its relative concentration being <0.1% of the total DIC.

- 2) Removal through ASG:  $CDR_{ASG} = (kg\ CO_2\ \text{stripped from seawater} - CDR_M) \times R_E$

$CDR_{ASG}$  refers to the mass of  $CO_2$  that is calculated to be re-introduced into the sea after discharge of our outfall. Based on the nature of ASG and the bicarbonate equilibrium, a simplification of this calculation is that each kg of  $CO_2$  that is physically stripped will be replaced by 1 kg of  $CO_2$  from the atmosphere. This simplification can then be corrected based on a replacement efficiency factor  $R_E$  which will be dictated by improving models for ASG based on ocean mixing, temperature, outfall discharge depth and wind speed, among others.

- 3) Gross Removal Including Sequestration:  $CDR_G = (CDR_M + CDR_{ASG}) \times \text{Sequestration Efficiency (\%)}$

Finally, our gross removal of  $CO_2$  is the sum of what we directly observe and what is expected to occur via the natural draw-down mechanism, corrected for sequestration efficiency which in the case of our injection sequestration partners is effectively 100%. Net removal will be this value subtracted by our emissions, as determined through a third-party LCA.

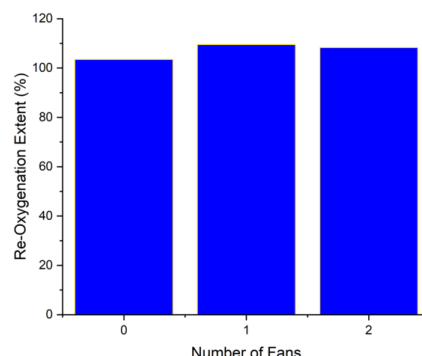
- c. **Risks:** What are the biggest risks and how will you mitigate those? Include technical, project execution, measurement, reporting and verification (MRV), ecosystem, financial, and any other risks. 500-1000 words

There are several important risks to consider for our mCDR approach, ranging from the potential to negatively affect ocean biogeochemical make-up, to the financial impacts that stem from MRV



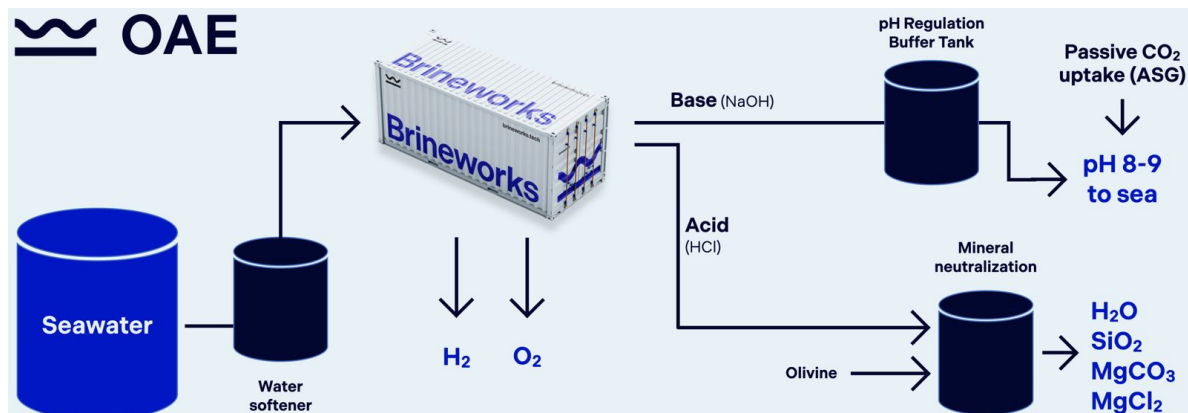
challenges. For us, these include:

**Ecosystem impacts of de-oxygenated and/or de-carbonated outfall discharge into the sea:** Depleted oxygen levels pose an imminent danger to most aquatic life below dissolved oxygen (DO) concentrations of  $\sim 2.0$  ppm, and treatment of acidified seawater with a gas-transfer membrane as in our DOC process results in DO levels  $< 1.0$  ppm. Therefore it is critical that we ensure our outfall is either sufficiently re-oxygenated prior to discharge or is re-oxygenated during the process of discharge. System tests so far demonstrate that we readily achieve higher DO levels in our outfall than in the input stream, and our mitigation strategy moving forward is to implement our proprietary system for re-oxygenating our outfall.



**Potential for low acceptance of ASG as a reliable mechanism for atmospheric CO<sub>2</sub> draw-down:** Despite high scientific confidence in the mechanism by which air-sea gas exchange introduces atmospheric CO<sub>2</sub> to bicarbonate-depleted seawater, it is currently the case that net CDR for both DOC and OAE is calculated with heavy dependence on ocean modeling, with a large degree of uncertainty. While we expect this uncertainty to decrease over time, **in the short term we will mitigate this risk by discharging a partially or completely re-carbonated outfall** where larger CDR<sub>M</sub>:CDR<sub>ASG</sub> ratios are most likely to instill sufficient confidence as ASG-based modeling protocols are refined. In the long term as these concerns are addressed, we expect that deploying our technology in an OAE scheme will be significantly more cost competitive.

In our OAE process scheme, our electrolyzer technology can drive ASG by increasing the alkalinity of seawater to shift the equilibrium of surface waters toward CO<sub>3</sub><sup>2-</sup>. This shift causes a net uptake of atmospheric CO<sub>2</sub> into the surface water. In this process organization, HCl from our electrolyzer will be neutralized with alkaline materials which, depending on the material (e.g. Mg<sub>2</sub>SiO<sub>4</sub>) can lead to additional CO<sub>2</sub> drawdown over long enough timescales.



**Insufficient demand for engineered mCDR in the next decade:** A large financial concern for engineered mCDR for the next decade will be the cost competitiveness with more mature land- and bio-based solutions which have lower removal costs at present. It is likely that even in the short term, the appetite of off-takers for CDR prices  $> \$200/\text{ton}$  will be low. To mitigate this concern, we can leverage favorable market prices for green H<sub>2</sub> (4-5 \$/kg) to subsidize our net cost of CDR, maintaining a price target between \$100-\$200 per ton removed. As H<sub>2</sub> prices approach the “\$1/kg in one decade” Earthshot target from the U.S. DOE, our solution projects to reach the \$100/t CDR price target without reliance on H<sub>2</sub> subsidization.

**Cost of high-quality MRV for DOC and OAE:** Well-defined MRV protocols for mCDR today that rely on ASG require heavy investment into monitoring infrastructure like sensors, sampling vessels, and external water analysis equipment, and it is still likely that costly modeling work will be necessary. We

mitigate this risk in the short term by engineering atmospheric re-carbonation into our DOC process, such that additionality can be readily monitored and reported. While this will necessarily increase CapEx and OpEx in the short term, our projections indicate that <10% of our total CDR cost will be directed to re-carbonation.

**Difficulties in leveraging green hydrogen co-production:** While H<sub>2</sub> sales under current market conditions greatly balance high short-term CDR costs, it is critical that we have off-takers for the produced hydrogen. Our strategy for addressing this has been to advance site discussions with partners where there are parties clearly interested in utilizing our hydrogen for e.g. sustainable aviation and maritime fuel synthesis, or for fuel cell applications. Early discussions to this end have been moving forward quickly through our network of partners in Iceland, as well as across the globe (e.g. The Bahamas, Spain, Denmark, Netherlands). Where off-takers do not yet exist, however, as a last result it is possible that hydrogen is safely vented without significantly complicating any health and safety protocols.

**Slow advances toward state-of-the art electrolysis membrane levelized cost reduction:** For high-current density water electrolysis systems to operate with high stability at low energy inputs, it is important that the cost of high-flux ion exchange membranes be reduced without compromising chemical and physical durability. As mCDR and other membrane-dependent electrochemical processes become more commonplace, we expect economies of scale with increased manufacturing capacity to lower this cost, although we have designed our system to minimize membrane use altogether.

- 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.

<b>Proposed CDR</b> over the project lifetime (tons) <i>(should be net volume after taking into account the uncertainty discount proposed in 5c)</i>	400
<b>Delivery window</b> <i>(at what point should Frontier consider your contract complete? Should match 2f)</i>	2027
<b>Levelized cost</b> (\$/ton CO <sub>2</sub> ) <i>(This is the cost per ton for the project tonnage described above, and should match 6d)</i>	1,256
<b>Levelized price</b> (\$/ton CO <sub>2</sub> ) <sup>3</sup> <i>(This is the price per ton of your offer to us for the tonnage described above)</i>	1,256

<sup>3</sup> 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).