



# Carbon to Stone

## Carbon Dioxide Removal Purchase Application

Fall 2022

### General Application - Prepurchase

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

Company or organization name

Carbon to Stone

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

Ithaca, NY

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

Greeshma Gadikota

Brief company or organization description

We develop transformative energy- and material-efficient integrated direct air capture and carbon mineralization technologies using earth abundant alkaline materials. In close collaboration with our industrial partner, Nucor Inc., we aim to commercialize this technology which is based on patents licensed from Cornell University and developed in Gadikota Research Group.

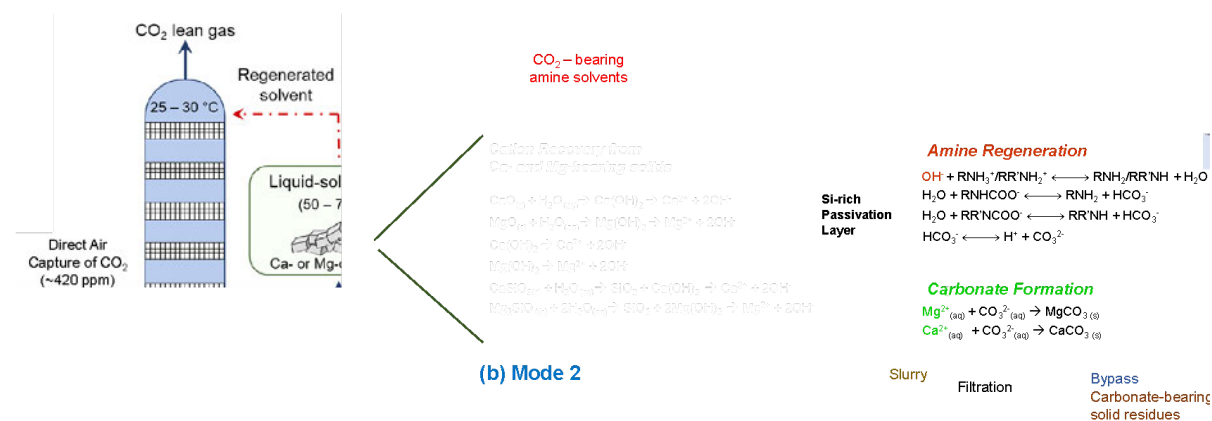
#### 1. Project Overview<sup>1</sup>

- a. Describe how the proposed technology removes CO<sub>2</sub> from the atmosphere, including as many details as possible. Discuss location(s) and scale. Please include figures and system schematics. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar technology.

**Technology Description:** The technology harnesses regenerable solvents such as sodium glycinate to capture CO<sub>2</sub> from air followed by carbon mineralization in which CO<sub>2</sub>-loaded solvents react with alkaline materials such as slags, fly ash or mine tailings to produce Ca- or Mg-bearing carbonates and

<sup>1</sup> 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.

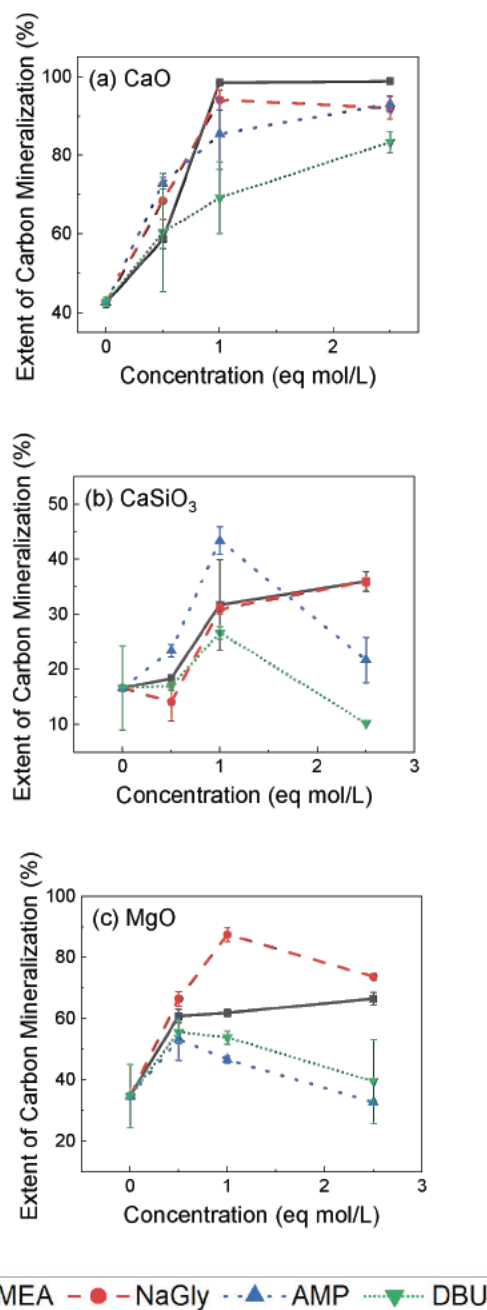
regenerate the solvents. **Figure 1** is a schematic representation of this approach.



**Figure 1.** Schematic representation of the integrated approach for the direct air capture and carbon mineralization to produce solid carbonates with inherent solvent regeneration.

Our laboratory experimental results show that CO<sub>2</sub>-loaded sodium glycinate is effective in converting >95% of CaO to Ca-carbonate, > 90% of MgO to Mg-carbonate, and > 30-35% of CaSiO<sub>3</sub> to Ca-carbonate, as shown in **Figure 2**.<sup>1</sup> These reactions occur in three hours with 15 wt% solid loading and constant stirring. Comparable results are achieved at 20 wt% and 25 wt% solid loading. These results demonstrate the laboratory-scale feasibility of carbon mineralization using CO<sub>2</sub>-loaded solvents. Ca- and Mg-oxides, hydroxides, and silicates are abundant in alkaline residues such as iron and steel slags, fly ash, and mine tailings, which opens the possibility of using these materials for the integrated DAC and mineralization technology. As an alternative to thermal regeneration of the solvent, our technology chemically regenerates the solvent by partitioning CO<sub>2</sub> in the formation of carbamate or (bi)carbonate species in the aqueous phase into a solid carbonate.

Our results also demonstrate that sodium glycinate (Na-glycinate) is more effective as a solvent for CO<sub>2</sub> capture and mineralization compared to other solvents such as 2-amino-2-methylpropanol (AMP) and 1,8-diazabicyclo [5.4.0] undec-7-ene (DBU). At higher concentrations of AMP and DBU (e.g., 2.5 M), the extents of carbon mineralization are lower compared to concentrations at 1 M due to the formation of gel-like and mass transfer limiting considerations. Similar reactivities are noted with Na-glycinate and MEA for Ca-bearing materials, while Na-glycinate is more effective for converting MgO to Mg-carbonate compared to MEA. The mechanism for CO<sub>2</sub> capture using MEA proceeds via the formation of a carbamate which then reacts with the alkaline resource to produce solid carbonate, while that for Na-glycinate proceeds via the formation of (bi)carbonate species. The higher chemical and thermal stability of Na-glycinate compared to MEA and limited chemical degradation of Na-glycinate compared to MEA favor the use of Na-glycinate as a preferred solvent for integrated DAC and mineralization. To further support the use of Na-glycinate, researchers at ORNL have published the effectiveness of using this solvent for DAC.<sup>2</sup>



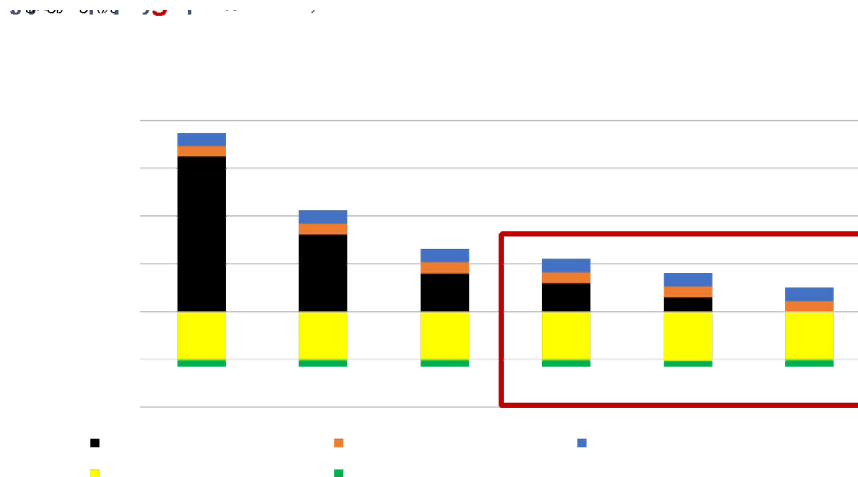
**Figure 2.** Extent of carbon mineralization of CaO (a), CaSiO<sub>3</sub> (b), and MgO (c) reacted in the presence of 0 eq mol/L, 0.5 eq mol/L, 1.0 eq mol/L, and 2.5 eq mol/L monoethanolamine (MEA, black square), sodium glycinate (NaGly, red circle), 2-amino-2-methylpropanol (AMP, blue upward facing triangle), and 1,8-diazabicyclo [5.4.0] undec-7-ene (DBU, green downfacing triangle). All the experiments are performed at 75 °C, CO<sub>2</sub>-loaded solvents, reaction time of 3 hours and a stirring rate of 300 rpm.

#### *LCA and TEA for integrated DAC and mineralization using regenerable solvents.*

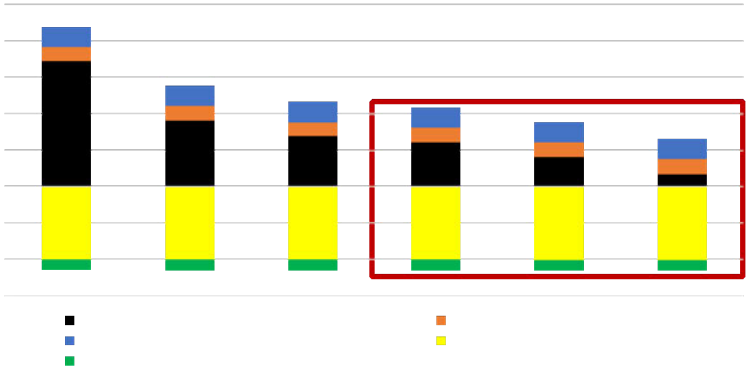
To identify the factors that have the highest impact on the net negative carbon footprint of the integrated DAC and mineralization technology, we investigated the influence of various factors including solvent regeneration and recycle, reactivity of the alkaline residues, transportation, and

energy needs. Co-locating our technology in regions where alkaline industrial residues and mine tailings are already co-generated limits CO<sub>2</sub> emissions associated with transportation needs. Also, harnessing energy from waste heat and renewable resources further limits CO<sub>2</sub> emissions. Regardless, the impacts of transportation and energy from non-renewable resources are included in the analyses and the figures below. Our LCA captures realistic compositions of alkaline industrial residues (e.g., slags) that can contain 30-40% of CaO or Ca(OH)<sub>2</sub> and the conversion of these Ca-bearing components into Ca-carbonate.

Our analyses showed that the use of CO<sub>2</sub> capture solvents has the most significant impact on CO<sub>2</sub> emissions. Therefore, high solvent regeneration efficiencies are needed. Transportation (if co-located where the alkaline materials are available) and the associated energy needs are minor contributors to CO<sub>2</sub> emissions compared to the use of sodium glycinate as a CO<sub>2</sub> capture solvent. The carbon negative impacts arise from the chemical conversion of CaO-bearing alkaline industrial residue to Ca-carbonate and the use of the end product to displace other Ca-carbonate bearing materials in the marketplace. **Figure 3** shows that net carbon negative scenarios are realized when the solids loading are solvent regeneration of 96% or higher is achieved. When similar reactivities are achieved using lower concentrations of sodium glycinate (i.e., 1 M vs. 2.5 M), the associated CO<sub>2</sub> emissions are also lower, as shown in **Figure 4**. When lower concentrations of Na-glycinate are used, solvent regeneration needs to be 93% or higher to achieve net carbon negativity compared to the scenario of 2.5 M Na-glycinate in which 96% solvent regeneration is needed.

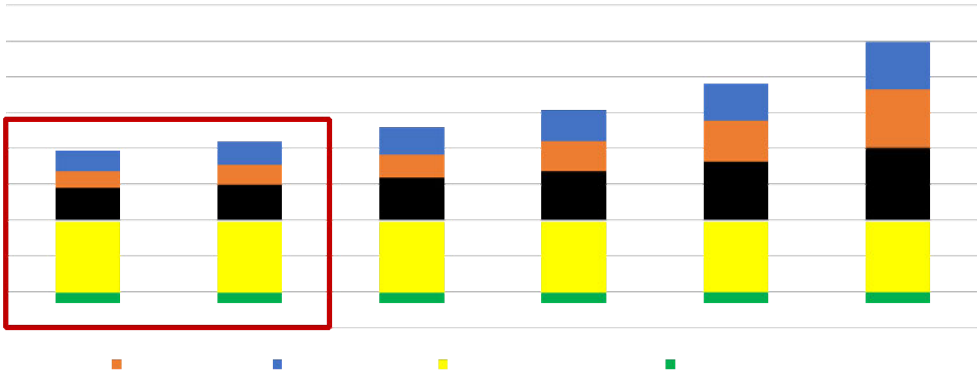


**Figure 3.** Life cycle CO<sub>2</sub> emissions for integrated direct air capture and carbon mineralization approach for various CO<sub>2</sub> capture solvent regeneration scenarios with 2.5 M Na-glycinate. The composition of Ca-oxide and hydroxide in alkaline industrial residue (e.g., slag) is assumed to be 37% and 95% of this content reacts to produce Ca-carbonate.

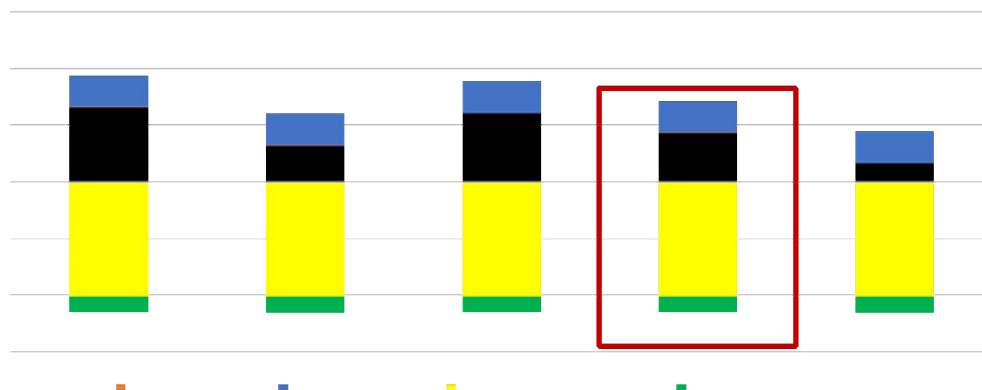


**Figure 4.** Life cycle CO<sub>2</sub> emissions for integrated direct air capture and carbon mineralization approach for various CO<sub>2</sub> capture solvent regeneration scenarios with 1 M Na-glycinate. The composition of Ca-oxide and hydroxide in alkaline industrial residue (e.g., slag) is assumed to be 37% and 95% of this content reacts to produce Ca-carbonate.

Another key consideration is the reactivity of the solids needed to achieve overall net negative carbon emissions. Our analyses show that the overall net carbon negative scenarios are achieved when extents of carbon mineralization are 80% or higher, assuming that non-renewable energy resources are used for transportation and for meeting the process needs. If renewable energy resources are used, then converting even 40% of the alkaline materials into solid carbonates is sufficient for achieving carbon negative scenarios, as shown in **Figure 5**. The best-case scenario for achieving overall net negative carbon removal is one which involves lower concentrations of CO<sub>2</sub> capture solvent, higher solvent regeneration efficiency, and 20 wt% of solids, as shown in **Figure 6**.



**Figure 5.** Life cycle CO<sub>2</sub> emissions for integrated direct air capture and carbon mineralization approach for various CO<sub>2</sub> capture solvent regeneration scenarios with 1 M Na-glycinate. The composition of Ca-oxide and hydroxide in alkaline industrial residue (e.g., slag) is assumed to be 37%.



**Figure 6.** Life cycle CO<sub>2</sub> emissions for integrated direct air capture and carbon mineralization approach for various concentration of Na-glycinate, solid loading, and solvent regeneration. The composition of Ca-oxide and hydroxide in alkaline industrial residue (e.g., slag) is assumed to be 37% and 95% of this content reacts to produce Ca-carbonate.

TEA of this technology revealed that in materials with 60 wt% of highly reactive Ca- and Mg-hydroxides and oxides vs. 30 wt% of Ca-oxide or hydroxide, the costs are \$ 83 and \$ 126/ton of CO<sub>2</sub> captured from air and mineralized. These analyses were conducted assuming 1 M Na-glycinate, 95% solvent recycle per DAC and carbon mineralization loop, and 95% conversion of the alkaline content into solid carbonates, with gross and net CDR of 400,000 and 90,000 tons per year for 20 years.

**Next steps:** Based on the LCA and TEA, our aim is to design a pilot-scale and then full-scale facility in the next 8 years to achieve solvent regeneration > 96% per cycle and reactivity (or conversion of CaO- and MgO-bearing alkaline residues to > 90% carbonates) since these factors are essential for achieving overall net carbon negative removal with durable storage. Our next steps involve demonstrating this technology in a continuous manner at an industrial location with abundant alkaline industrial residues (e.g., slags generated by Nucor).

**Differentiation:** Our technology integrates direct air capture and durable carbon storage in manner that is verifiable and quantifiable in a finite period (~1-3 hours) as opposed to natural solutions where quantification is a challenge. This technology can be deployed in a distributed manner where alkaline residues are located as an alternative to transporting enormous quantities of alkaline residues to flue gas resources. Furthermore, the energy needs for this technology are modest since CO<sub>2</sub> capture and mineralization occurs well below 100°C, compared to other DAC companies (e.g., Carbon Engineering). Waste heat generated during steel making and renewable energy resources can be harnessed for meeting the modest energy needs of this technology. Furthermore, the generated end-products which are carbonate-bearing materials can be reused as aggregates in construction and pavement materials, which serves as an additional revenue source for this technology. The end product which is a solid carbonate ensures durable carbon storage. The process parameters such as temperature, solid wt%, and solvent concentration and composition can be easily adapted for a wide range of alkaline residues including Mg(OH)<sub>2</sub> or brucite-rich mine tailings, CaO and MgO-rich slags (e.g., ladle slag generated by Nucor). While carbon mineralization has been achieved by digesting

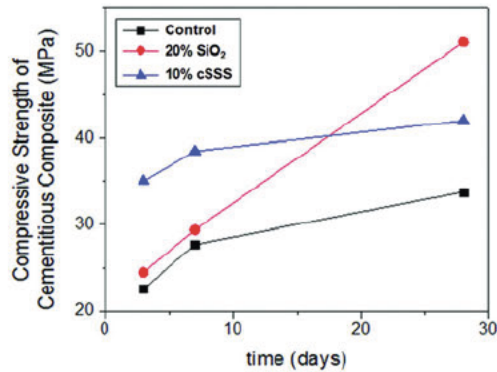
alkaline materials in strong acids followed by using bases to facilitate solid carbonate precipitation, the consumption of acids and bases makes these pathways chemically-intensive<sup>3</sup> and the overall carbon footprint can be high. In comparison, our approach of harnessing regenerable solvents is far less chemically intensive and has a much lower carbon footprint. This technology has been extensively validated at the bench-scale at Cornell University and the patent filed with Cornell Technology Licensing is currently being exclusively licensed to Carbon to Stone. By delivering DAC and mineralization together, our technology circumvents the costs and challenges of CO<sub>2</sub> transportation and subsurface CO<sub>2</sub> storage. The conservative and more reasonable estimated cost of \$ 126 (in materials with 30 wt% reactive Ca-content) and \$ 83 (in materials with 60 wt% reactive Ca- and Mg-content) per ton of CO<sub>2</sub> captured from air and mineralized are highly competitive in the existing marketplace for carbon management.

**References:** (1) Liu, M., Hohenshil, A. and Gadikota, G., 2021. *Energy & Fuels*, 35(9), pp.8051-8068. (2) Custelcean, R., Williams, N.J., et al., 2019. *Industrial & Engineering Chemistry Research*, 58(51), pp.23338-23346.

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

The current technology readiness level is 4. This status is substantiated by extensive bench-scale evidence of carbon mineralization as shown in Figure 2 in the previous response. The data shows that alkaline industrial residues bearing oxides, hydroxides, and silicates of calcium and magnesium can be effectively converted into solid carbonates using regenerable solvents. We have identified that temperatures in the range of 25-75°C, solid wt% in the range of 15-25 wt%, CO<sub>2</sub> capture solvents such as Na-glycinate (1 – 2.5 M) and monoethanolamine (MEA) (30 wt%) are effective in single-step CO<sub>2</sub> capture and conversion of the materials abundant in alkaline industrial residues such as oxides, hydroxides and silicates of Ca and Mg. Furthermore, we have shown that fly ash<sup>1</sup> and slags (results in review) can be successfully mineralized to carbonates using regenerable solvents at the conditions described above. This technology can be easily adapted for on-site processing of alkaline industrial residues that are generated, such as slags generated during iron and steel making process. We have shown that the integration of carbonate-bearing slags in construction materials enhances their mechanical strength, as evident from **Figure 7**<sup>2</sup> below. These results demonstrate the feasibility of replacing Ordinary Portland Cement with carbonate-bearing slags for producing high strength construction materials.





**Figure 7.** Compressive strengths of cementitious composites prepared with no additives (control case), 20% Si-rich materials and 10% carbonated stainless steel slag (cSSS).<sup>2</sup>

**References:** (1) Yin, T., Yin, S., Srivastava, A. and Gadikota, G., 2022. Regenerable solvents mediate accelerated low temperature CO<sub>2</sub> capture and carbon mineralization of ash and nano-scale calcium carbonate formation. *Resources, Conservation and Recycling*, 180, p.106209. (2) Gadikota, G., Fricker, K., Jang, S.H. and Park, A.H.A., 2015. Carbonation of silicate minerals and industrial wastes and their potential use as sustainable construction materials. In *Advances in CO<sub>2</sub> Capture, Sequestration, and Conversion* (pp. 295-322). American Chemical Society.

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

Key performance parameter	Current observed value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
Extent of carbon mineralization	95% conversion to solid carbonate	98% conversion to solid carbonate	Our current value is based on lab-scale studies and data shown for CaO in Figure 2 (a). Increasing the residence time is one way to enhance reactivity.
Solids loading	15 wt%	25 wt%	Our ongoing experiments show that similar reactivities are achieved with higher solids loading and similar solvent concentrations.
Reaction temperature	50-75C	25-50C	With Ca-bearing residues, it is possible to lower the reaction temperatures to the range of 25-50C as opposed to 50-75C and still achieve high extents of carbon mineralization. This approach would



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

<p>The key people who will be working on this concept include co-founders, Greeshma Gadikota, Sravanth Gadikota, Hassnain Asgar, and Sohaib Mohammed. Our team combines decades of expertise in designing integrated CO<sub>2</sub> capture and mineralization pathways, and industry expertise in new product development, and commercialization.</p> <p>Greeshma Gadikota is a faculty member at Cornell University and is a world-leading expert in carbon mineralization. She has published more than 60 peer-reviewed publications on topics related to carbon capture and mineralization, fluid-particle interactions for sustainable energy and resource recovery. She has raised more than \$5 million in federal grants from DOE, NSF, and DOD to support research related to CO<sub>2</sub> capture and mineralization, which is the basis of eight patents that are licensed to Carbon to Stone. She is the recipient of CAREER awards from DOE, NSF, and ARO, Sigma Xi Young Investigator Award, Cornell Rising Women Innovator Award, Cornell Engineering Research Excellence Award, and Young Researcher Award, The 15<sup>th</sup> International Conference on Gas-Liquid and Gas-Liquid-Solid Reactor Engineering Conference.</p> <p>Hassnain Asgar and Sohaib Mohammed received their PhDs in Civil and Environmental Engineering from Cornell University in 2021 and 2020, respectively. They published extensively on fluid-solid interactions associated with carbon transformations, carbonate crystallization, and sustainable energy and resource recovery technologies. Sohaib has extensive experience in multi-scale modeling ranging from the molecular scales to process scales. Both, Hassnain and Sohaib have expertise in advanced reactor design and novel pathways to integrate carbon transformations with sustainable energy and resource systems.</p> <p>Sravanth Gadikota received his MBA from New York University and has a bachelor’s degree in Electrical Engineering. He has nearly two decades experience in new product development and commercialization at small and large companies. Additionally, the team is looking to recruit commercialization specialists who will develop long-term strategic relationships with industrial partners to co-implement these technologies.</p>
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- e. Are there other organizations you’re partnering with on this project (or need to partner with in order to be successful)? If so, list who they are, what their role in the project is, and their level of commitment (e.g., confirmed project partner, discussing potential collaboration, yet to be approached, etc.).

Partner	Role in the Project	Level of Commitment
Nucor Inc., located in Auburn, NY	Nucor will supply various types of slag generated during iron and steel making process needed for carbon removal. They generate significant quantities of	Nucor will provide access to their facility and slag materials for our direct air capture and carbon mineralization

	slag materials that are essential for this technology. Nucor is a committed and confirmed partner for our team. They have been supplying significant quantities of slag materials for our project. They are eager to partner to advance carbon removal technologies.	technology.
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- f. What is the total timeline of your proposal from start of development to end of CDR delivery? If you're building a facility that will be decommissioned, when will that happen?

Pre-pilot validation and testing will begin in 2023. Scale-up will begin in 2025 with December 2028 as the end of CDR delivery. A plant operating life of 20 years starting 2028 is assumed.

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

The project will start in Q2 - 2023 with the facility delivering > 10,000 tons/year in 2028. CDR will first occur in pre-pilot modes in 2023 and 2024 leading up to pilot scale implementation in 2025 and 2026. In 2023 and 2024, we are focused on achieving efficient solvent recycle and establishing an end market for the carbonate-bearing materials. By 2026, the pilot scale facility will deliver up to 40 tons/year. We will then scale up to the order of > 1,000 tons/year starting 2027. This commercialization timeline of 9-12 years is consistent with the product-to-market strategy implemented by CarbonClean Solutions (<https://www.carbonclean.com/technology-licence>).

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

Year	Estimated gross CDR capacity (tonnes)
2023	0.5 kg/day = 150 – 175 kg/year
2024	1 kg/day = 300 – 365 kg/year
2025	10 kg/day = 3 – 4 tons/year
2026	100 kg/day = 30 – 40 tons/year
2027	10,000 kg/day = 3000 – 4000 tons/year
2028	100,000 kg/day = 30,000 – 40,000 tons/year
2029	500,000 kg/day = 50,000 – 60,000 tons/year

2030	1,000,000 kg/day = 300,000 – 400,000 tons/year
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- i. List and describe at least three key milestones for this project (including prior to when CDR starts), that are needed to achieve the amount of CDR over the proposed timeline.

	Milestone description	Target completion date (eg Q4 2024)
1	Achieve > 93% recovery of solvent regeneration per cycle for integrated DAC and carbon mineralization	Q4 2023
2	Deploy a continuous DAC and mineralization process based on solvent recycle efficiency and kinetics of carbonate conversion	Q2 2024
3	Develop a commercialization strategy for utilizing carbonate-bearing end products in construction materials	Q4 2024
4	Establish a pilot facility for converting slags into carbonate-bearing materials in collaboration with Nucor	Q2 2025
5	Develop a fully operating facility for converting slags into carbonate-bearing materials	Q1 2028

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

<p>The IP was developed at Cornell University and licensed to Carbon to Stone in 2022. Here is the patent: <b>G. Gadikota</b>, "Methods and Processes for Producing Inorganic Carbonate Compounds and Inorganic Bicarbonate Compounds," Provisional patent filed on September 3, 2020. Full patent filed on July 28, 2022 (pending).</p> <p>This patent discusses the use of regenerable CO<sub>2</sub> capture solvents for integrated carbon mineralization and solvent regeneration. All solvents that capture CO<sub>2</sub> to produce carbamate and (bi)carbonate species which can then react with Ca- and Mg-bearing alkaline residues to produce solid carbonates are covered under this patent. The approach to modulate chemical transformations in slurry phases for this application are discussed in this patent.</p> <p>In addition, G. Gadikota has filed five additional patents this year. These patents are related to energy critical metal recovery and H<sub>2</sub> recovery with inherent carbon removal. These patents will be licensed to Carbon to Stone, if needed to expand the scope of commercialization activities.</p>
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- k. How are you going to finance this project?

<p>Our path to finance the project is discussed in terms of short-term and long-term strategy. In the short-term (1-2 years), we will harness the resources of the Praxis Center for Venture Development at Cornell University including the lab space, facilities, and commercialization support to develop a</p>
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fully integrated and continuous DAC and carbon mineralization prototype that will operate using slag materials obtained from Nucor. We will determine strategies to recover >95% of solvent per cycle to achieve overall carbon negative potential. These activities are enabled by the fellowship awarded by Praxis Center to Hassnain Asgar, co-founder which covers salary and expenses for materials, equipment, and supply. In addition, we are applying for the Activate Fellowship for Sohaib Mohammed, another co-founder of the company. We are also applying to non-dilutive federal funding opportunities to further advance this concept. In the past two years, G. Gadikota received the NSF I-Corps, NSF Partnership for Innovation (PFI), and support from DOE and ARPA-E to support research and development leading to commercialization. We have harnessed these opportunities to engage in customer discovery and identify strategic partners such as Nucor Inc.,

In the past two months, we have been approached by several angel investors and venture capital firms to invest. We are actively working on raising a seed round of funding to support the activities for the next two years which involve developing a continuous process for DAC and mineralization. Once we develop several working prototypes with various alkaline industrial residues, we will raise Series A funding for large scale implementation.

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

We have initiated discussions with Chevron and Nucor on CDR purchases. No contract has been signed at the time of submission of this Frontiers application.

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

We will co-produce carbonate-bearing aggregates that can be harnessed as construction materials. Granulated slag sells for **\$14.50/ton** (<http://www.northernagg.com/pricesheet.php>). A conservative estimate is that carbonate-bearing slag materials obtained after direct air capture and carbon mineralization will command a similar price in the marketplace. Slags and other types of alkaline industrial residues such as sludge that are not used in carbon mineralization are typically landfilled and the cost of landfilling is in the range of **\$ 50 - \$ 55/ton**, which is avoided using our technology. Furthermore, we will harness 45Q incentives which provide \$ 130/ton for DAC and utilization, as noted in the provisions in the Inflation Reduction Act of 2022. Furthermore, we have additional patents on the recovery of energy critical metals such as Mn, Ni, Cr, and Co that can be combined with this proposed DAC + mineralization technology, if economical. This approach will serve as an opportunity to increase revenue.

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

Risk	Mitigation Strategy
Technical Risk: Solvent	As noted in the LCA, achieving solvent recycle > 90% is essential

regeneration (low risk)	for achieving carbon negative scenarios. We have already achieved this in the lab and need to increase solvent recycle > 93%. This can be easily achieved by increasing filtration efficiency.
Technical Risk: Availability of waste heat and electricity from renewable energy resources (low risk)	Our LCA shows that overall net negative carbon emissions can be achieved by using non-renewable energy sources (see Figures 2-4) given the modest energy needs of this technology. We discussed the availability of waste heat in Nucor's facilities for our process and this integration is highly feasible. Furthermore, Nucor has experience in electric arc furnaces, which can be harnessed to meet the energy needs using electricity as opposed to heat.
Technical Risk: Variability of alkaline industrial residues (medium risk)	The metal composition in alkaline industrial residues can vary based on industrial processing conditions, which in turn can impact carbon removal efficiencies. To address this challenge, we will investigate the compositional ranges of alkaline industrial residues that can be used to achieve reasonable extents and kinetics of carbon mineralization without changing the process conditions.
Commercialization Risk: Competing uses of alkaline industrial residues (low risk)	Alkaline industrial residues such as fly ash are dwindling in supply since coal fired power plants are no longer in operation in the United States. However, other sectors such as iron and steel and aluminum are growing in the US. Further, vast quantities of legacy mine tailings in the US need remediation. Our technology addresses the need to harness these solid waste emissions that continue to remain an environmental challenge.
Commercialization Risk: Licensing technology (low risk)	Our company has exclusive license to the patents that are developed by G. Gadikota's Research Group at Cornell University. As a result, other companies cannot license our technology.
Project Risk: Scale-up considerations (medium risk)	Significant deviation in direct air capture and carbon mineralization rates in the scaled-up technology from anticipated conditions is a project risk. To address this, we propose extensive pre-pilot and pilot scale trials, and the use of wide margins in operating conditions during scale-up to account for variability in inlet compositions without incurring additional capital costs.
Financial Risk: Actual project costs exceeding budget allocations (medium risk)	To ensure that the project costs do not exceed the allocated budget, we have estimated the budget based on a conservative scenario in which only 30 wt% of alkaline industrial residue (e.g., slag or ash) has CaO or MgO that is reactive with CO <sub>2</sub> . In reality, certain alkaline residues such as ladle slag can contain more than 60% of CaO and MgO that is highly reactive. By choosing a more conservative estimate of CO <sub>2</sub> reactivity, we aim to avoid challenges associated with underestimating our project costs.

## 2. Durability

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

One of the unique aspects of our technology is that permanent and durable removal of CO<sub>2</sub> is achieved by producing solid Ca- and Mg-bearing carbonates, which are environmentally benign. (1) Ca- and Mg-carbonates are stable up to 750C and 350C, respectively. (2) These materials are chemically stable at pH up to 2. (3, 4) When used to replace OPC to make construction materials, these materials retain their carbonate form. (5) However, calcining these carbonate-bearing materials to produce CO<sub>2</sub> will not lead to the permanence of these materials, and is therefore not recommended.

The upper bounds of durability are > 1000 years if the carbonate-end materials are simply stored in environments where pH is not less than 2 and if these materials not reused. The lower bounds of durability are to the order of 100 years if these materials are used in construction materials and these construction materials are recycled to regenerated Ca-silicates and CO<sub>2</sub> (a current ARPA-E project for G. Gadikota). If these carbonates are used for soil liming, then then are expected to dissolve and the durability is less than 2 years.

In the context of carbon removal, our preferred option is to retain the permanence of these materials by storing them indefinitely. For example, carbonate-bearing construction materials may be recycled every 50-100 years in which the permanence is to the order of 50-100 years. If these materials are landfilled, that would constitute durable removal to the order of 1000 years or longer. Alternatively, if these carbonate-bearing materials are stored in reclaimed mines, that would constitute durable carbon removal. Our LCA considers the scenario in which carbonate-bearing materials made from anthropogenic CO<sub>2</sub> replace materials prepared from conventional non-anthropogenic sources. This approach contributes to net carbon removal.

### References:

- (1) Lackner, K.S., 2002. Carbonate chemistry for sequestering fossil carbon. *Annual review of energy and the environment*, 27(1), pp.193-232.
- (2) López-Periago, A.M., Fraile, J., López-Aranguren, P., Vega, L.F. and Domingo, C., 2013. CO<sub>2</sub> capture efficiency and carbonation/calcination kinetics of micro and nanosized particles of supercritically precipitated calcium carbonate. *Chemical engineering journal*, 226, pp.357-366.
- (3) Eubank, W.R., 1951. Calcination studies of magnesium oxides. *Journal of the American Ceramic Society*, 34(8), pp.225-229.
- (4) Gadikota, G., Fricker, K., Jang, S.H. and Park, A.H.A., 2015. Carbonation of silicate minerals and industrial wastes and their potential use as sustainable construction materials. In *Advances in CO<sub>2</sub> Capture, Sequestration, and Conversion* (pp. 295-322). American Chemical Society.

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

The key durability risks are chemical in nature. For example, if the end carbonate products are used in soil liming for enhanced crop fertility, the materials will dissolve to release bicarbonate and carbonate ions, whose end fate is uncertain. Prolonged exposure to carbonates to acidic solutions with pH < 2

dissolves the minerals which is a risk that needs to be mitigated in the context of durable carbon storage. Another key consideration is the lifetime of the construction materials bearing carbonates. If these carbonate-bearing construction materials are recycled every 50-100 years with the same composition, CO<sub>2</sub> will be recycled after the initial removal. Therefore, it is important to consider the relative quantities and associated economic value of carbon removal and durable storage vs. removal and utilization (in construction materials). We aim to unlock these insights over the course of the first year of our project.

3. Gross Removal & Life Cycle Analysis (LCA)

- a. How much GROSS CDR will occur over this project’s timeline? All tonnage should be described in **metric tonnes** of CO<sub>2</sub> here and throughout the application. Tell us how you calculated this value (i.e., show your work). If you have uncertainties in the amount of gross CDR, tell us where they come from.

Gross tonnes of CDR over project lifetime	Starting 2030, we anticipate removing ~ 400,000 metric tons of CO <sub>2</sub> per year. Assuming plant operation of 25, 50, and 100 years, we will remove 10, 20, and 40 million tons of CO <sub>2</sub> , respectively.
Describe how you calculated that value	Domestic (U.S.) and global blast furnace slag production in 2018 was about 6-7 and 312-374 million tons, respectively. We anticipate that blast furnace slags will be retired and most slag generation will occur in electric arc furnaces. Even if we process just 2 million metric tons per year in the United States and assume that 20% of the slag is converted into solid carbonate, this accounts for 400,000 tons of CO <sub>2</sub> removed as solid carbonates.

- b. How many tonnes of CO<sub>2</sub> have you captured and stored to date? If relevant to your technology (e.g., DAC), please list captured and stored tons separately.

To date, we have captured and stored 2 kg of CO<sub>2</sub> as Ca- or Mg-carbonates using regenerable solvents such as sodium glycinate.

- c. If applicable, list any avoided emissions that result from your project. For carbon mineralization in concrete production, for example, removal would be the CO<sub>2</sub> utilized in concrete production and avoided emissions would be the emissions reductions associated with traditional concrete production. Do not include this number in your gross or net CDR calculations; it’s just to help us understand potential co-benefits of your approach.

Carbonate-bearing slags can replace up to 20-30% of ordinary portland cement (OPC) to produce high strength construction materials. In conventional cement making, about 0.9 – 1 ton of CO<sub>2</sub> is evolved per ton of cement produced. Assuming 20% of OPC is replaced with carbonate-bearing slags, about CO<sub>2</sub> emissions are reduced by 0.18 - 0.2 tons per ton of cement produced. About 1 ton of



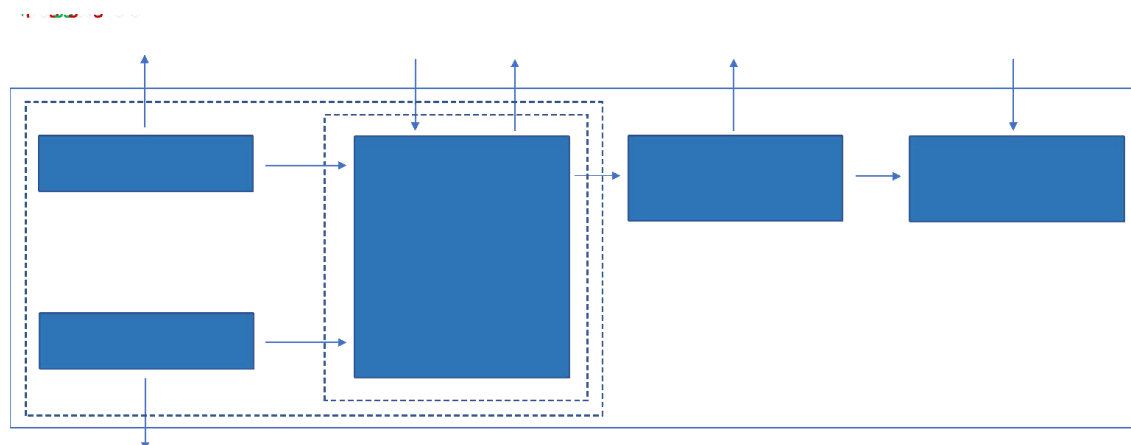
carbonate-bearing slags contains 0.2 tons of CO<sub>2</sub> removed from air. Thus, 1 ton of carbonate-bearing cementitious materials represent ~0.2 tons of CO<sub>2</sub> emissions avoided and ~0.04 tons of CO<sub>2</sub> captured from air.

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

Gross project emissions over the project timeline (should correspond to the boundary conditions described below this table)	Assuming the <u>most conservative scenario</u> involving 20 wt% of alkaline residue in 1 M Na-glycinate solvent, 95% reactivity, gross project emissions are 890 kg of CO <sub>2</sub> per ton of CO <sub>2</sub> captured and removed using alkaline industrial residue such as slag or ash. Starting 2030, we anticipate removing ~ 400,000 metric tons of CO <sub>2</sub> per year or 10 million tons in 25 years. Assuming plant operation of 25 years, the gross CO <sub>2</sub> emissions are 7.75 million metric tons.
Emissions / removal ratio (gross project emissions / gross CDR—must be less than one for net-negative CDR systems)	Emissions/removal ratio (conservative scenario) = 0.775
Net CDR over the project timeline (gross CDR - gross project emissions)	Net CDR over the project timeline = Gross CDR – Gross Project Emissions = 10 – 7.75 billion tons = 2.25 million metric tons

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

- The LCA scope should be cradle-to-grave
- For each step in the PFD, include all Scope 1-3 greenhouse gas emissions on a CO<sub>2</sub> equivalent basis
- Do not include CDR claimed by another entity (no double counting)
- For assistance, please:
  - Review the diagram below from the [CDR Primer](#), [Charm's application](#) from 2020 for a simple example, or [CarbonCure's](#) for a more complex example
  - See University of Michigan's Global CO<sub>2</sub> Initiative [resource guide](#)
- If you've had a third-party LCA performed, please link to it.



Process flow diagram representing gross **positive** CO<sub>2</sub> emissions in **red** and gross **negative** CO<sub>2</sub> emissions in **green**. Overall net **negative** CO<sub>2</sub> emissions are 258 kg/ ton of gross CO<sub>2</sub> removed. The CO<sub>2</sub> equivalent data shown in the figure is normalized to 1 ton of CO<sub>2</sub> removed on a gross basis in the integrated DAC + carbon mineralization process. The process is based on the conversion of alkaline industrial residues containing 37% CaO. 95% of the CaO content is converted to Ca-carbonate in 1 M Na-glycinate at 50 °C, with 20 wt% of solid, and a solvent regeneration efficiency of 95% per cycle (and solvent makeup of 5% per cycle).

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

Boundary conditions include the use of 1 M Na-glycinate as the CO<sub>2</sub> capture solvent, 95% solvent recycle per DAC + mineralization cycle (or 5% solvent makeup per cycle), 20 wt% solid, and alkaline residue bearing 37% CaO or Ca(OH)<sub>2</sub> and 95% conversion of these materials to CaCO<sub>3</sub>. Temperature for DAC + mineralization is 50°C. Energy and transportation needs are met using non-renewable resources. Replacing CaCO<sub>3</sub> from the process in commercial products contributes to avoided emissions. Alkaline industrial residues are assumed to be available in the granulated form. Based on the Bond Index Factor [1], energy needs associated with grinding are 14.3 MWh/ton of material ground from 5 mm to 6 microns. The associated cost is \$1.49/ton of material ground. If electricity from renewable energy resources or waste heat is harnessed, there are no associated CO<sub>2</sub> emissions – which is assumed in this scenario. Based on our discussions with Nucor, this scenario is highly feasible. Alternatively, if non-renewable energy resources are harnessed, then 0.4 kg of CO<sub>2</sub> emissions are associated with the use of 1 MWh of energy [2], amounting to 5.72 kg of CO<sub>2</sub> emitted per ton of material ground. We plan to avoid these CO<sub>2</sub> emissions using renewable energy resources or waste heat, and therefore is not accounted in the LCA.

#### References:

[1] Kirchofer, A., Brandt, A., Krevor, S., Prigiobbe, V. and Wilcox, J., 2012. Impact of alkalinity sources on the life-cycle energy efficiency of mineral carbonation technologies. *Energy & Environmental Science*, 5(9), pp.8631-8641.

[2] <https://www.eia.gov/tools/faqs/faq.php?id=74&t=11>

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

Process Step	CO <sub>2</sub> (eq) emissions over the project lifetime (metric tonnes)	Describe how you calculated that number. Include references where appropriate.
Energy needs for integrated DAC and mineralization	1.79 million tons	Energy needs account for 23% of gross CO <sub>2</sub> emissions which are 7.75 million tons over 25 years. Natural gas is assumed as the energy resource.
Solvent use with 95% recycle per DAC + mineralization loop	3.56 million tons	1 M Na-glycinate is used and 5% solvent makeup is assumed (conservative estimate). Solvent needs account for 46% of gross CO <sub>2</sub> emissions.
Transportation costs	2.39 million tons	Carbonate-bearing materials are transported to facilities making construction materials and account for 31% of gross CO <sub>2</sub> emissions.
Integrated DAC and carbon mineralization	-8.70 million tons	CO <sub>2</sub> is removed in this integrated DAC and mineralization process to produce solid carbonates, and accounts for 87% of gross CDR.
Synthesized carbonates replace natural carbonates in the marketplace	-1.29 million tons	Synthesized carbonate-bearing materials prepared from DAC replace existing materials and account for 13% of gross CDR.

These numbers are based on LCA which used the framework presented by Kirchofer and co-workers.<sup>1</sup>

**Reference:** [1] Kirchofer, A., Brandt, A., Krevor, S., Prigiobbe, V. and Wilcox, J., 2012. Impact of alkalinity sources on the life-cycle energy efficiency of mineral carbonation technologies. *Energy & Environmental Science*, 5(9), pp.8631-8641.

## 4. Measurement, Reporting, and Verification (MRV)

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

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

CDR quantification is first achieved through extensive laboratory scale experiments. Some of these data are published [1-5] while other data is under review. Our experimental protocols involve extensive efforts to capture and convert CO<sub>2</sub> into solid carbonates using regenerable solvents. We have identified the physico-chemical parameters that lead to >95% conversion of Ca-oxides and hydroxides which are solid wt% in the range of 15-25%, temperatures in range of 25-75C, 1 – 2.5 M Na-glycinate (or 30 wt% MEA), reaction times ranging from 0.5 – 3 hours, and particle sizes in the range of 5 – 30 microns. The CO<sub>2</sub> uptake is measured based on the extents of carbonate formation quantified using Thermogravimetric Analyses, Total Inorganic Carbon Analyses, and Quantitative X-Ray Diffraction. The kinetics of DAC using glycinate solvents have been reported by ORNL [6]. This information along with the extensive data on carbon mineralization using regenerable solvents serves as the input into the LCA models.

For the LCA, conservative estimates for the quantity of reactive Ca-oxide or hydroxide bearing materials (37% in slag or ash is assumed; reactive Ca- and/or Mg-content in slags, ash, and tailings can reach up to maximum up to 65-70% which can result in more favorable LCA and TEA). Solvent recycle of 95% with 5% makeup per DAC + mineralization loop is also conservative and achieving carbonate conversions of 95% or higher from Ca/Mg-oxide or hydroxide precursors is consistent with the experimental data. Another conservative assumption is the use of non-renewable energy resources to meet the modest energy needs. This technology operates at 50-75C which is lower than the temperatures needed for solvent regeneration in conventional CO<sub>2</sub> capture systems. Increasing solids loading and using less solvents leads to more energy savings. Grinding energy needs are modest and can be met using waste heat or renewable energy and associated CO<sub>2</sub> emissions can be abated using renewable energy. Net negative emissions are realized through the chemical conversion of slags to carbonate-bearing solids and using these materials to replace natural carbonates in the marketplace.

**References:** [1] Liu, M. and Gadikota, G., 2018. *Energy & Fuels*, 33(3), pp.1722-1733. [2] Liu, M. and Gadikota, G., 2020. *Fuel*, 275, p.117887. [3] Liu, M., Hohenshil, A. and Gadikota, G., 2021. *Energy & Fuels*, 35(9), pp.8051-8068. [4] Liu, M., Asgar, H., Seifert, S. and Gadikota, G., 2020. *Sustainable Energy & Fuels*, 4(3), pp.1265-1275. [5] Gadikota, G., 2020. *Nature Reviews Chemistry*, 4(2), pp.78-89. [6] Custelcean, R., Williams, N.J., et al., *Industrial & Engineering Chemistry Research*, 58(51), pp.23338-23346.

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

Durability of the carbon sequestered is determined directly by quantifying the extents of carbonate formation and the phases of solid carbonate formed. A key consideration is the formation of metastable carbonate phases such as aragonite (CaCO<sub>3</sub>), vaterite (CaCO<sub>3</sub>), nesquehonite (MgCO<sub>3</sub>·3H<sub>2</sub>O) as opposed to stable calcite (CaCO<sub>3</sub>) or magnesite (MgCO<sub>3</sub>). When exposed to ambient conditions, metastable phases transform to stable carbonate phases over time.

From a systems level perspective, indefinite storage of these materials (i.e., > 1000 years) in relatively inert environments is the best strategy for durable removal. When considering the use of these materials in construction materials, it is important to consider the circular use, timescales, and end-of-life strategies of these materials. In this context, we will use LCA for construction materials including those developed by CarbonCure for the downstream use of the carbonate-bearing materials produced from our technologies. Alternatively, if the carbonate-bearing materials are used for soil

liming, the durability is less than 2 years. These analyses will be a robust consideration if we are selected to move forward with our Frontiers application.

- c. This [tool](#) diagrams components that we anticipate should be measured or modeled to quantify CDR and durability outcomes, along with high-level characterizations of the uncertainty type and magnitude for each element. We are asking the net CDR volume to be discounted in order to account for uncertainty and reflect the actual net CDR as accurately as possible. Please complete the table below. Some notes:
- In the first column, list the quantification components from the [Quantification Tool](#) relevant to your project (e.g., risk of secondary mineral formation for enhanced weathering, uncertainty in the mass of kelp grown, variability in air-sea gas exchange efficiency for ocean alkalinity enhancement, etc.).
  - In the second column, please discuss the magnitude of this uncertainty related to your project and what percentage of the net CDR should be discounted to appropriately reflect these uncertainties. Your estimates should be based on field measurements, modeling, or scientific literature. The magnitude for some of these factors relies on your operational choices (i.e., methodology, deployment site), while others stem from broader field questions, and in some cases, may not be well constrained. We are not looking for precise figures at this stage, but rather to understand how your project is thinking about these questions.
  - See [this post](#) for details on Frontier's MRV approach and a sample uncertainty discount calculation and this [Supplier Measurement & Verification Q&A document](#) for additional guidance.

<b>Quantification component</b> Include each component from the <a href="#">Quantification Tool</a> relevant to your project	<b>Discuss the uncertainty impact related to your project</b> Estimate the impact of this component as a percentage of net CDR. Include assumptions and scientific references if possible.
Achieving > 95% solvent recycle and < 5% solvent makeup per DAC + mineralization loop	Our lab scale studies indicate that this is feasible and achievable. Solvent makeup is the single biggest contributor to CO <sub>2</sub> emissions based on the LCA (see Figures 3 – 5).
Energy needs	We assume non-renewable energy resources for operating the process at 50-75C and the CO <sub>2</sub> emissions impact is the third largest after solvent recycle and transportation. We have discussed the use of waste heat and renewable energy resources with Nucor and this approach is feasible.
Transportation needs	The carbonate-bearing materials are transported to the cement making facility for making carbonate-bearing construction materials by replacing 20-30% OPC. Transportation is the second biggest contributor to CO <sub>2</sub> emissions based on our LCA. We will continue to explore alternative approach to transport the materials (e.g., electric vehicles) to reduce CO <sub>2</sub> emissions.
Integrated DAC + mineralization process	To enhance the overall carbon removal efficiency of this most important process, we are currently evaluating approaches to increase solid to liquid ratio, decrease solvent loading and

	concentration, and reduce temperature needs while achieving > 95% reactivity of Ca-or Mg-bearing materials.
Use of carbonate-bearing materials	The implications for durable storage can vary based on whether the carbonate-bearing material is: (1) stored and not used, (2) used in construction materials by replacing 20-30% of OPC, or (3) used as a liming agent in soils. The first, second, and third cases have durabilities > 1000 year, ~ 100 years, and ~ 2 years, respectively. We assume the first two scenarios in our models.

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

Based on the uncertainties noted, about 7.5 – 10% of CDR can be discounted. The discount of 7.5% or lower applies for durable carbon storage. Higher discounts need to be considered if carbonate-bearing materials are used for soil liming which causes these materials to dissolve and release (bi)carbonate ions into soils.

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

The project will help advance quantification for carbon mineralization using a combination of analytical techniques given the complexity in the phases formed. Oxides, hydroxides and silicates of Ca and Mg in alkaline industrial residues are highly reactive and multiple carbonate phases including as hydrate-bearing carbonates (e.g., nesquehonite,  $\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$ ) can be formed. Thus, a combination of analytical techniques including Total Inorganic Carbon (TIC), Total Carbon, Thermogravimetric Analyses, and Quantitative X-Ray Diffraction are needed for quantifying the kinetics and extents of carbon mineralization.

Furthermore, our life cycle assessment model is uniquely suited for assessing the net negative carbon removal scenarios for ex-situ carbon mineralization technologies and can be easily adapted to include additional parameters for consideration. Our LCA methodology has been crucial in helping us identify that solvent recycle, transportation, and energy needs as positive contributors to gross  $\text{CO}_2$  emissions (in this order), and DAC + mineralization and the use of these materials to replace carbonate materials sourced from non-anthropogenic carbon are contributors to gross CDR. With this information, we can further tune the processing conditions to achieve higher net CDR. If selected to participate in the Frontiers Program, we would be delighted to share the modeling framework with other companies interested in carbon mineralization.

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

Our intended plan will occur in phases of two years each. In 2023 and 2024, we will establish the physico-chemical parameters that will lead to high extents of carbon mineralization while reducing gross CO<sub>2</sub> emissions including the optimal solvent recycle and solvent concentrations that will enable us to achieve 95% or higher conversion of non-carbonated Ca-/Mg-bearing content in alkaline residues such as slags. In 2025 and 2026, we will pilot this technology in collaboration with Nucor using their waste heat and alkaline residues such as slags. Nucor generates a wide range of alkaline residues including slag, sludge, and dust materials that are ideally suited for DAC and carbon mineralization. We have developed protocols for quantifying CO<sub>2</sub> removal based on the changes in the compositions of CO<sub>2</sub> in the gas, liquid (using solvent) and solid phases as Ca- or Mg-bearing carbonates. After 2026, we will systematically scale-up our technology to full scale operation (as noted in our timeline). At this point, we anticipate working closely with the Frontiers and Stripe team, and our industrial partner, Nucor Inc., to register and deliver credits. As we scale-up our technology starting 2025, additional validation will be needed and at that point, we anticipate working with third party auditors for carbon removal verification.

5. Cost

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

- a. What is the levelized price per net metric tonne of CO<sub>2</sub> removed for the project you’re proposing Frontier purchase from? This does not need to exactly match the cost calculated for “This Project” in the TEA spreadsheet (e.g., it’s expected to include a margin), but we will be using the data in that spreadsheet to consider your offer. Please specify whether the price per tonne below includes the uncertainty discount in the net removal volume proposed in response to question 4(d).

The current levelized price per metric ton of CO<sub>2</sub> removed at present is \$ 393.9/ton of CO<sub>2</sub> captured from air and mineralized to a solid carbonate, for the conservative scenario in which 30 wt% of the solid contains reactive Ca-content and \$ 326/ton of CO<sub>2</sub> captured from air and mineralized to a solid carbonate, for a high scenario in which 60 wt% of the solid contains reactive Ca- and Mg-carbonates. The conservative scenario represents electric arc furnace slags, and the high scenario represents ladle slag, both of which are generated at Nucor facilities. For NOAK scenarios, the costs are \$ 126 and \$ 83/ton of CO<sub>2</sub> captured from air and mineralized for the conservative and high scenarios. In all cases, 95% of the reactive Ca/Mg content is converted to solid carbonate.

Lower capital and operating costs are realized in materials with higher quantity of reactive content (high case) due to more efficient use of the alkaline residues for carbon removal. These two scenarios capture the uncertainty discounts discussed in response to question 4 (d).

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

Here we present two scenarios.  
SCENARIO 1: Conservative estimate based on 30 wt% of the solid containing reactive Ca content and 95% conversion of this reactive content to produce solid carbonates.



Component	Levelized price of net CDR for this project (\$/tonne)
Capex	\$ 150.6/ton
Opex (excluding measurement)	\$ 164 (fixed) + \$ 79.3 (variable) = \$ 243.3/ton
Quantification of net removal (field measurements, modeling, etc.) <sup>2</sup>	0 (plant will be built to reactivity specification; process scale validation is built into operating expenditures as contingency costs)
Third party verification and registry fees (if applicable)	0
<b>Total</b>	<b>\$ 393.9/ton</b>

SCENARIO 2: High estimate based on 60 wt% of the solid containing reactive Ca and Mg content and 95% conversion of this reactive content to produce solid carbonates.

Component	Levelized price of net CDR for this project (\$/tonne)
Capex	\$ 144.1
Opex (excluding measurement)	\$ 132.6 (fixed) + \$ 50 (variable) = \$ 182.2
Quantification of net removal (field measurements, modeling, etc.) <sup>3</sup>	0 (plant will be built to reactivity specification; process scale validation is built into operating expenditures as contingency costs)
Third party verification and registry fees (if applicable)	0
<b>Total</b>	<b>\$ 326.3/ton</b>

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

Parameter with high impact on cost	Current value (units)	Value assumed in NOAK TEA (units)	Why is it feasible to reach the NOAK value?
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<sup>2</sup> This and the following line item is not included in the TEA spreadsheet because we want to consider MRV and registry costs separately from traditional capex and opex.

<sup>3</sup> This and the following line item is not included in the TEA spreadsheet because we want to consider MRV and registry costs separately from traditional capex and opex.

Capital expenditure (or Bare Erected Cost)	\$ 0.76 million (high)	\$15.04 million (high)	We assume a scaling factor of 19.8 from gross DAC of 10,281 tons to 400,000 tons per year, which is a 40-fold increase. This assumption is reasonable given economies of scale and absence of high temperature or pressure equipment conventionally needed for DAC projects
	\$0.79 million (conservative)	\$ 15.7 million (conservative)	
Cost of chemicals	\$ 0.10 million (high)	\$ 3.08 million (high)	Enhancing solvent recycle will enable us to reach NOAK value.
	\$ 0.15 million (conservative)	\$ 4.66 million (conservative)	

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

We are unsure of how to precisely account for energy needs. This challenge arises from the fact that waste heat is available at Nucor facilities for DAC and mineralization. Regardless, we accounted for the use of electricity and heat resources in our TEA which leads to a more conservative estimate for our costs for DAC and mineralization.

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

The CDR costs calculated in the TEA spreadsheet are closely aligned with the results predicted from our models. A key factor is the reactivity of the materials given their heterogeneous compositions. We accounted for this challenge by considering a “conservative” and “high” scenario for DAC and mineralization.

In our prior analyses, we estimated that the costs can be as low as \$ 40 - \$ 50 per ton of CO<sub>2</sub> captured from air and mineralized, when brucite rich mine tailings, MgO-rich alkaline residues, or CaO-rich fly ash is used for carbon mineralization, as opposed to more heterogeneous slags. Regardless, our estimates are in line with the reactivity and composition of slag materials supplied by Nucor, our industrial partner on this project.

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

Improved insights into the market for alkaline industrial residues and their uses would greatly accelerate the commercialization of our technology. Though information on this topic is typically collected by USGS, the reports do not capture trends in the recent years.

## 6. Public Engagement

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

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

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

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

The key industry stakeholder is Nucor Inc., who is partnering with us on this effort. Given the stringent need to comply with EPA standards, Nucor is the only iron and steel making facility in NY. They have made significant investments in Auburn, NY and are among the leading employers in NY state. By co-locating our operating facility in collaboration with Nucor Inc., our aim in the long-term is to create a decarbonization hub that provides high skilled job opportunities to the local communities. Auburn is less than an hour away from Ithaca, NY where the offices for Carbon to Stone are located. The Finger Lakes Region which Ithaca and Auburn are located have low levels of participation of underrepresented minorities in emerging industry. This project will provide the impetus to unlock the community benefits that decarbonization solutions can offer. Nucor, Carbon to Stone, and Cornell University acknowledge that the land belongs to Cayuga Nation. By advancing technologies that limit the use of landfills and advance a sustainable climate, we are aligned with Cayuga Nation's mission of preserving our natural resources. As we expand the scale and scope of our operations, we will continue to engage with local local and Native American communities to ensure that the technologies that are developed in a manner that are just and equitable for the current and future generations inhabiting this region.

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

While Carbon to Stone has not directly engaged with local communities, Nucor Inc., has a long history of engaging with stakeholder and communities. They regularly provide sustainability reports that discuss environmental controls being implemented and discuss how community recycling efforts can be advanced.

See Nucor's human rights policy:

[https://assets.ctfassets.net/aax1cfbwhqog/1QVrXSK1NzyqxPYgLm8b0M/a20784c40dbe6344d1d6396018db779e/Nucor\\_Human\\_Rights\\_Policy.pdf](https://assets.ctfassets.net/aax1cfbwhqog/1QVrXSK1NzyqxPYgLm8b0M/a20784c40dbe6344d1d6396018db779e/Nucor_Human_Rights_Policy.pdf)

With this approach as an inspiration, Carbon to Stone will aim to disseminate and publicly disclose and disseminate the community level impacts of our technology and the environmental gains that are realized.

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

During our customer discovery interviews with companies and community outreach efforts we learnt that the people in the Finger Lakes Region view large-scale landfill disposal of alkaline industrial residues as a major concern. Furthermore, NY state and NYSERDA are highly supportive of advancing sustainable climate solutions. The congruence of customer led need for this technology (e.g., Nucor), the urgency to deploy sustainable climate solutions in NY supported by local governments and NYSERDA, and the opposition of local communities to landfill disposal of alkaline industrial residues due to concerns associated with heavy metal leaching into drinking water and soil resources, motivate our team to accelerate the deployment of our technology.

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

We have not yet explored alternative uses of carbonate-bearing materials beyond the construction industry. For example, carbonate-bearing materials can be used for soil liming. However, concerns associated with heavy metal contamination and loss in durability due to the dissolution of solid carbonates to release (bi)carbonate ions remain. These factors are important consideration as we explore other markets for the carbonate-bearing end products when we scale up to the megaton scale of operation.

## 7. Environmental Justice<sup>4</sup>

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

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

By removing CO<sub>2</sub> emissions and eliminating the landfilling of alkaline industrial residues, our technology delivers environmental justice to our communities. The negative impacts of landfilling alkaline wastes and associated releases of metals into the soil and freshwater resources are disproportionately experienced by underserved and low-income communities. By co-locating our facility with Nucor Inc., we will aid decarbonization efforts in the region. If supported by Frontiers,

<sup>4</sup> For helpful content regarding environmental justice and CDR, please see these resources: C180 and XPRIZE's [Environmental Justice Reading Materials](#), AirMiners [Environmental and Social Justice Resource Repository](#), and the Foundation for Climate Restoration's [Resource Database](#)

we will conduct a thorough analysis of the impacts of our company operations on the local communities.

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

Our technology has a positive impact not only on climate and the land (by eliminating landfilling of alkaline industrial residues), but it is also crucial for preventing the release of heavy and toxic metals such as chromium, manganese and nickel into our drinking water supplies. Our technology operates at moderate pH conditions in 6-8, which will not leach these metals and instead locks these metals into the solid carbonate matrix. This approach provides a solution to the crucial problem plaguing the iron and steel industry which is the sustainable disposal of their alkaline industrial residues.

## 8. Legal and Regulatory Compliance

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

There are two main considerations associated with the deployment of our technology. The first consideration is the stability and durability of the materials. Once solid carbonates are formed, they also lock up significant quantities of heavy metals and prevent their release. It is crucial to ensure sustainable and long-term storage of the carbonate-end materials so heavy metals are not leached into soil and drinking water resources. The second consideration involves ensuring that the carbonate-bearing construction materials are compliant with ASTM standards for use in various structural environments (e.g., pavement materials and building construction materials). This approach is essential to avoid any detrimental impacts on human life associated with structural failures.

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

A key consideration is the transfer of liability for handling alkaline industrial residues from Nucor to Carbon to Stone. We will need to comply with EPA regulations for safe and sustainable end-of-life management of the carbonate-bearing slags, sludge and dust materials generated by Nucor. Having the appropriate permits in place is crucial for us to scale-up the technology in 2025 after the initial bench-scale studies in 2023 and 2024.

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

We do not anticipate importing alkaline industrial residues from other countries for DAC in the United States. Therefore, we do not anticipate being subject to any international legal regimes.

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

At this point of time, clear guidance from ASTM on the incorporation of carbonate-bearing slags in construction materials does not exist. We anticipate that these discussions will occur in parallel to our technology development cycle over the course of the next 8 years. The team has relationships with NIST (where G. Gadikota was a researcher) to help develop standardized testing strategies to advance low carbon cements for a sustainable future.

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

We do not anticipate receiving tax credits during the delivery window for Frontiers now. If such a conflict does arise, we will discuss with the Frontiers and Stripe team on the best approach forward, given the nascent nature of carbon markets.

9. Offer to Frontier

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

<b>Proposed CDR</b> over the project lifetime (tonnes) <i>(should be net volume after taking into account the uncertainty discount proposed in 4(c))</i>	1269 tonnes
<b>Delivery window</b> <i>(at what point should Frontier consider your contract complete? Should match 1(f))</i>	2027-2028
<b>Levelized Price</b> (\$/metric tonne CO <sub>2</sub> ) <i>(This is the price per tonne of your offer to us for the tonnage described above)</i>	\$ 394/ton of CO <sub>2</sub> removed (conservative case is assumed)

# Application Supplement: DAC

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

*Note: these questions are with regards only to air capture: e.g. your air contactors, sorbents or solvents, etc. Separately, there exist Geologic Injection and CO<sub>2</sub> Utilization supplements. We anticipate that most companies filling out this DAC supplement should ALSO fill out one of those supplements to describe their use of the CO<sub>2</sub> stream that's an output of the capture system detailed here.*

## Physical Footprint

1. What is the physical land footprint of this project, and how do you anticipate this will change over the next few years? This should include your entire physical footprint, i.e., how much land is not available for other use because your project exists. Also, what is the estimated footprint if this approach was removing 100 million tons of CO<sub>2</sub> per year?

Land footprint of this project (km <sup>2</sup> )	~ 0.25
Land footprint of this tech if scaled to 100 million tons of CO <sub>2</sub> removed per year (km <sup>2</sup> )	~ 10

## Capture Materials and Processes

1. What material(s) is/are you using to remove CO<sub>2</sub>?

Sodium glycinate is used to capture CO<sub>2</sub> from air and alkaline industrial residues such as slags generated during iron and steel making are used to regenerate the solvents while removing CO<sub>2</sub> to produce solid Ca- or Mg-bearing carbonates.

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

The materials are sourced from Nucor Inc., which is one of the leading iron and steel making industries with facilities in Auburn, NY (~45 minutes away from Ithaca, NY where Carbon to Stone is located). Nucor generates a wide range of slag materials including electric arc furnace slags, ladle slag, sludge, and dust materials with varying metal compositions. Regular slags contain about 30 – 35 wt.% Ca-oxide and 4-5 wt. % Mg-oxide while ladle slags contain ~ 30-35 wt.% CaO and 25-35% MgO. These materials are typically stockpiled for several years, and the landfilling or use of these materials is challenged by the release of Mn, Cr, or Ni into soil and ground water resources. Our technology is ideally suited for preventing the release of Mn, Cr, and Ni and stabilizing these metals in Ca- or Mg-carbonates. Our team has a long-standing relationship with Nucor Inc and we have sourced materials from the Auburn site. We plan to co-locate the DAC facility in Auburn to harness the alkaline industrial residues produced by Nucor Inc.



3. How much energy is required for your process to remove 1 net tonne of CO<sub>2</sub> right now (in GJ/tonne)? Break that down into thermal and electrical energy, if applicable. What energy intensity are you assuming for your NOAK TEA?

Electrical and thermal energy needs are estimated to be 0.012 GJ/ton of CO<sub>2</sub> captured from air and mineralized. A key consideration is the availability of waste heat at Nucor Inc., which can further reduce the energy needs for the scalable implementation of this technology.

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

For the TEA, we assume that thermal and electrical energy needs are met using natural gas and non-renewable (fossil) resources, respectively. Carbon intensity of natural gas is about 53 kg of CO<sub>2</sub> per million Btu. This remains unchanged over the duration of the project. Given the abundance of waste heat available in iron and steel making facilities, we anticipate that energy needs, and associated CO<sub>2</sub> emissions will be lower.

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

The other resources we need are aqueous solvents for CO<sub>2</sub> capture. We plan to harness these resources from the Finger Lakes region. We will reuse water over multiple cycles. We will send the used water to wastewater treatment facility for processing after carbon removal.

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

Our experimental data shows that 95% of solvent is regenerated after every experiment and 5% solvent makeup is needed. The losses occur during filtration and washing of the material. Keeping all other factors constant, the CDR performance does not change over time. For example, > 95% conversion of CaO to CaCO<sub>3</sub> in 3 hours when reacted in 1 M Na-glycinate at 25, 50 or 75C with 15 wt.% solid and in a well stirred system. These results are discussed in the technology description section.

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

The capture medium at the end-of-life is sent to the wastewater treatment facility for safe treatment and disposal. We anticipate that these solvents will contain some dissolved metals such as Ca and Mg. We will characterize these materials to ensure their safe and sustainable treatment and disposal.

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

Current technologies for DAC result in a higher concentration of CO<sub>2</sub> which is either converted to another value-added products or injected in subsurface environments. The cost of DAC alone exceeds \$100/ton of CO<sub>2</sub> and does not include the cost of conversion in case of utilization or monitoring and verification costs in case of storage. These challenges motivated us to develop a technology that integrates DAC and mineralization with costs ranging from \$ 83 - \$ 126/ton of CO<sub>2</sub> removed.

Our technology is truly transformative for several reasons. First, solvent regeneration is coupled to carbon mineralization and occurs at 50-75C as opposed to >90C, which is a major energy saving. Second, the carbon content in the product is quantifiable and verifiable in an unambiguous manner as an alternative to natural solutions. Third, the carbonate-bearing product can be stored indefinitely or used as an additive in construction materials. Fourth, our technology offers multiple co-benefits including the chemical stabilization of alkaline industrial residues via carbonate formation and preventing the release of heavy metals such as manganese, chromium, and nickel into soils and ground water by locking these metals in carbonate matrices. Fifth, once the solid carbonates are formed, these materials are durable for more than 1000 years. Thus, the low costs of DAC and mineralization and multiple benefits offered by our technology differentiate it from existing DAC technologies.

# Application Supplement: Surface Mineralization and/or Enhanced Weathering

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

## Source Material and Physical Footprint

1. What source material are you using, and how do you procure it?

Our source materials are slags generated during iron and steel making. Depending on how the slag is formed, the compositions can range from combined Ca- and Mg-content of 30 wt.% to 60 wt%. The reactivity of these materials with CO<sub>2</sub> is high and > 95% of the Ca- and Mg-content is converted into solid carbonates using our coupled DAC and mineralization technology. We are collaborating with Nucor Inc., a leading iron and steel industry with operations in NY to provide these materials for our technology.

2. Describe the ecological impacts of obtaining your source material. Is there an existing industry that co-produces the minerals required?

The ecological impacts of stockpiling slags and leaving them untreated is detrimental for the environment. When untreated slags come in contact with water, the resulting solution pH is very high and additional unit operations are needed to treat these wastewater streams. Thus, chemical stabilization of these materials via carbonate formation is crucial since these materials are more stable and lock up toxic metals as Cr, Mn, and Ni in the solid carbonate matrices. Furthermore, these carbonate-bearing materials can be re-used as additives in construction materials. We are collaborating with Nucor Inc., who will provide us these materials for DAC and mineralization.

3. Do you process that source mineral in any way (e.g., grinding to increase surface area)? What inputs does this processing require (e.g. water, energy)? You should have already included their associated carbon intensities in your LCA in Section 3.

Assuming that the slag materials are available to us at particle sizes of 5 mm, these materials will need to be ground to sizes below 30 microns to enhance their reactivity. Using Work Index from Bond's Law, the associated energy needs to grind materials from the sizes of mm to microns is about 14.3 kWh/ton. Assuming electricity costs of \$ 0.104/kWh, the energy costs are \$1.49 per ton of processed material, which is very modest. Assuming carbon intensity of 475 gCO<sub>2</sub>/kWh, the associated emissions are 6.8 kg/ton of processed material. We propose to power our grinding processes using electricity from renewable resources, which helps us avoid these CO<sub>2</sub> emissions.

4. Please fill out the table below regarding your project's physical footprint. If you don't know (e.g. you procure your source material from a mining company who doesn't communicate their physical footprint), indicate that in the table below.

	Land area (km <sup>2</sup> ) in 2021	Competing/existing project area use (if applicable)
Source material mining	Slags are already mined. These stockpiles occupy about ~ 0.5 km <sup>2</sup>	n/a
Source material processing	Grinding the materials is estimated to require ~ 0.2 km <sup>2</sup>	n/a
Deployment	At the scale of 10 million tons of CO <sub>2</sub> removed per year, we will need ~ 10 km <sup>2</sup> of area for our integrated DAC and mineralization process.	n/a

5. How much CDR is feasible globally per year using this approach? Please include a reference to support this potential capacity.

Based on the annual generation and availability of slags, our gross CO<sub>2</sub> removal will be 400,000 tons in 2028, associated gross CO<sub>2</sub> emissions are ~ 310,000 tons of CO<sub>2</sub> per year and the net CDR is ~90,000 tons per year. Assuming a project lifetime of 20 years starting 2028, we will have achieved net CDR of 1.8 million of tons just from one iron and steel making facility in NY. Our commercialization plan includes scaling and deploying this technology at multiple facilities and anticipate realizing the removal of several tens (if not hundreds) of tons of net CDR.

6. If you weren't proceeding with this project, what's the alternative use(s) of your source material? What factors would determine this outcome?

The alternative uses of slags include their use as pozzolanic additives in construction materials. With increasing interest in energy critical metal recovery, these materials are used as a resource for Mn, Fe, Cr, Zn, and Ni which can be reused in iron and steel making.

## Human and Ecosystem Impacts, Toxicity Risk

7. What are the estimated environmental release rates of heavy metals (e.g. Cr, Ni, Pb, Hg)? Dust aerosol hazards? P loading to streams? How will this be monitored?

The environmental releases are typically into the aqueous phase. Since the pH of system during carbon mineralization is typically in the range of 5.5 – 8, minimal leaching of Cr, Ni, Pb and Hg is noted, and concentrations of these metals are below 10 ppb after DAC and mineralization. There is

extensive evidence to suggest that the metals are stabilized in solid carbonate matrices on carbon mineralization. We will continue to measure the concentrations of the dissolved metals every cycle to inform scale-up while minimizing detrimental environmental impacts.

8. If minerals are deployed on croplands, what are the estimated effects on crop yields? Include citations to support this claim. How will actual effects be monitored?

We do not anticipate deploying the carbonate-bearing materials from slag precursors in farmlands since there are concerns of leaching of heavy metals into soils and loss in durability of carbon removal due to dissolution to produce (bi)carbonate species.

9. How will you monitor potential impacts on organisms in your deployment environment? (e.g. health of humans working in agricultural contexts, health of intertidal species, etc.)

Since we do not anticipate using the carbonate-bearing materials for soil liming, we will not need to monitor potential impacts on organisms. We will monitor the potential degradation of the solvent over multiple cycles and the impacts of the degraded products on organisms in the first two years of the project.

# Application Supplement: CO<sub>2</sub> Utilization

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

## CO<sub>2</sub> Feedstock

1. How do you source your CO<sub>2</sub>, and from whom? If your approach includes CO<sub>2</sub> capture and it's described above (e.g., general application and one of the supplements), simply respond N/A here.

N/A

2. What are alternate uses for this CO<sub>2</sub> stream?

The products produced from our process are carbonate-bearing slag materials. Using these materials as additives that can replace 20-30% ordinary portland cement is a durable solution. A less durable solution is the use of these materials for soil liming in which case the carbonate-bearing solids dissolve to release (bi)carbonate-rich fluids into the soils.

## Utilization Methods

3. How does your solution use and permanently store CO<sub>2</sub>? What is the gross CO<sub>2</sub> utilization rate? (E.g. CO<sub>2</sub> is mineralized in Material at a rate of X tCO<sub>2</sub> (gross) / t storage material).

Our solution stores and uses CO<sub>2</sub> as mineralized carbonate-bearing solids that replace 20-30% of OPC in construction materials. Depending on the alkalinity content of the slags about 0.1 – 0.25 tons of CO<sub>2</sub> can be stored as solid carbonates per ton of slag materials.

4. What happens to the storage material (e.g. concrete) at the end of its service life, and how does that impact its embodied carbon storage over time? How do you know?

Construction and demolition waste (CDW) is typically landfilled at the end of service life. If this is the case, then carbon is removed in a durable manner through CDW bearing solid carbonates. Alternatively, if the construction and demolition waste bearing solid carbonates are recycled every 50 years – 100 years, then the durability of these materials is only 50-100 years.

5. How do you ensure that the carbon benefits you are claiming through a CO<sub>2</sub> utilization process are not double counted? (E.g. If sourcing CO<sub>2</sub> from a DAC system, or selling your product to a user interested in reducing their carbon footprint, who claims the CDR benefits and how could an independent auditor validate no double counting?)

We will provide detailed documentation that discusses the LCA of the overall process including CO<sub>2</sub> emissions avoided using carbonate-bearing materials in construction materials and net CO<sub>2</sub> removal assuming various scenarios of storage and recycle to the customer. It is then the responsibility of the customer to responsibly communicate and use this information. We will also make this information publicly available so there is clarity in the marketplace regarding the scenarios associated with carbon removal.