ZS2 Technologies Ltd.

Carbon dioxide removal prepurchase application

Summer 2023

General Application

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

Public section

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

Company or organization name

ZS2 Technologies Ltd.

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

Calgary, Canada

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

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Brief company or organization description <20 words

ZS2 has developed magnesium-based cement and concrete formulations that sequester and utilize 10-22 wt.% CO_2 from point sources or DAC.

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

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

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

your project addresses any of the priority innovation areas identified in the RFP, tell us how. Please include figures and system schematics and be specific, but concise. Aim for 1000-1500 words.

ZS2 has developed a novel process for waste to cement production with a low-cost modular carbon capture system that sequesters CO_2 into high strength carbon negative cement and concrete. A patent pending magnesium-based cement formulation with commercial demand is the primary differentiator for our organization. ZS2 is presently operating a working pilot demonstration with commercial orders fulfilled for tiles with up to 20 wt.% CO_2. The magnesium cement formulation has 100 times the typical CO_2 storage capacity of conventional Portland cement. This only accounts for the CO_2 stored as solid carbonates, and does not account for the CDR potential of biochar produced by our partners that is another CDR component. The secondary differentiator is the low cost, low land footprint and high carbon capture rate system that can handle both air and point source emissions. The patent pending process incorporates waste brine into a breakthrough CO_2 storage technology that shows significant cementing properties and yields carbon negative building products.

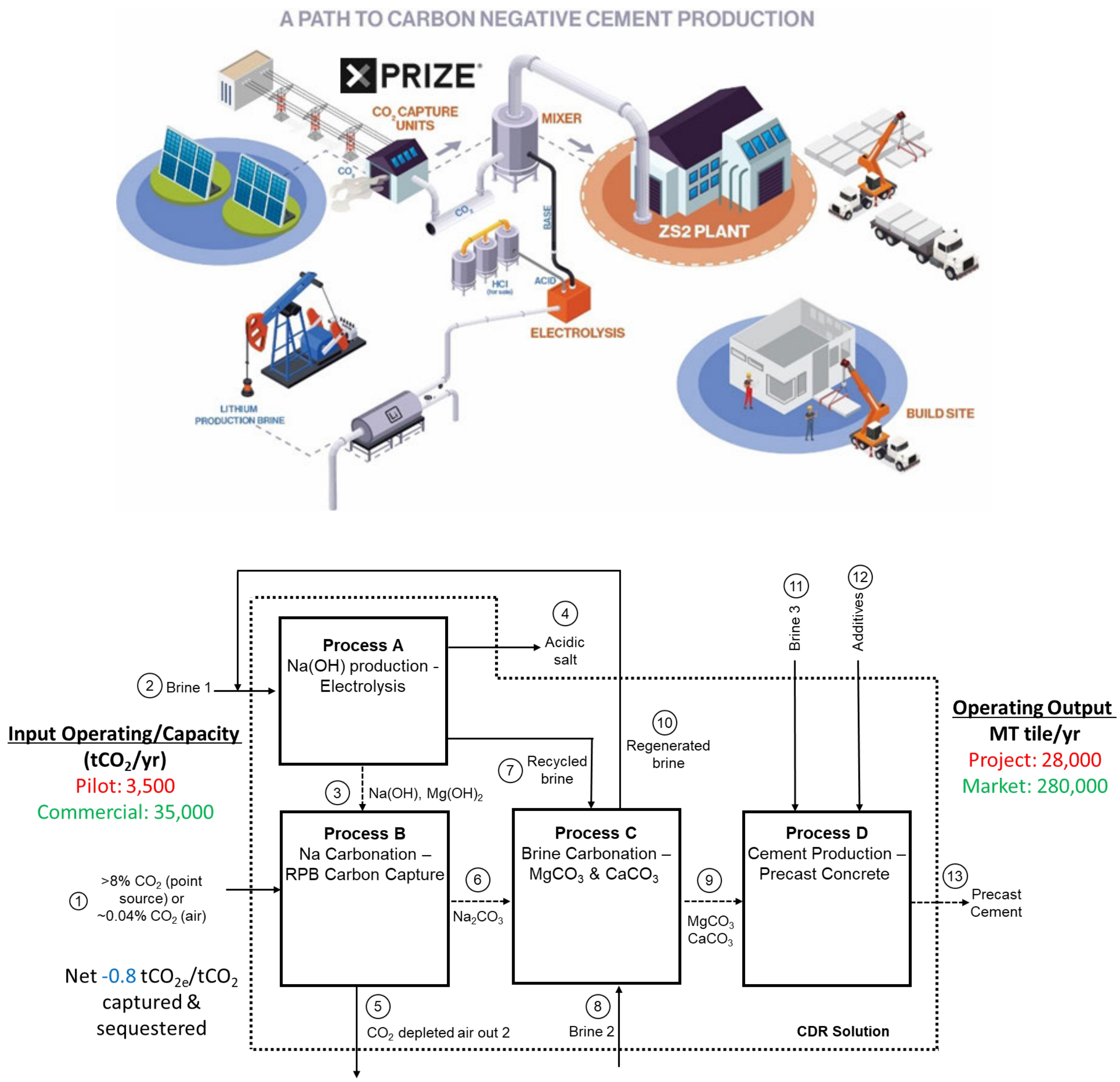

Figure 1: Schematic of waste to mineralization cement process.

The schematic above roughly illustrates the CDR approach which is described as Processes A through D. In some cases, alkaline brine waters are carbonated directly and this results in a process that operates at 3.35 GJ/tCO_2 captured and stored. This would bypass process A and represent a greater than 50% decrease in energy costs on technologies currently being deployed (Climeworks, Carbon Engineerings, etc. see below) at a significantly smaller level of capital equipment deployment (~$5M system). If the brines are neutral pH or acidic, ZS2 is deploying an electrolysis treatment process (additional 3.49 GJ/tCO_2) to provide a system that can mineralize CO_2. This is being developed in partnership with sHYp (A Columbia University Start-up that published groundbreaking work in the field https://www.pnas.org/doi/10.1073/pnas.2114680119). Their process is designed to produce green hydrogen, but ZS2 is able to extract the hydroxide base streams as a by-product for carbon capture. This system requires ~0.7 kWh/kg OH^- whereas the conventional chlor-alkali electrolysis process consumes 5 kWh/kg OH^-.

ZS2's solution provides a capture to storage solution that is cost competitive at the 3300 tCO_2/yr scale. Most other CDR solutions require economies of scale to reach financial feasibility. The technology processes gas streams with CO_2 injected into a scalable rotating packed bed (RPB) denoted as process B. A central system controls the ejection of liquid sorbent radially outwards to force counter flow. The mechanical rotation shears the liquid to form ultrathin layers that enhance carbon capture rates and efficiencies that are gas/liquid surface diffusion limited. This reduces the size of the carbon capture system versus existing technologies such as cooling towers by an order of magnitude.

Process C takes the carbonates and reacts with the residual minerals in waste brines or salt water. This precipitates $CaCO_3$ and $MgCO_3$ that are used in the production of magnesium based cements (MBC). The precipitate is separated with residual waste water that makes up the entirety of the water required for concrete production. The concrete can tolerate impurities such as NaCl, which is a substantial advantage compared to conventional Portland cement. MBC saves significant cost and energy by minimizing the need for mined products, purification, and fresh water. Over the last year, ZS2 has demonstrated a process at 30 tCO_2/yr scale of DAC to carbonate brine water. The carbonation of waste brine water creates $CaCO_3$ and $MgCO_3$ that is directly isolated as "cakes" through a filter press. The cakes are incorporated into a cement mix with additional aggregates from waste and recycled products.

The resulting product was turned into precast concrete tiles in a test demonstration plant (process D). The tiles contained 10 – 20 wt.% CO_2 while still meeting strength requirements for commercial application. Current companies, such as CarbonCure, sequestering CO_2 into Portland cement (Ca-based) observe that CO_2 content above 0.2 wt.% result in reduced mechanical performance of concrete. Compared to Ca-based alternatives, magnesium carbonates such as nesquehonite ($MgCO_3$-$3H_2O$) is self-cementing when thermally activated and remixed with water.[2] This makes it a good binder for cement. The concrete strength over 28 days exceeds 30 Mpa - compared to the industry baseline of 20 MPa for a Type I concrete. The hydration of MBC yields $Mg(OH)_2$, which is quite weak. However, the addition of CO_2 yields the formation of hydrated magnesium carbonates that significantly enhance strength. This strength is also attributed to the formation of acicular and fibrous crystals.[3] In conventional cement $CaCO_3$ inhibits and competes with the cementing hydration reactions. The CO_2 stored in the concrete displaces an equivalent amount of MgO that would otherwise have been required. This provides a dual benefit of removing a portion of the carbon intense MgO that is conventionally manufactured and replacing it with a CO_2 gas that needs to be stored for disposal. The proposed technology produces MBC building materials that represent the majority of the building envelope for ZS2's projects.

The growing need for the CDR solution is evident from global warming. The need for a sustainable

[2] https://www.sciencedirect.com/science/article/pii/S0008884616302575
[3] https://www.sciencedirect.com/science/article/pii/S0008884613001816

and climate resilient building product such as MBC is also growing. The MBC market in North America is ~$200MM USD/yr and is growing rapidly, as it continues to replace less resilient and less environmentally friendly conventional products based on Portland cement and/or gypsum. It has been estimated that the tiles market is approximately 6.75 billion USD in the USA alone with a compound annual growth rate (CAGR) of 5.2%.[4] This does not account for the global cement tile market due to lack of data. Another comparable market is cement boards where one report estimates the market will reach $27 billion USD in 2032 with a CAGR of 4.3%.[5] The other market we anticipate competing in is cement siding. This is estimated to be a $6.23 billion USD market by 2028 with a CAGR of 6.7%.[6]

The primary storage or sequestration of most commercial carbon capture companies is through compression, purification and transportation to pumped underground cavities or for enhanced oil recovery. Our proposed process avoids the need for compression, purification and transportation of CO_2 by providing a capture to utilization solution at a much lower cost. Our process is designed to utilize as little energy as possible to achieve CDR. We are in the process of engineering, procuring and constructing a microgeneration solar cell facility to power the next generation of the plant. Solar power is more feasible than wind power renewables because of the lower initial capital investment and land usage.

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

ZS2 expects to implement carbon capture, utilization and storage (CCUS) solutions around the world to exceed the target and achieve 1 Gt by 2050. One of the long-term trends in the construction industry is the increasing focus on carbon-conscious decisions and sustainable building practices. Capturing CO2 emissions and utilizing carbon-negative, waste-based cement and building materials offer a viable global path toward achieving net-zero emissions inclusive of the avoidance of carbon intensive conventional cement. ZS2's carbon capture technologies allow for the extraction of excess Mg and Ca from waste brines in the form of $MgCO_3$ and $CaCO_3$. This acts as a key product to strengthen our proprietary cement and concrete formulations and reduce costs. Waste brine is widely available throughout the world. This includes salty waters from the ocean, desalination, oil and gas production, underground aquifers and factory plants. Very few companies are looking at utilizing the vast resource of Ca and Mg from these brines that have considerable synergies with burgeoning lithium extraction industry. Mg and Ca are hard minerals that foul membranes in many industrial processes including desalination and lithium extraction.

The CO_2 is first captured in an alkaline brine solution that is accelerated from the center via high speed rotation creating a thin liquid film that enhances carbon capture versus packed cooling towers. The CO_2 is then reacted with Mg and Ca in brines to precipitate $MgCO_3$ and $CaCO_3$. The 2-step process substantially enhances rate kinetics and enables smaller systems to be used. The goal of ZS2 is to develop a compact and modular system to capture and permanently sequester CO_2. This system

[4] https://www marketresearchfuture.com/reports/u-s-cement-tiles-market-5954

[5] https://www.prnewswire.com/news-releases/fiber-cement-board-market-value-to-grow-by-almost-us-27-billion-in-2032--future-market-insights-inc-301597857 html

[6] https://www.globenewswire.com/en/news-release/2022/02/28/2393074/28124/en/Global-Fiber-Cement-Siding-Market-Forecast-to-2028-COVID-19-Impact-and-Analysis.html

can be utilized by small and medium enterprises with suitable salty wastewater sources. The system is also designed to be scalable to meet the needs of heavy emitters.

ZS2 is also trying to develop a construction solution that reaches net negative carbon emissions and decarbonizes the world's largest industry. We have brought together a consortium to develop a fully integrated CDR solution. The patent pending carbon capture and sequestration processes and cement formulations offer a shift away from high GHG intensity conventional construction solutions. The CO_2 storage generates additional revenue versus many CDR solutions that rely on carbon credit pricing and regulations to make the solution financially feasible. Our CDR solution incorporates carbon capture, sequestration and utilization processes to yield a final commercial product beyond CO_2. This means that overall cost reflects not only the CDR, but a high demand commercial product – MBC. The commercialization and sale of this end product and replacing other cementitious materials with CO_2, in the form of carbonates, is the only thing that needs to happen to realistically reach Frontier's $100/t target. ZS2 has already completed commercial orders ahead of schedule from the pilot demonstration.

The secondary objective of the consortium is to disrupt the construction industry by developing an advanced manufacturing solution to address the pressing global need for affordable, climate-adaptive, energy-efficient, and sustainable housing. Canada, like the rest of the world, requires many new homes to address affordable housing challenges. CMHC estimates this value to be 5.6 million. However, the industry faces a shortage of skilled workers. The proposed solution involves designing, manufacturing, and commercializing durable structural building materials. We leverage advanced manufacturing techniques to enable faster, greener, and more climate-adaptive construction with a smaller skilled labour force. The project develops the magnesium resources necessary for both mineralization CDR and MBC-based construction. China, Russia and North Korea are the current primary producers of magnesium.

The first plant is located in Alberta, Canada. It is expected to capture, sequester, and utilize approximately 3150 tCO_2/yr with a rated capacity of 3500 tCO_2/yr. This system is expected to have capital cost of approximately $6,000,000 with a 30 year lifespan. The majority of the cost is associated with the engineering, procurement and construction of a microgeneration solar farm. This system is expected to be optimized and expanded to reach a rated capacity of 35,000 tCO_2/yr. ZS2 then expects to expand beyond Alberta into the east and west coast, as well as southern USA. The development of multiple plants minimizes strain on local resources while serving localized construction industries. This also reduces emissions from the transport of CO_2 utilization end products (MBC tiles).

The current solution is aimed at exhaust capture from industrial processes. The current plant is expected to be commissioned at partner LithiumBank's site to capture exhaust from their direct lithium extraction processes. Partner company Baymag Inc. also has ~170,000 tCO_2/yr of emissions that is expected to be captured and sequestered for the next generation of ZS2's system. ZS2 has strategically partnered with these companies because they produce critical materials that are needed regardless of the green transition. Lithium is a critical mineral for batteries that will be needed to make renewable energy sources and electric cars feasible. Baymag produces MgO that is critical for water remediation, wastewater treatment, air purification and soil remediation. ZS2 is also actively DAC with the same RPB technology. However, exhaust capture makes more sense from a technical, financial and risk standpoint for the pilot demonstration. Future plants explore DAC if and when exhaust capture from heavy and critical commercial emitters is completed.

The CO_2 removed will be quantified at each step. Sensors are in place to monitor the input and output into the rotating packed bed (RPB) carbon capture system. The output from the RPB is the input to the brine carbonating sequestration system. The amount of solid precipitates is measured to determine the effective CO_2 sequestered. Inductive coupled plasma tests are also run before and after to determine the extent of mineralization. The mineralized carbonates are then added to cement and concrete formulations at known ratios to verify the carbon utilization. These processes utilize calibrated load cells communicating to a central control panel to verify the CDR approach. The CDR solution will be quantified in partnership with Carbonomics. They will help to quantify, validate and register the CO_2 removed. Currently, we are looking to adjust VM0043 created by CarbonCure and Carbonomics to encompass our carbon capture solution and the sequestration into precast cement.

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

Technical risks:

(1) The high energy consumption of sorbent generation has been mitigated by a novel hydrogen-enhanced electrolysis process that is being developed in partnership with sHYp and Columbia University. They have presently proven out their technology at the 1 kW scale, and are continuing to scale. ZS2 has also engaged ThyssenKrupp for detailed quotes on a chlor-alkali electrolysis unit and wholesale manufacturers of Na(OH) as contingencies.

(2) Technology scale up of carbon capture from 32 t/yr up to 3500 t/yr risks are mitigated by having the right team in place. Dr. Doug Brown and Dr. Matt Henderson were both founding/early team members of Carbon Engineering. They took their knowledge of packing materials and carbon capture and applied it to a more efficient rotating packed bed system. Post secondary institutions have also been contracted to assist with the modelling, optimization and manufacturing of the carbon capture solution.

(3) Risks from feedstock shortages, especially brine production and mineral content, have been mitigated by designing the system to accept an range of input feedstock concentrations. The system was initially designed to accept water mimicking ocean conditions. However, ZS2 is located in land-locked Alberta. We have since pivoted to using substantially saltier (higher mineral content) brines produced by lithium extraction companies. We have firm agreements in place with one project partner, and have engaged in ongoing discussions with 2 additional lithium extractors that produce substantial quantities of waste brine. The solution can also utilize brines from desalination, oil and gas and industrial processes.

(4) Risks with sequestration solution (tile plant) being able to meet carbon capture capacity have been mitigated through engineering designs and automation. The first-of-a-kind sequestration plant has been designed to have automated throughputs with logic controllers and sensors to maximize throughput.

Reporting and Verification

(1) Risks with reporting and verification have been mitigated by a partnership with Carbonomics. They have experience in guiding CarbonCure through the reporting and verification process. They will advise on the necessary sensor placements and controls to ensure verification. They will help create a methodology to report and register carbon credits through Verra.

(2) Controls and sensor malfunctions will be mitigated with regular maintenance and engineered redundancies as advised by Carbonomics. Sensors will be calibrated based on advised manufacturer schedules.

Ecosystem risks:

(1) Risk of emitting CO_2 sorbent (NaOH) into the ecosystem is mitigated by system design. The systems are designed to be gas tight, and thus ecosystem contamination is low risk. The air outlet systems are equipped with mist eliminators as a last line of defense.

(2) Risk of overproducing from underground brine reserves is mitigated by reinjecting excess brine (stripped of necessary minerals) back underground.
(3) High energy consumption of an electrolysis-based process is mitigated through the use of solar power to generate all the necessary electricity with designed excess.

Financial risks:

(1) High project costs are supported by government funding. Sustainable Development Technology Canada, Emissions Reduction Alberta, Next Generation Manufacturing Canada and Natural Sciences and Engineering Research Council of Canada have contributed or confirmed contribution of more than $5 MM towards the advancement of the project.
(2) Potential budget overruns of the proposed CDR solution are mitigated by a planned Series A raise that is backed by success from a recently completed convertible debenture.

Other risks:

(1) Any shifts in personnel may pose risks. However, ZS2 has assembled a large consortium of partners with a common benefit achieved from this overall CDR solution. Consortium members offer additional experience and expertise that help mitigate any personnel change risks.
(2) There are associated IP risks. Filed patents could be delayed or rejected by patent office. ZS2 has contracted a large legal firm (Oyen Wiggs) to represent ZS2's interests in patent filings. The consortium has IP agreements in place, and ZS2 has legally binding NDAs signed with those exposed to trade secrets.
(3) Commercialization of final magnesium cement tiles is a risk. The commercialization helps to subsidize the price of the CDR solution because the solution replaces 10-20 wt.% of aggregates in the tile. ZS2 has gained substantial commercial traction and has sold the first commercial orders running the pilot plant in batch mode.

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

Proposed CDR over the project lifetime (tons) *(should be net volume after taking into account the uncertainty discount proposed in 5c)*	1000
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	Q4 2026
Levelized Price (\$/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	447

** This does not need to exactly match the cost calculated for "This Project" in the TEA spreadsheet (e.g., it's expected to include a margin and reflect reductions from co-product revenue if applicable).*