Frontier

MK Collect

Carbon dioxide removal prepurchase application

Summer 2024

General Application

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

Public section

The content in this section (answers to questions 1(a) - (d)) will be made public on the Frontier GitHub repository after the conclusion of the 2024 summer purchase cycle. Include as much detail as possible but omit sensitive and proprietary information.

Company or organization name

MK Collect

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

Melbourne, Australia

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

Masood Alivand, Kathryn Mumford

Brief company or organization description <20 words

MK Collect develops highly scalable, low-cost, and energy-efficient direct air capture (DAC) technologies using catalytic membrane pervaporation.

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

a. **Description of the CDR approach:** Describe how the proposed technology removes CO_2 from the atmosphere, including how the carbon is stored for > 1,000 years. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar approach. If your project addresses any of the priority innovation areas identified in the RFP, tell us how. Please include figures and system schematics and be specific, but concise. 1000-1500 words

Summary

MK Collect is developing a novel approach called Catalytic Membrane Pervaporation (CMP) using green amino acid solvents for low-cost, energy-efficient liquid-based direct air capture (DAC). This innovative

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

technique integrates two in-house developed technologies: membrane pervaporation and catalytic solvent regeneration.

CMP-DAC replaces conventional, capital- and energy-intensive solvent regeneration techniques, with a low-temperature system, operating affordably and effectively in the 70-100 °C range, enhancing the scalability of liquid-based DAC. CMP-DAC modules are powered by renewable electricity supplies, such as solar grids, and utilize dense hollow fiber membrane modules (HFMs) and acidic nanocatalysts to achieve a very high CO_2 desorption performance in a simple, compact design. While other DAC technologies are constrained by cost-intensive in-house-made components, our technology leverages the existing manufacturing infrastructure for nanocatalysts and membranes, enabling rapid and efficient scale-up. This results in a low-cost, green, and highly scalable DAC solution for large-scale deployment, paving the way for achieving CO_2 removal at scale.

Process Description

MK Collect's technology comprises three main parts: absorption, heat recovery and heating systems, and desorption (Figure 1):

1. **CO_2 Absorption:** Our process begins with the CO_2 absorption section. Air is pulled through the system using industry-modified cooling towers, designed for high surface area contact with minimal pressure drop per unit volume. As the air passes through the cooling towers, it contacts an aqueous amino acid solvent at room temperature with negligible vapor pressure and solvent loss. The CO_2, present at 400 ppm, is chemically absorbed by the solvent and stored as stable CO_2-containing species. This process effectively captures CO_2 from the air, resulting in a CO_2-rich solvent.
2. **Heat Recovery and Heating Systems:** Once the solvent is saturated with CO_2, the rich solvent is pumped into a heat exchanger. The heat exchanger allows for efficient heat recovery, significantly reducing energy consumption by the solar-powered electrical heater. The solvent then passes through the heater to reach the temperature required for optimal CO_2 diffusion through the membrane, achieving high desorption performance in the presence of nanocatalysts.
3. **CO_2 Desorption:** The heated rich solvent is directed through dense hollow fiber membrane modules in the presence of acidic nanocatalysts under vacuum conditions. The nanocatalysts facilitate the breakdown of CO_2-containing species, while the dense membrane layer ensures a constant CO_2 desorption rate to achieve minimal CO_2 concentration in the liquid phase. This setup facilitates the desorption of CO_2 molecules, along with some H_2O molecules acting as a carrier medium. After condensing the water vapor back into liquid form, high-concentration CO_2 is collected. The regenerated solvent, now referred to as lean solvent, is cycled back through the heat exchanger to reclaim residual heat before returning to the absorption column to capture more CO_2. Unlike conventional distillation technology, no boiling occurs during desorption, saving the latent heat of evaporation and decreasing operating costs.

At the commercial scale, the cooling tower and solvent tanks sit on the ground, while the other facilities are housed within a shipping container, offering modular scalability.

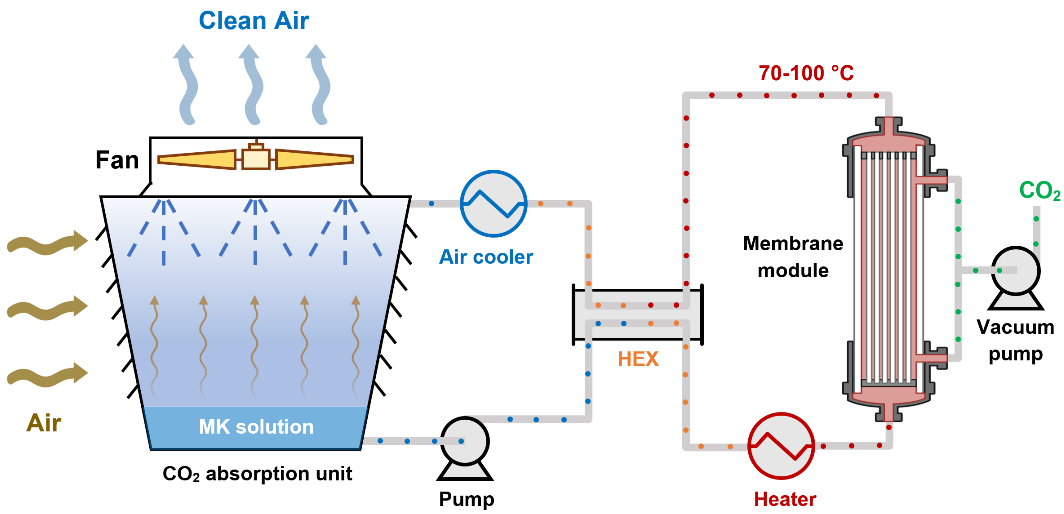
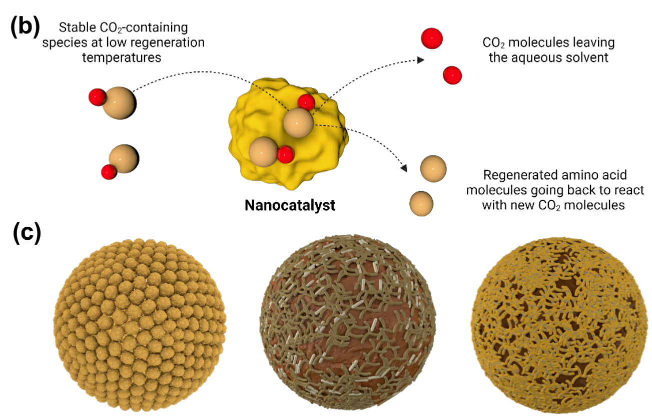


Figure 1. *The process flow diagram of the CMP-DAC process.*

Differentiation

MK Collect has introduced a novel approach to DAC that uniquely stands out from existing DAC technologies. To the best of our knowledge, this is only low-temperature DAC technology utilizing aqueous amino acid solvents without any solid precipitation, complicated solid handling, or high-cost electrochemical regeneration. Our CMP-DAC technology combines low-temperature solvent regeneration with catalytic membrane pervaporation, addressing a significant challenge in the field. Traditional low-temperature solvent regeneration has low CO_2 desorption kinetics and cyclic capacity, necessitating high-temperature (~140 °C), energy-intensive distillation columns. MK Collect is the only company to overcome this with an efficient, low-cost solution.

CMP-DAC technology excels in CO_2 desorption during low-temperature operations, enhancing its feasibility for large-scale, energy-efficient DAC (Figure 2). Acidic nanocatalysts alter reaction pathways, breaking down stable CO_2-containing species, promoting CO_2 desorption and reducing total energy consumption, during low-temperature membrane pervaporation. Our advanced nanocomposite hollow fiber membranes (HFMs) feature a nanoporous support coated with an ultra-thin dense layer, ensuring minimal mass transfer resistance and maximizing CO_2 desorption flux. Both membrane pervaporation and catalytic operation, which are the base of CMP-DAC technology, are used in industries at scale, giving MK Collect a unique position in the competitive market to achieve gigaton scale deployment in the expected timeframe.



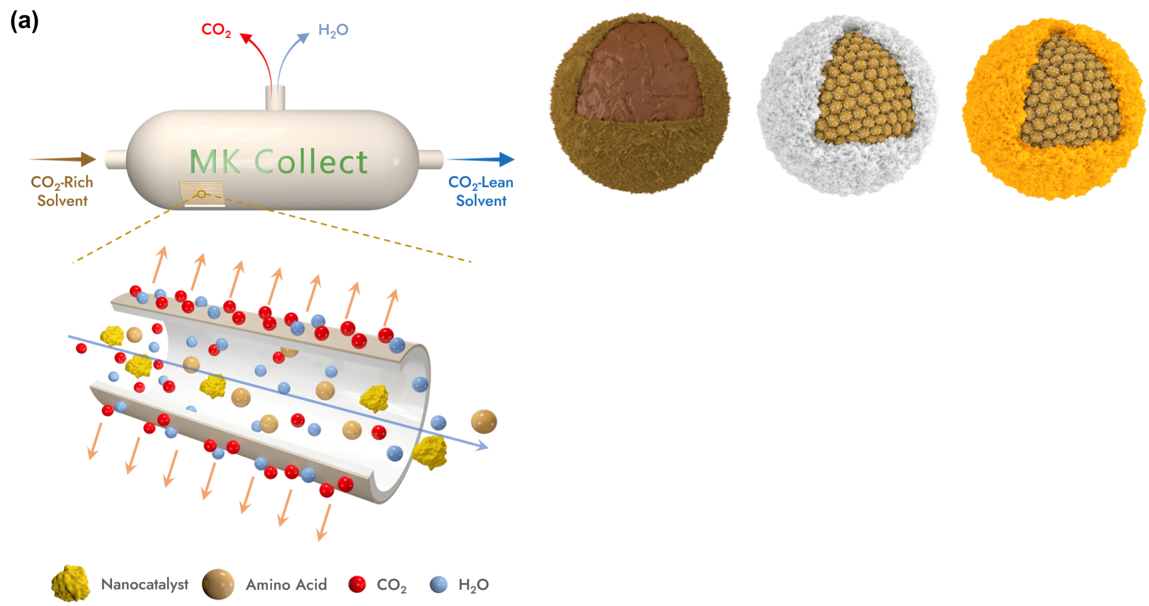


Figure 2. *(a) The scheme of the CMP-DAC module developed by MK Collect and its operation mechanism through nanocomposite membrane in the presence of nanocatalysts. (b) The reaction mechanism of catalytic solvent regeneration, and (c) the library of developed nanocatalysts with different features.*

CMP-DAC technology brings several advantages, including:

1. **Green Solvent**: Our proprietary solvent is green, sustainable, environmentally friendly and highly effective in CO_2 absorption from the air, including high CO_2 uptake and fast absorption kinetics. This aqueous amino acid salt benefits from negligible vapor pressure and minimal solvent loss during operation. More importantly, the solvent benefits from high thermal and oxidation stability, ensuring good longevity.
2. **High Energy Efficiency**: Our patent-protected technology enables low-temperature solvent regeneration in the 70-100 °C range, significantly reducing energy consumption and operating expenses (OPEX). CMP-DAC achieves high CO_2 desorption performance without consuming latent heat of evaporation, unlike conventional distillation columns. Our technology can achieve 4 GJ/tCO_2 energy consumption at NOAK scale using solar electricity and waste heat.
3. **Scalability:** Utilizing off-the-shelf components and existing infrastructure, our design accelerates large-scale DAC deployment with minimal in-house fabrication and low capital expenditure (CAPEX). MK Collect's industry partners provide a robust supply chain for all components, including dense nanocomposite HFMs, nanocatalysts, cooling towers, and amino acid salt. The well-established supply chain for amino acids, widely used in various industries, further ensures cost-effective scalability even at the gigaton scale.
4. **Modular Design**: Our system is designed for modular scalability, allowing for easy expansion and integration into various settings. The cooling towers and solvent tanks are ground-based, while other facilities are housed within shipping containers, facilitating flexible and scalable deployment.
5. **Low CO_2 Cost**: Our DAC facilities are engineered to remove CO_2 from the atmosphere at a cost of less than $100 per ton by 2030 on the NOAK scale. The compact, simple design, and low-cost hollow fiber membrane (HFM) modules, along with the use of existing infrastructure for mass production contribute to this affordability.

Priority Innovation Areas

MK Collect's CMP-DAC technology addresses several priority areas outlined by Frontier for 2024:

1. **Leveraging Existing Industrial Assets:** CMP-DAC integrates well with existing industrial processes due to its reliance on widely available components like nanocatalysts, hollow fiber membranes, and

cooling towers. This compatibility with existing infrastructure reduces costs and accelerates scalability. For instance, utilizing existing cooling systems and solar grids aligns with Frontier's focus on repurposing resources for carbon removal at scale.

2. **Regional Focus:** CMP-DAC is currently deployed in Australia, which falls under the APAC region. The technology is adaptable to various regions, including the Middle East, Africa, and Latin America, due to its reliance on solar energy and off-the-shelf components. This adaptability ensures that CMP-DAC can be deployed globally, tapping into regions with high solar potential and established industrial bases.
3. **Lowering Costs Through Additional Revenue:** CMP-DAC offers potential for additional revenue streams through the use of captured CO_2 for sustainable cement production. This approach aligns with Frontier's vision of making carbon removal financially viable by creating resilient business models. By converting captured CO_2 into valuable products, CMP-DAC reduces overall operational costs and contributes to the circular economy.
4. **Environmental and Economic Co-benefits:** Our green solvent and low-energy process contribute to local environmental benefits by reducing reliance on fossil fuels and minimizing waste. Additionally, the economic benefits include job creation in the manufacturing and deployment of CMP-DAC units, fostering local economies and garnering policy support.
5. **Efficient Energy Use:** CMP-DAC's innovative use of solar energy, heat recovery, and low-temperature operations exemplifies efficient and effective energy procurement. The fundamentals of catalytic membrane pervaporation are focused on energy-efficient DAC, ensuring minimal carbon footprint during operation. By utilizing solar energy and innovative design, CMP-DAC achieves high energy efficiency, making it a sustainable and scalable solution.

By addressing these priority areas, MK Collect's CMP-DAC technology positions itself as a leading solution in the DAC field, capable of achieving significant carbon removal at low costs while delivering environmental and economic benefits.

b. **Project objectives:** What are you trying to build? Discuss location(s) and scale. What is the current cost breakdown, and what needs to happen for your CDR solution to approach Frontier's cost and scale criteria?[2] What is your approach to quantifying the carbon removed? Please include figures and system schematics and be specific, but concise. 1000-1500 words

Proposed Pilot Plant: CMP-DAC v3.0

MK Collect proposes building the CMP-DAC v3.0, a pilot plant with a capacity of 200 tCO_2 per year, to be located in Melbourne, Australia. This facility is expected to remove over 5,000 tons of CO_2 throughout its 25-year lifespan. CMP-DAC v3.0 will include one cooling tower, one solvent storage tank, and three modular shipping containers, including the heating system, membrane modules, catalytic packed beds and other equipment, each designed to produce up to ~70 tCO_2 per year with over 99% purity. This containerized design allows for flexible placement near storage sites or mineral production facilities.

Given MK Collect's development-oriented strategy, CMP-DAC v3.0 will be built based on the initial pilot plants, managed in two consecutive project phases:

Phase 1: This phase was initiated in Q2 2023 and involved designing and constructing our CMP-DAC v2.0 pilot plant with a 20 tCO_2 per year capacity. The construction of CMP-DAC v2.0 was completed in Q2 2024 and is currently located at the Werribee campus as part of our partnership with the University

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

of Melbourne. This phase provided valuable insights and lessons learned for future planning and upscaling.

Phase 2: Currently underway, Phase 2 aims to optimize and scale up to CMP-DAC v2.1 with a 40 tCO_2/y capacity. Operations for CMP-DAC v2.1 are set to begin in Q3 2024 at the same Werribee campus, which has become a hub for innovative technologies, including DAC, CO_2 capture, and hydrogen production. CMP-DAC v2.1 will be integrated with the solar panels provided on the Werribee campus to supply energy for continuous operation of the facility. The lessons learned from CMP-DAC v2.0 and v2.1 will inform the development of CMP-DAC v3.0, aligning with MK Collect's strategic growth plan. This phase will play a key role in achieving TRL6+, developing strategic partnerships and solidifying the technology status for faster upscaling.

Regarding permanent CO_2 sequestration, we are exploring both i) geological storage for medium- to long-term plans at larger scales, and ii) mineralization within concrete for short-term at smaller scales. MK Collect will collaborate with industrial CO_2 storage partners for multiple locations with different geotechnical characteristics to deliver at Frontier's scale. For mineralization, particularly on a smaller scale in the short term, we are targeting partnerships with cement companies in nearby industrial regions adjacent to the pilot plant's location, such as CarbonCure in Geelong, within an acceptable distance for the transportation of liquid CO_2 using trucks.

Cost Breakdown

Based on the techno-economic analysis and costs of CMP-DAC v2.0 and CMP-DAC v2.1, the current cost breakdown for CMP-DAC v3.0 is ~$1,370 per tCO_2 (DAC + Sequestration). Capital costs account for ~75% and operating costs for ~25% of the total, as detailed in the TEA calculations. The operating cost includes both energy requirements and the operation and maintenance of the unit with a 1:2 ratio. The offered price for CDR to Frontier is higher than the target for commercial scale due to the small size of the pilot plant. This includes high design and construction costs, equipment procurement, R&D expenses, learning costs at the pilot scale, and notably, operation and maintenance costs. This pattern is common across early-stage technology development endeavors.

Pathway to 0.5 Gt CDR/year at $100/ton

We are confident in our ability to achieve a cost below $100/$tCO_2$ for our CMP-DAC technology. To accomplish this, we will focus on several key strategies:

- **Economies of Scale**: There is a consensus that DAC is a capital-intensive technology in nature. By scaling up production and deployment, we can significantly reduce the per-unit cost of key components and materials. Bulk purchasing and large-scale manufacturing will drive down costs significantly, paving the way for achieving $100/$tCO_2$.
- **Improved Component Design:** We will continuously refine and optimize the design of our CMP-DAC units, focusing on efficiency, durability, and ease of maintenance. This will include advancements in membrane technology, nanocatalyst structure, and solvent formulations.
- **Optimized Manufacturing Processes:** Streamlining our manufacturing processes will further reduce costs. This includes automating production lines and utilizing advanced manufacturing techniques to improve efficiency and reduce waste.
- **Energy Efficiency Improvements:** Enhancing the energy efficiency of our DAC systems is crucial. This will involve increasing heat recovery rates and integrating renewable energy sources, such as solar power, to minimize operational energy costs.
- **Partnerships and Collaboration:** Collaborating with energy providers and CO_2 storage facilities will help us secure low-cost, clean energy and cost-effective sequestration solutions. These partnerships will be instrumental in achieving large-scale deployment at competitive costs.

Regarding scale, we are confident in our internal capabilities, developed partnerships, technical skills and technology status to capture 0.5 gigatons of CO_2 per year, as established by Frontier. To facilitate this path and achieve 0.5 gigaton deployment more quickly, we will:

- **Modular Deployment:** Develop modular CMP-DAC units that can be easily replicated and deployed across multiple sites. Each unit will be designed for quick assembly and integration, allowing for rapid scale-up. Our CMP-DAC v4.0 commercial plant with a capacity of 2,000 tCO_2/y will be designed using 4 shipping containers. Achieving 0.5 gigatons per year will require producing 250,000 CMP-DAC v4.0 units with 1,000,000 shipping containers, made possible through modular scalability.

- **Strategic Partnerships:** Form strategic alliances with industrial partners, governments, and research institutions to facilitate large-scale deployment. These partnerships will provide the necessary support and infrastructure for expansion. MK Collect has already partnered with numerous suppliers, engineering companies, and research centers to constantly improve its technology readiness and accelerate its scale-up. Expanding these partnerships will further advance us towards achieving 0.5 gigaton of deployment.
- **Licensing and Technology Transfer:** To accelerate global adoption, we will license our technology to other project developers and operators. This will enable widespread implementation and contribute to achieving our gigaton-scale target.
- **Investment in R&D:** Continued investment in research and development will drive innovations that enhance the efficiency and scalability of our technology. This includes exploring new materials, improving system integration, and optimizing process conditions.
- **Regulatory Support and Market Development:** Advocate for supportive regulatory frameworks and market incentives for carbon removal. Engaging with policymakers and stakeholders will help create a favorable environment for large-scale CMP-DAC deployment.

By following this comprehensive pathway, MK Collect is confident in our ability to achieve the ambitious target of capturing 0.5 gigatons of CO_2 per year at a cost of $100 per ton, contributing significantly to global efforts to combat climate change.

Quantifying Carbon Removal

To ensure accurate quantification of the carbon removed, MK Collect will implement a robust monitoring, reporting, and verification (MRV) system aligned with emerging best practices and industry standards. Our approach to quantifying carbon removal will include:

- **Real-Time Monitoring:** Implementing accurate sensors and gas flowmeter, and monitoring systems to continuously measure CO_2 concentrations and capture rates throughout the process.
- **Mass Balance and Verification:** Conducting regular mass balance calculations and third-party verifications to ensure accurate reporting of CO_2 removal.
- **Robust MRV Protocols:** Developing and adhering to rigorous monitoring, reporting, and verification (MRV) protocols to maintain transparency and credibility in our carbon removal claims. We will engage independent third-party organizations to verify our carbon removal data and methodologies, ensuring transparency and credibility.

We will adhere to the CO2RE Principles for Credible Removal, which encompass comprehensive quantitative and qualitative metrics. These principles cover traditional MRV considerations such as greenhouse gas (GHG) balances, storage permanence, and material footprint, as well as broader environmental, social, system integration, legal, and business model aspects. Our approach includes lifecycle accounting of net removals, ensuring that all stages of the process, from capture to sequestration/mineralization, are accurately accounted for.

By implementing these comprehensive quantification measures, MK Collect aims to ensure the highest standards of accuracy and reliability in reporting the amount of CO_2 removed through our CMP-DAC technology. This rigorous approach will support our goal of achieving large-scale, cost-effective, and verifiable carbon removal solutions.

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

In any large-scale project, identifying and addressing potential risks is crucial to ensure successful execution. MK Collect has conducted a thorough risk assessment for the CMP-DAC v3.0 project and developed comprehensive strategies to mitigate these risks. The following outlines the primary risks associated with the project and our plans to manage them effectively:

Risk 1 – System Underperformance: Transferring performance criteria from prototypes to the continuous operation of CMP-DAC v3.0 at scale presents challenges. There is a risk that the system may not perform as well as anticipated. To mitigate this risk, we will leverage our CMP-DAC v1.0 rig (lab-scale) and CMP-DAC v2.0 pilot plant for extensive testing and optimization. By analyzing data from these earlier models, we can make informed adjustments to the design and operation of CMP-DAC v3.0. Continuous performance monitoring and iterative improvements during these phases will ensure reliable scaling and performance. Moreover, the experience gained from deploying CMP-DAC v2.0 on the Werribee campus will be invaluable in refining our processes and addressing any unforeseen issues that arise.

Risk 2 – Permitting Delays: Obtaining necessary permits for the facility development in Melbourne could face delays, impacting the project timeline. Given that CMP-DAC v2.0 has already been successfully deployed at the Werribee campus, this experience should mitigate the risk of location-related issues for v3.0. Our familiarity with local regulations and permitting processes will streamline the application and approval stages. Additionally, alternative sites, such as Melbourne University's campuses at Ballarat and Burnley, have been identified as potential locations for deploying the CMP-DAC pilot plant, ensuring project continuity in the event of unforeseen permitting challenges.

Risk 3 – Cost Overruns: There is a significant risk of cost overruns, which are common in first-of-a-kind projects. To control costs, we will utilize data and experience gained from the CMP-DAC v1.0 and v2.0 phases. MK Collect has a team of experienced engineers with a great track record in the design, construction, and automation of these systems. Additionally, MK Collect has engaged with INNACO, an EPC company, for the design and construction of CMP-DAC v2.0 and v2.1, which further mitigates this risk. Engaging experienced engineering, procurement, and construction (EPC) firms will help maintain strict cost management and control. Detailed project planning, regular financial reviews, and contingency planning will further mitigate the risk of cost overruns. This combined experience and expertise will help ensure that the project remains within budget and on schedule.

Risk 4 – Lack of Recognized MRV Framework: The MRV framework for our specific DAC technology may not be widely accepted initially, posing a risk to the project's credibility. To address this, we will align our MRV protocols with emerging best practices, such as the CO2RE Principles for Credible Removal. Consulting with stakeholders during the development phase will ensure that our MRV approach is robust and comprehensive. Additionally, seeking third-party verification will help establish credibility and acceptance. We will also actively participate in industry forums and working groups to stay updated on MRV developments and contribute to the evolution of best practices.

Risk 5 – Insufficient Financing: Raising sufficient capital to build the facility is a potential risk, which could hinder project progress. To mitigate this risk, we will utilize a project finance structure for our pilot projects to build a track record of delivery and establish robust future revenue streams. Developing strategic partnerships with financial institutions and investors will be crucial in securing the necessary funding. Additionally, we are seeking dilutive funding from external investors to further support the project. We will also explore various funding sources, including government grants, private investments, and public-private partnerships. By diversifying our funding strategies and demonstrating the project's viability through successful pilot phases, we aim to build investor confidence and ensure financial stability.

By proactively identifying and addressing these risks, MK Collect aims to ensure the successful deployment and operation of the CMP-DAC technology. Our comprehensive risk management strategies will support the project's growth and contribute significantly to global carbon removal efforts.

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)*	~330 tCO_2
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	2025-2028
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	~$1370/$tCO_2$
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	~$1520/$tCO_2$ (~10% margin)

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