Mormaír Ltd
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

Mormair Ltd

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

Glasgow, Scotland

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

Valerie Findlay

Brief company or organization description <20 words

We use Chemical Looping Combustion (CLC) to capture CO2 while producing electricity and heat. By using biomass, we capture environmental CO2.

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

[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.

Chemical Looping Combustion (CLC) is an established energy transition technology which can use nearly any carbon-based fuel source with zero-emissions; when using biofuels, the carbon captured at the end of the process is environmental carbon. CLC is an approach to combustion where the fuel doesn't directly interact with the air. Since CO_2 isn't mixed with other gases, we produce medical-grade CO_2, which we capture at the end of the process and temporarily store in cannisters.

Unlike other Carbon Dioxide Removal (CDR) methods, CLC-CDR is unique since it produces energy as a valuable co-benefit while it captures CO_2 (i.e. CLC-CDR produces 3MWh/tCO_2). Depending on the source of the biofuel (i.e. rapeseed oil (RsO), rapeseed press cake (RPC), sunflower oil, sunflower press cake, rice husks, sludge cake) and due to how LCAs are currently structured, the scope 3 emission profiles of our chosen biofuels are variable; LCAs currently attribute 100% of emission to main products and 0% of emissions to waste by-products. Because CLC can use both as feedstock, we are currently incentivised to just use the waste by-product. Using current LCAs in the EcoInvent database, we calculate that a CLC-CDR process powered by RPC has a net CO_2e removal efficiency of ~45%, whereas if we use RsO CLC-CDR has a net CO_2e removal efficiency of ~2%. Therefore, utilising both RPC and RsO, our net CO_2e removal efficiency would be 15-22%.

However, we believe this figure to be a gross underestimation of CLC-CDR CO_2e removal efficiency as current LCAs in the EcoInvent database which account for the emissions in RsO, assume that RsO production is powered by non CLC-CDR derived energy which have positive kg/CO_2e/kWh emission profiles. CLC-CDR in the other hand has negative kg/CO_2e/kWh emission profiles. Thus, were RsO/RPC production phases to be powered by CLC-CDR we believe that CLC-CDR CO_2e net removal efficiencies would at the very least double to 30-44%. Because CLC-CDR is not currently an identified methodology with any CDR certifying authority, we are working with Dr. Christian Bauer from the Paul Sherrer Institute to a) update the EcoInvent Database to account for CLC-CDR, b) produce a Gold-Standard methodology for CLC-CDR, and c) create a modularised LCA process to account for the optionality available in CLC-CDR optionality.

Regarding storage, while at a fundamental level we do not ascribe to the principle of >1,000yr durable storage, any net CO_2e tonnes Mormair retires under contract with Frontier will be stored via geological injection. Utilizing the infrastructure of the Northern Endurance Partnership in the UK's East Coast Cluster, the Humber Carbon Capture Pipeline will transport the gross tonnes of CO_2 we capture and store them in the Endurance Reservoir. We will have a direct connection to the pipeline (Wilton Intl. section) which connects the cluster to the Endurance Reservoir in the North Sea. Transportation, storage and monitoring will be outsourced to the Northern Endurance Partnership.

Current studies estimate \$4 to \$40 of cost per tonne of CO_2 for transportation and storage (Smith et al., 2021). We will be estimating a cost of \$20 per tonne of CO_2 transported and stored for this project.

We will begin retiring Frontier pre-purchase credits from our operations in 2027 when the pipeline infrastructure to storage is planned to be operational.

There are only a handful of organizations working on CLC. Babcock & Wilcox's BrightLoop® and SINTEF's CHEERS programme are our two closest competitors in the field of CLC. However, whereas both B&W and SINTEF are focussed on decarbonising fossil fuels—while also having identified biofuels as a possibility—neither is currently focussing on CDR. This is due to fossil fuels being far cheaper than biofuels. Only with mechanisms such as CDR credits combined with offsetting credits is the economic case made for using biofuels, and thus CLC-CDR.

Mormair currently owns the best-in-class CLC solution for two main reasons: our reactor design and oxygen carrier composition. We had two distinct breakthroughs in CLC: we nestled the air and fuel reactors with a novel "reactor-in-reactor" design, solving a heat loss problem, and produced an oxygen carrier 14x better than current best-in-class, solving the durability problem. These two solutions produced a radically different approach and design to CLC without hindering the oxidation and reduction loop. Both B&W and SINTEF use the classic CLC reactor design, which consists of separate air and fuel reactors; they are already producing energy using CLC. However, it's not adopted because their plant designs are just too big and expensive to be practically deployed. Because of our breakthroughs we have been able to miniaturise CLC to the point that it is now practical—and affordable enough—to be deployed at scale. While we have miniaturized our reactor system—our largest reactor, the E650, produces 650 kWth and fits inside of a 40ft shipping container—B&W's CLC facility in Barberton, Ohio produces 250 kWth and is a large, 4-story plant. CHEERS project is a 3 MWth reactor and currently is the largest CLC unit at 30m in height. Our design/technology is the only practical solution to broad CLC adoption.

Fig 1: E650 reactor circa. 2022

Our proposed project addresses the Biomass Carbon Removal and Storage (BiCRS) RFP. For this project, we will be using RPC as our fuel source; this is a waste by-product of RsO manufacturing. RPC is commercially available at the amounts we will require. Our CLC reactors are housed in shipping containers, thus modular and scalable; we can cascade these reactors in parallel and series to satisfy any level of demand. Because CLC-CDR have additional revenue sources (e.g. we produce heat and power, which we sell below market rate to secure D2C contracts), the levelized cost of CO2 removal is merely a function of an economic equation plus the cost of transportation and storage over x period of time, weighed up against the cost of what we are able to achieve for the CO2 on the spot market plus the cost of transportation. Durable storage costs money, whereas CO2 has value as a commodity. It makes more sense to use the CO2 in a manner that keeps it out of the atmosphere (while making money) than to spend resources (e.g. energy, money) throwing it away.

For every MW of generating capacity per year, our process captures ~7,500t (gross) of environmental CO2 (oceanic and/or atmospheric, depending on the biomass). For every gross tonne of CO2 we capture, we create 3MWh worth of energy. Using the proposed project of 250kW at MPI in Teesside, we estimate capturing ~1,875t (gross) of CO2 per year.

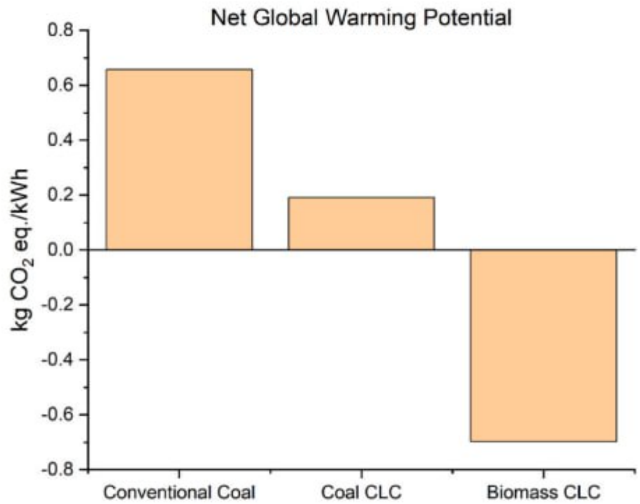

Fig. 10. The net global warming potential comparison of the three scenarios.

Fig 2: *LCA results of another proposed biomass CLC project utilizing rice husks which has net global warming potential of –0.7kg/CO2e/kWh (https://www.sciencedirect.com/science/article/pii/S0013935122022034).*

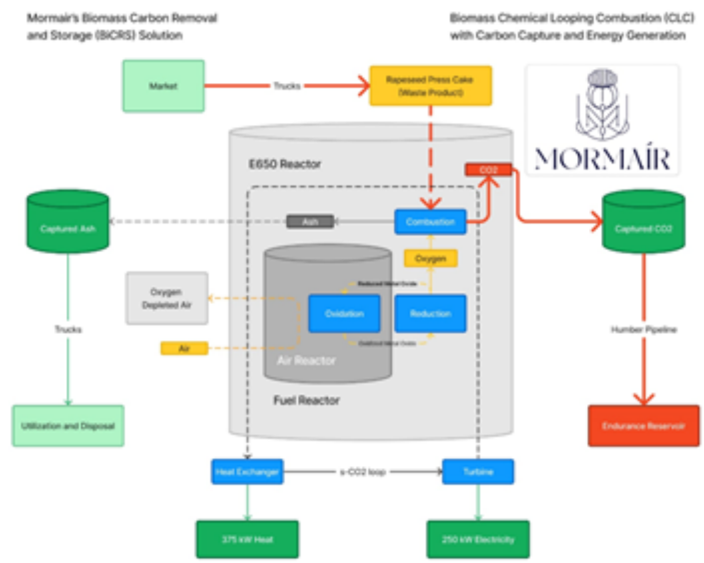

Fig 3: *Simplified process schematic of our CLC-CDR process.*

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

We have been awarded two InnovateUK (IUK) grants totalling £1m. These grants will fund two projects (BoB.zero an BoB.one) and will result in the manufacture and deployment of five E650 reactors to produce 1.25MW of power on-site at the Materials Processing Institute (MPI) in Teesside, Middlesborough, England from Q1 of 2025.

MPI is a research organization focused on decarbonizing materials (e.g. steel, iron, advanced materials) and associated industrial processes. Operations there are supported by their extensive expertise and lab facilities. Teesside is a CCUS hub in the UK and is establishing itself as one of Europe's most attractive locations for future clean industrial development. This makes this site an ideal place for a CDR project with all of the requisite skills, expertise, services, and facilities available.

These five reactors will be generating energy, and we will be selling heat and power directly to MPI, with excess electricity being sold to the grid. Of the five reactors we are deploying to MPI, one reactor will be fuelled using RPC biomass because its development has been funded under an IUK "African Innovation Collaborations for Net Zero Places" grant which forms part of the "Net Zero Living programme." This RPC reactor will capture atmospheric CO2 and constitutes CDR.

Because our equipment is containerized, we can move and continue to operate even if our partnership with MPI come to an end; thus ensuring project longevity. It is from this RPC fuelled CLC-CDR reactor that the net CO2e CDR credits—retired from 2027—we produce we offer to Frontier's prepurchase programme. This CLC-CDR reactor will be capturing and storing ~1,875t (gross) of CO2/year for 20-years at a conservative estimate net removal efficiency of ~45%, and we are offering ~47.5% of our net CO2e CDR credits in exchange for a $500,000 pre-purchase.

CAPEX: Each E650 reactor unit costs £80,000 to manufacture.
OPEX: Our main OPEX is fuel cost, in this case RPC can be bought for ~$100/t.

The grants we've been awarded will cover most of the project's CAPEX costs; we are in the process of securing matched funding to cover the 30% the government doesn't cover along with the project's non-eligible costs (e.g. contract manufacturer in South Africa, ineligible under UK grants). Due to the nascent nature and scale of the biofuel production sector, CDR credits and offsetting credits are needed to make the cost of biofuels economical versus the cost of fossil fuels (hence why our competitors are not focussing on CDR). Once we have tested our reactors in this TRL7 operational context, we will ramp up manufacturing capacity in line with revenue from operations.

We do have a pathway towards megatonne removal by 2027 and gigatonne removal by 2035: it revolves around how our technology is manufactured (mass manufacturing á la car factories), and requires that:

1. our biofuel production solution is implemented and keeps pace with our scaling/demand (Project: Paguroidea); and

[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.

2. our pipeline transportation system (Project: BiFlow, see the animation in the technology section on our under-construction website at https://biflow.framer.website/ for a better understanding) is quickly adopted and implemented by the gas network operators under instruction from legislators.

We are actively working on both problems/solutions. Regarding Project: Paguroidea, we are in discussions with multiple people in Shell and have been informing them of how they can extend the lifespan of their ageing offshore installations by becoming biomass farmers, replacing current plant and operations with CLC-powered hydrothermal liquefaction and pyrolysis to manufacture syngas, biochar, pyrolysis-oil, and bio-crude from macroalgae grown on a framework of rope trellises robotically farmed in the surrounding water column in a radial multilevel operation centered on each asset (imagine a 3D multilevel spider web of ropes on which seaweed is grown and farmed with the asset in the center). If Shell aren't interested in this type of project, we have also informed them that we are happy to acquire their end-of-life offshore assets along with their associated decommissioning liability to enact the plan ourselves. In short, each m3 of the water column can produce at least 5kg of seaweed annually. By growing different species of seaweed at different depths (between 20m and 70m) and radii (between 500m and 5,000m) from the assets, we estimate that each offshore asset can produce between 700,000-70,000,000bbl of biocrude annually. There are currently 12,000 offshore platforms; biocrude production from seaweed utilizing even a fraction of such assets can remove net gigatonnes of environmental CO2 and offset even more as biocrude manufactured in this manner will be able to completely replace fossil derived hydrocarbons. For example, if 1/6 of existing offshore platforms are converted as per Project: Paguroidea, with farming operations at a radius of 2,500m ~100% of current global oil demand will be met by biocrude; in order to meet ~100% of global demand with farming operations at a radius of 5,000m only ~500 existing platforms will need to be converted.

Further, we have also identified a bottleneck in carbon transportation. We have enabled and produced a CDR solution which makes affordable and sustainable energy a reality and which can also be rapidly deployed. We can manufacture our E650 reactors on an assembly line; in a factory of a similar scale to a medium sized car plant ,we can produce 10,000 E650 reactors per month. From one facility we will be bringing online 2.5GW of decentralised and distributed electrical generating capacity per month. Given an assumption that Project: Paguroidea is successfully implemented on time and 40% of our reactors are powered by biocrude, we will be removing an extra 625,000 gross tonnes of environmental CO2 month-on-month. We will be capturing an insane amount of CO2 very quickly over a wide geographical area in multiple countries. We require a pipeline transportation solution to be available to transport the CO2 we capture. A solution does not currently exist. Out of anticipated necessity, we have begun work on Project: BiFlow which aims to retrofit operational natural gas pipeline networks with specialized relay and storage stations to enable the system to work bidirectionally. This allows the removal of the captured CO2 (via natural gas transmission pipelines to designated storage clusters for further utilization and storage) without disrupting the energy supply to industries or having to build new pipeline infrastructure.

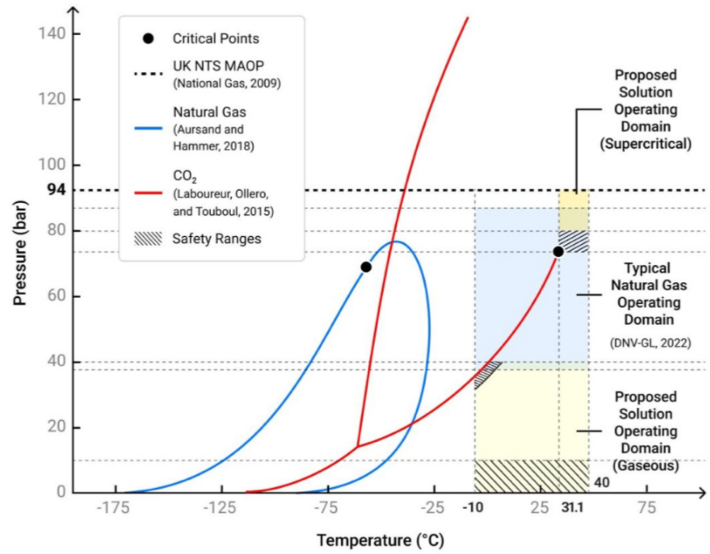

Fig 4: *Possible operating parameters for BiFlow proposed solution to carbon transportation*

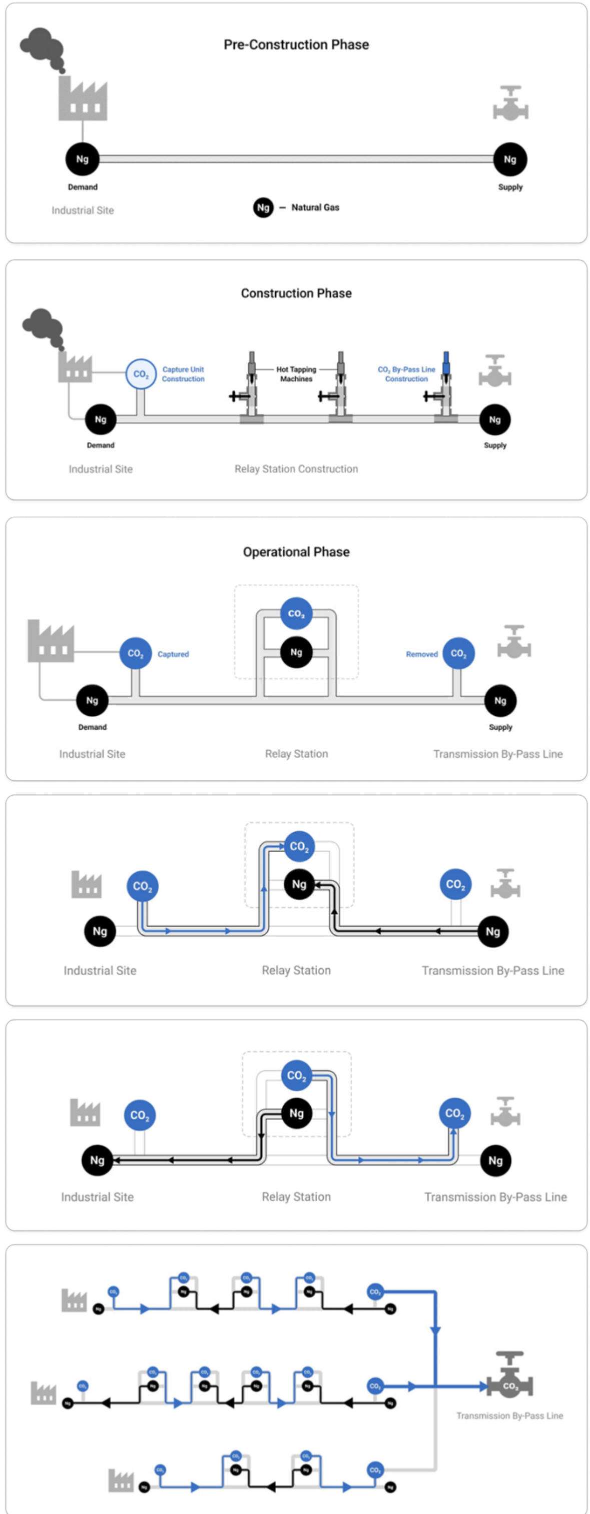

Fig 5: *BiFlow proposed process diagram (i.e. sequenced removal utilising gas network infrastructure retrofitted with BiFlow's relay stations (powered by Mormair's CLC))*

We have yet to formulate our MRV approach but are working with PSI to develop an appropriate methodology for our processes and Cula Technology to integrate our sensor data with their software platform to enable real-time monitoring/tracking of our datapoints, including but not limited to CDR from cradle to grave. We will be confirming our CDR with scheduled and randomized measurements taken at each stage of our process.

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

Main Risks and Uncertainties: Inputs critical to project completion include the expertise of our development team to deliver the R&D and development of the technologies and solutions. These can lead to scaling difficulties and slow down project delivery leading to cost overruns while we develop build capacity and engage new engineering teams. However, our contract engineering firm has extensive experience of and knowledge in infrastructure/energy project development and will be involved in each step of the project.

Technical Risks: Main technical risks are:

1. Key staff and/or subcontractors leaving leading to slow project development, cost overruns, and missed deadlines. Succession plans, staff recruitment strategies, preselected replacements for key roles will ensure continuity.
2. Poor collaboration and/or communication addressed through well-established relationships, formal collaboration agreements, and close collaboration on design and build. Our OEM, Resonant Nuteq has hired a project manager for the aim of this project. He helps bridge the communication gap with biweekly progress meetings, stakeholder meetings and other relevant information needed for a successful collaboration between the companies and success of the grants.
3. Our ''reactor-in-reactor'' design and improved oxygen carrier composition are unique and untested at scale. While these may solve the heat loss and durability problems, they also introduce risks associated with new technologies operating in real-world conditions. Extensive computer simulations and testing have been done to mitigate this risk. Also, during the course of the project, the E650 reactor design will be operational for 2 months during the testing, validation and optimization phase before it is certified.
4. We aim to rapidly scale from a 250KW demonstration to megatonne and eventually gigatonne removal. This might present some technical challenges considering we intend to manufacture 10 CLC generators a month. The revenue from one generator can cover the production cost for another within 3 weeks, which means we intend to double our manufacturing capacity every 3 weeks. This will help us reach > 1000 generators in 8 months.
5. Long-term durability of equipment: The long-term performance and maintenance requirements of the CLC reactors in continuous operations are yet to be proven. Mormair has already discussed this aspect with all partners and agreed to invest in high-quality materials, robust component testing & generator field of prototypes.

Management Risks: Includes scope creep and estimating/scheduling errors resulting in delays to stage completions & project progression, increased development and cost overruns. **Risk Mitigation:** We prioritize risk mitigation through comprehensive assessments. Risks, assessed for likelihood and impact, are RAG rated. Adopting specific mitigations eliminates or minimizes risk, with contingency plans addressing residual concerns. Quarterly reviews ensure continuous relevance, reinforcing a proactive approach to risk management and project success. **MRV:** While a comprehensive MRV plan is not outlined, we are contracting with Cula Technologies to integrate our data into their software package to enable real-time tracking and monitoring. **Independent validation:** The Paul Scherrer Institute will oversee the LCAs and TEAs to incorporate the CLC technology into the EcoInvent database for validation. **Regulatory Compliance:** Unforeseen changes in regulatory environment might increase bureaucracy, restrictions on operations delays in bringing the generators online. We intend to work closely with environmental agencies, stay up to date with regulatory changes and have a regulatory compliance plan in place.

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)*	This project will capture 37,500t/CO2 (gross) between 2027 and 2047 with a conservative net removal efficiency of 45% (i.e. 16,875t/CO2e removal). As part of this proposal Mormair is offering Frontier 400t/CO2e per year for 20-years starting in 2027 (subject to the commissioning of the Humber Carbon Capture Pipeline).
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	2027-2046
Levelized cost ($/ton CO_2) *(This is the cost per ton for the project tonnage described above, and should match 6d)*	$45/tCO2e (pipeline storage and

	transportation)
Levelized price ($/ton CO_2)[3] *(This is the price per ton of your offer to us for the tonnage described above)*	$62.50/tCO2e

[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).