Electro-Active Technologies, Inc.

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

Electro-Active Technologies, Inc.

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

Knoxville, TN

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

Abhijeet Borole and Alex Lewis

Brief company or organization description <20 words

A scalable and modular system for conversion of food waste into clean hydrogen and fertilizer with CO2 sequestration.

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.

[public answer]

Our approach is based on a novel method which parallels the BECCS or BiCRS approach integrated with production of zero-emission fuels. We have developed a pathway to capture CO2 from the atmosphere via photosynthesis and then use the biomass generated to produce clean hydrogen fuel and a CO2 stream, which can be sequestered. The food and agriculture industry is a major contributor to GHG emissions. Our approach proposes a new pathway to CDR and provides this industry a novel alternative to reduce its emissions, while continuing to provide food for the world. We have focused on food waste and plant biomass as a feedstock for hydrogen production and are developing a modular and scalable solution to deploy our product in the market. The approach is also being utilized for production of algae via a similar photosynthetic route, followed by production of clean hydrogen and CO2, which can be captured as a pure stream and sequestered.

Our core technology produces clean hydrogen from biomass and organic waste. It generates carbon dioxide as a byproduct, which is 90-99% pure CO2 that can be captured and sequestered. The primary technology used to make hydrogen is microbial electrolysis, which is a bioelectrochemical process that uses microbes to breakdown organic matter into electrons, protons and CO2 in the anode. The electrons and protons are combined at the cathode to produce hydrogen. The anode is separated from the cathode by a membrane, which results in a relatively pure CO2 gas stream. This CO2 can be stored underground via injection into subsurface or sequestered via reaction with quick lime producing calcium carbonate.

Our process also generates a high pH liquid stream as an effluent, which retains CO2 and generates bicarbonate and carbonate species. Calcium can be added in the form of quicklime to this stream to precipitate the CO2 and store it as permanent carbon for > 1000 years. Storage of gaseous CO2 injected into the subsurface can also result in a 1000+ year permanent storage.

The total CO2 that can be sequestered via our process is 10 tons per ton of green hydrogen produced. This includes the gaseous CO2 produced as well as any amount retained in the aqueous high pH effluent.

We are the best-in-class in this area for a number of reasons. First, the core technology was developed at a US DOE National Laboratory focused on anode biocatalyst development by the researchers who founded EAT and then licensed the technology for commercial development. The Founders then advanced the technology using VC funding and developed additional IP to improve the engineering aspects of the technology.

The approach used is unique. It offers a new pathway to sequester CO2 from air via biomass as an intermediate (produced via photosynthesis), which is then converted into hydrogen and CO2 by our process. This pathway offers a novel way to sequester CO2 and remove it from air permanently by pumping it in underground reservoirs or turning it into rock. Photosynthesis is a natural route for CO2 capture from air, which we utilize and combine with our novel process to achieve decarbonization. The innovation of our approach is the development of microbial electrolysis technology to produce hydrogen economically while producing a pure stream of CO2 gas. We have also obtained an exclusive license for part of the technology originally developed at Oak Ridge National Laboratory and added new IP for commercial deployment. Thus, we have exclusive rights to commercialize this technology worldwide.

The conversion of food waste into biogas in digesters can be considered as an alternative pathway, however, it is hardly a competing pathway for decarbonization of the food

industry. This alternate pathway generates methane, which is typically referred to as RNG or renewable natural gas. The CO_2 produced in digesters is typically mixed with the methane and it requires expensive separation technology to separate it from the methane. The raw biogas also has hydrogen sulfide and siloxanes which have to be removed to prevent poisoning of RNG end use equipment. This makes the RNG a highly expensive fuel and it cannot be produced unless there are huge subsidies or renewable credits. Lastly, and most importantly, a mere 1.3% leakage of the methane product from the waste to fuel process can negate the benefits of the whole undertaking as it would result in a worse GHG emission scenario compared to aerobic treatment of the food waste (Methane has a 80X GMP 20 compared to CO_2, so leakage of 1.3% methane is equivalent to an excess of 104% release of CO_2e). Typically, lifecycle analyses assume 2% leakage which indicates a 60% higher release of CO_2e compared to aerobic treatment. With respect to decarbonization, this approach will likely not qualify as half of the carbon is actually emitted by vehicles using the RNG. Additionally, the cost of CO_2 separation and sequestration for the other half of CO_2 generated in the process is higher compared to our approach due to the separation step required for RNG production.
Another alternative to producing hydrogen and CO_2 from food waste is via a multi-step process consisting of anaerobic digestion – gas separation - gas clean up – steam methane reforming (SMR). This has been suggested and is currently being implemented, however, it is also prone to methane leakage along the multiple steps and has lower yield than our process of direct conversion of food waste into hydrogen via microbial electrolysis. Fuel Cell Energy has proposed an alternative to SMR via conversion of methane to hydrogen using their high temperature fuel cell/electrolysis systems. This also suffers from similar drawbacks as above, but can be considered a competing technology. The economics of our process will still be better as we use lower cost materials for our (bio)electrolyzer and have less steps in our process.
The proposed project addresses following priority research areas listed in the call:

Novel approaches to CDR and crosscutting technologies

- We utilize a waste stream to enable decarbonization in our process. While the call does not specify food waste, we believe, this is a waste that has significant implications for climate change if not managed properly, and should be considered for decarbonization.
- Secondly, our process also generates a high pH stream which can help with precipitation/removal of CO_2 from any gas or liquid streams.

New DAC approaches that enable dramatic cost reductions

- Our novel approach provides significant reduction in energy needs as compared to DAC. Our process intrinsically generates an almost pure CO_2 stream
- We believe our approach is a new pathway which does not exist in the current Frontier portfolio.

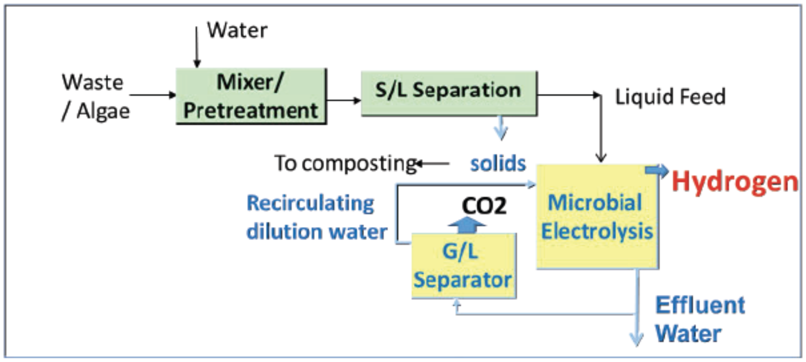
Approaches to BiCRS that co-optimize CDR efficiency and energy production, with nutrient export and cost

- Our approach maximizes CDR efficiency and reduces cost of CO_2 removal/sequestration, due to the ability of our technology to generate relatively pure CO_2. The primary costs for CO_2 sequestration will be transportation and injection underground, which amounts to a maximum of about $55/ton, if CO_2 gas injection is practiced.
- Our approach also has significant co-benefits, which include: food waste treatment, zero-emission fuel production, co-production of a fertilizer (portion of food waste that is associated with solids and difficult to degrade is converted into

a fertilizer for regenerative agriculture). One of the co-benefits (food waste treatment), will cease to exist when using algae as an intermediate to capture and sequester CO2, however, we plan to use hydrothermal liquefaction mentioned in the call, which is tailored to algal biomass.

- Lastly, our system is modular and can be implemented in a wide array of locales depending on availability of feedstocks/conditions suitable for minimizing transport and logistics costs related to biomass transport.

Process schematic/ Diagram: The separated from separator is pure and can captured and sequestered process to CDR.



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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.

[public answer]

What are we building: We are building a modular and scalable bio-electrolyzer to break down organic matter into hydrogen and CO2. These bio-electrolyzers will be 1-2 m3 each and can be stacked to address the volume needed to process the at each location. In case of food waste, these systems can be deployed as a distributed solution across urban areas with a minimum volume suitable for CO2 capture and transportation. The hydrogen in this case is envisioned to be used on site or near site, for instance to fuel gas stations or by utilities as an energy source for distributed hydrogen supply to their customers in future. The use of algal feedstock on the other hand is envisioned to be more in remote areas where algal ponds can be set up and large amounts of CO2 can be captured from atmosphere and released in a concentrated form via biorefinery-scale electrolyzer systems and then pumped into reservoirs.

Location and Scale: At present, two mini-pilot projects are being planned for demonstration of the approach, one which is more suitable for a distributed solution, while the other one for potential larger scale application similar to a biorefinery scale. The former is planned to be installed in the Southeast US (TN or AL), while the other one is planned for installation in the Central Valley in California. While the eventual scale of operation is different for the two locations, the planned pilots are similar in volume and generate a small amount of CO2, on the order of 3-4 tons per year as a POC in the first Year, followed by a demonstration plant producing over 700 tons/year. The TRL of this technology is between 5 and 6 at present and the pilots represent the initial commercialization efforts in scaling this technology in the US. EAT has previously installed a smaller prototype of the bio-electrolyzer in S. Korea at a food waste treatment plant, so the team has had a first-hand exposure to the challenges of building and installation of the system on actual sites.

Cost Break down: The cost can be broken down into two components, one for the conversion of the waste into the hydrogen, which is the primary product and second, for collection, transportation and storage of CO2 into reservoirs. The core bio-electrolyzer technology for hydrogen production is new, however, most of the components needed for CO2 sequestration are shelf-ready and can be installed without much new development. The cost of the latter is therefore well established and is similar to BECCS approach for say, ethanol plants, where CO2 can be compressed, transported and stored. This cost has been published by many organizations and is known to be on the order of $45 to $55/ton of CO2. Since the separation of CO2 from the biomass feedstock is associated with hydrogen, the overall cost is a function of the hydrogen production cost. We are on path to bring this cost to $ 2/kg of H2 in the next two years, at which point commercial deployment of this technology will begin. EAT is a recipient of the Hydrogen Earthshot Prize which is aimed at reducing the cost of hydrogen production to $1/kg by 2030. Thus, the goal is to simultaneously scale the bio-electrolyzer technology while investigating CO2 sequestration for impacting CDR at scale.

Approaching $ 100/tCO2. We can achieve Frontier's target cost under $ 100/ton once the bio-electrolyzer technology is mature and sequester > 0.5 Gt of CO2/yr via this green hydrogen pathway. Refer to the TEA for cost analysis details. In addition, there are a number of co-benefits with our approach. First, we have adapted the process to use food waste as the feedstock for producing hydrogen and CO2. The approach also helps develop a circular solution for the food waste problem, while generating another revenue stream from tipping fees obtained from food waste diversion from landfills. This adds to the economic feasibility of our process. Besides this, there are a number of policy directives which support this pathway, including a $3/kg-H2 hydrogen production credit, as our clean hydrogen meets the target of less than 4 tons of CO2/ton H2. The net GHG impact of our process is significant as discussed in Section 4, since it also includes methane emissions avoidance realizing a -104 ton CO2e/ton-H2 emission reduction. As requested by Frontier, we are not considering the avoidance related cost benefits in this proposal. Additional co-benefits include those derived from green fertilizer developed from food waste, which is targeted for application in regenerative agriculture and organic farming, resulting in bio-based carbon sequestration in soils. This fertilizer is derived from the solid portion of the waste separated from the waste feedstock in the first step of our process (S/L Separation). We are not including this at all in the calculations discussed in this proposal and the 10 tons of CO2 /ton-H2 does not include any bio-based carbon sequestration contribution.

The cost of CO2 gas sequestration underground including its transportation to injection well sites can thus be well below $ 100/ton, and has actually been reported to be less than $ 55/ton. The details are given in the TEA and Section 6. The cost of our equipment for hydrogen production will be covered by the sale of hydrogen and related revenues. Thus, the cost of CO2 sequestration will be below $ 100/ton as the deployment of this technology gets under way and the cost of the hydrogen production is reduced via economies of scale and via reduction in manufacturing costs.

Approaching 0.5 Gt CDR: Worldwide food waste generation is about 2.5 Gt per year (https://greenly.earth/en-us/blog/ecology-news/global-food-waste-in-2022). This does not include farm waste, which can be additional 1.2 Gt/year (https://earth.org/food-waste-on-farms/). Utilization of the food waste resource (https://www.fao.org/news/story/en/item/196402/icode/) can result in CO2 sequestration of about 0.74 Gt/yr via the hydrogen pathway we are developing. We are also developing the Bio-Electrolyzer technology for using algae waste, such as that from algal blooms or via algae production using wastewater. We have previously published an article in Journal of Cleaner Production on development of a circular pathway for producing green hydrogen and fertilizer using algae [1]. Additionally, many other biomass/Ag waste feedstocks are available for use in hydrogen production [2-7] via larger scale biorefineries with co-production of other bio-based products [5,8,9] similar to current petrochemical refineries which co-produce fuels and chemicals. Electro-Active's selection for the Hydrogen EarthShot Incubator program was targeted at advancing the use of algal biomass as the feedstock for hydrogen production to get to $ 1/kg H2 within a decade, which also captures CO2 from air and sequesters this via our integrated bio-electrolyzer-CO2 capture technology. Algae biomass a significantly large source of biomass using sunlight as the energy source, enabling carbon sequestration from air, which when coupled to our proposed approach can result in green hydrogen production and carbon dioxide sequestration. The proposed project, however, focusses on food waste, which in itself can result in over 0.5Gt of CDR.

Our goal is to develop economically and socially justifiable solutions and not just aimed at removing CO2, so we are targeting generation of 5 million MT (metric tons) of clean hydrogen via our pathway in the next decade using resources in US and to move the country into a hydrogen economy by 2030. Worldwide, this technology has potential to generate > 50 million MT of clean hydrogen. This will result in production of greater than 500 million MT of CO2, which can be captured and sequestered. Additionally, the US itself has an availability of up to one Gt of dry biomass per year for biofuel generation [10]. If part of this is used to produce hydrogen, it can result in substantial CO2 sequestration via our pathway.

Quantifying carbon removed. The quantification of CO2 will come from actual volumes produced from our process measured via gas meters that will be transported to injection wells to be pumped into subsurface. This will also be related to the hydrogen produced and feedstock entering the process/refinery which will be quantified separately.

References:

1 Satinover, S. J. *et al.* Green hydrogen from microalgal liquefaction byproducts with ammonia recovery and effluent recycle for developing circular processes. *Journal of Cleaner Production* **299**, 126834 (2021).

2 Satinover, S. J., Schell, D. & Borole, A. P. Achieving High Hydrogen Productivities of 20 L/L-day via Microbial Electrolysis of Corn Stover Fermentation Products. *Applied Energy* **259**, 114126 (2020).

3 Satinover, S. J., Rodriguez, M., Campa, M. F., Hazen, T. C. & Borole, A. P. Performance and community structure dynamics of microbial electrolysis cells operated on multiple complex feedstocks. *Biotechnology for biofuels* **13**, 1-21 (2020).

4 Satinover, S. J., Elkasabi, Y., Nuñez, A., Rodriguez Jr, M. & Borole, A. P. Microbial electrolysis using aqueous fractions derived from Tail-Gas Recycle Pyrolysis of willow and guayule. *Bioresource technology* **274**, 302-312 (2019).

5 Lewis, A. J. & Borole, A. P. in *Microbial Electrochemical Technology: Platform for Fuels, Chemicals and Remediation* Vol. https://doi.org/10.1016/B978-0-444-64052-9.00044-3 (eds S Venkata Mohan, Sunita Varjani, & Ashok Pandey) 1059-1085 (Elsevier, 2019).

6 Brooks, V. A. *et al.* Hydrogen Production from Pine-Derived Catalytic Pyrolysis Aqueous Phase via Microbial Electrolysis. *Biomass & Bioenergy* **119**, 1-9 (2018).

7 Lewis, A. J. *et al.* Hydrogen production from switchgrass via a hybrid pyrolysis-microbial electrolysis process. *Bior. Technol.* **195**, 231-241, doi:http://www.sciencedirect.com/science/article/pii/S0960852415008767 (2015).

8 Borole, A. P. in *Ethanol: Science and Engineering* Vol. 1st Edition (eds Angelo Basile, Adolfo Iulianelli, & Nejat Veziroglu) Ch. 9, (Elsevier, 2019).
9 Borole, A. P. *et al.* Efficient Conversion of Aqueous-Waste-Carbon Compounds into Electrons, Hydrogen, and Chemicals via Separations and Microbial Electrocatalysis. *Frontiers in Energy Research* **6**, 94 (2018).
10 Langholtz, M. H., Stokes, B. J. & Eaton, L. M. 2016 billion-ton report: advancing domestic resources for a thriving bioeconomy. (EERE Publication and Product Library, Washington, DC (United States), 2016).

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.

[public answer]
One of the biggest risk to the proposed approach is the ability to scale. This factor has also been identified as a primary risk by the Frontier team. Within this type of risk, there can be two individual types of risks: technology scale-up risk and volume scale-up risk (to enable an impact at global scale). We discuss both here. To begin with, we developed a modular approach to construct our systems right from the beginning. Use of modular system enables flexibility in scale across the board from deployment via mini-installations all the way to a biorefinery scale. This risk can also be often associated with feedstock availability. Our business model is based on sales of bio-electrolyzers vs owning it ourselves. We understand the distributed nature of the feedstock and the problem of acquiring the feedstock ourselves. So, we decided to focus on providing the technology as a turn-key solution to users who can themselves own and operate them. EAT plans to develop maintenance contracts with customers to provide technical support and performance guarantee. The system comes with autonomous process control and remote monitoring, so we can always keep an eye and help when problems arise.

Our approach also addresses the technology scale-up risk. Typically, the scale-up of a bioprocess requires management of intrinsic kinetics, mass transfer and hydrodynamics as the scale of application increases. EAT has developed a patented method for development of the bio-electrolyzers to scale these intrinsic processes within the modular systems, using cell size that can be reproduced and relied upon, so the technology risks are diminished significantly. This avoids the need to produce a million gallon bio-electrolyzer tank allowing scaling through numbers using smaller bio-electrolyzers vs. huge tanks.

In terms of the risk of volume scale-up, this is a known issue for the BECCS or biofuel approach due to the issues related to feedstock availability and transportation costs. We minimize those risks by deploying community scale bio-electrolyzers where distance of transportation is minimized and costs are also reduced. Secondly, the need for biofuels such as ethanol has not grown in past and is not expected to increase substantially in future. However, the demand for hydrogen is expected to be more than 50 million MT/year by 2050, as reported by US DOE in June 2023, in their National Hydrogen Plan (https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf). Thus, there is a significant demand pull for this type of BECCS (aimed at clean hydrogen production) vs. production of other biofuels. Thus, the risk of scalability is less via this

approach.
Additional management, economic and technical risks are also discussed in table below.

Description of Risk	**Risk Mitigation**
Management, Planning, and Oversight	
Lack of management support or engagement	Schedule regular project updates and ensure adequate communication between project leadership and organizational management. We expect to develop partnership agreements with suppliers and users to scale the approach, so have identified potential team members to join if this proposal is funded.
Communication issues due to team members working in different locations	Maintain regular communication among project team to ensure alignment. Regular virtual meetings will be scheduled. We are already working across the nation from the east coast to west coast and do not expect this to be an issue.
Difficulty to negotiate contractual agreements between parties	Contractual partners have prior experience working on government contracts and are familiar with the process.
Cost/Schedule	
Resource unavailability or conflict	Early commitment from management for allocation of experienced resources with technical know-how. Another resource we have to certainly pay attention to is the feedstock. With our existing partnership with Southern Co, we have a potential acquisition pipeline in place in the Southeast. We are also working with E. & J. Gallo Winery on the west coast, which owns 25% of the wine market and can be a beachhead customer, which can provide access to over 10 wineries in CA for deployment of our solution or hydrogen production and CO2 sequestration.
No or low-quality response to vendor RFPs	Leverage existing relationships with high quality vendors for early identification and engagement
Uncontrolled changes and continuous growth of scope	Control and simplify scope to the requirements of the FOA and define a clear change management process
Technical	
Hydrogen Production:	

Presence of contaminants in feed.	EAT has developed an autonomous process control system for identifying and resolving changes in intake stream. This is possible due to real-time tracking of current produced in bio-electrolyzer which is affected by contaminants in intake stream, with feedback loops in process control software to stop non-ideal feed streams from entering the bio-electrolyzer with response time of minutes.
Process stability and/or Loss of productivity over time	We have developed a maintenance protocol to be implemented approximately once a year to restore performance. We have also developed a patented approach with a growth/startup period and a production period to manage process stability. These methods are being applied to generate stability data under a DOE-funded project. We plan to implement this solution to demonstrate stability at prototype scale in the coming months.
Capital cost of technology is too high	Our partners on existing projects, e.g., T2M Global and others have experience in reducing electrolyzer costs (e.g., Reduction of HT stack costs from over \$20,000/kW to <\$2000/kW), which will be valuable foundation for our electrolyzer technology cost reduction.

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)*	[public answer] 1050 tons CO2
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	[public answer] 4 years
Levelized Price (\$/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	[public answer] \$476/ton

** 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).*

As the *note suggests, our levelized price does not match that calculated in 'This Project TEA'. This is primarily because all the funds needed to do this project are not coming from Frontier. We plan to put in some cost

share (cash). There is also other cost share (in-kind) which is above this, which is coming from existing DOE and CEC projects. However, we need confirmation from the existing partners for which discussions are underway.

[redacted]

[redacted]

[redacted]