Frontier

Graphyte

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

Graphyte, Inc

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

Memphis, Tennessee

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

Jay Dessy

Brief company or organization description <20 words

Graphyte, Inc permanently removes and sequesters CO_2 from the atmosphere through our proprietary Carbon Casting technology process.

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.

Graphyte's Carbon Casting technology offers a new approach to biomass-based carbon removal. Our first project will demonstrate the ability to permanently remove CO_2 in a commercial-scale application at a cost of $100 per ton.

The Biomass Opportunity

Biomass is one of the most abundant resources on earth. Plants convert over 100 gigatons of carbon from the atmosphere into biomass each year through photosynthesis (Sertolli, 2022). This immense production of biomass generates significant waste. Approximately 2.5 gigatons of waste biomass are produced annually from the agriculture and timber industries (Tripathi et. Al, 2019; Zhou and Wang, 2020). Today, almost all carbon contained in this waste biomass is re-emitted into the atmosphere as the biomass is burned or left to decompose. The availability of these underutilized waste resources presents an incredible opportunity to remove over 3 gigatons of CO_2 per year at low cost.

Graphyte's Carbon Casting process achieves an industry-leading carbon dioxide removal (CDR) efficiency of approximately 90% (87% under a conservative lifecycle assessment with potential to reach up to 98%). CDR efficiency represents the fraction of CO_2 that is permanently removed from the atmosphere after accounting for supply chain emissions (Chiquier et al, 2022). Other biomass-based solutions, like biochar and bio-oil, have CDR efficiencies well below 50% due primarily to carbon losses during biomass processing steps like pyrolysis (Arnold et al. 2017; Soerhman et al. 2022). Graphyte permanently sequesters ~90% of carbon stored in our feedstock, ensuring biomass resources are used most effectively to achieve carbon removal objectives.

CDR Approach	CDR Efficiency	Major efficiency losses
Carbon Casting	87-98%	No major efficiency losses
Afforestation	62-99%	Natural disturbances (e.g., wildfires)
BECCS	62-86%	Biomass processing, land use change
Biochar	16-39%	Pyrolysis
DACCS	52-80%	Energy requirements
Enhanced weathering	63-97%	Energy requirements

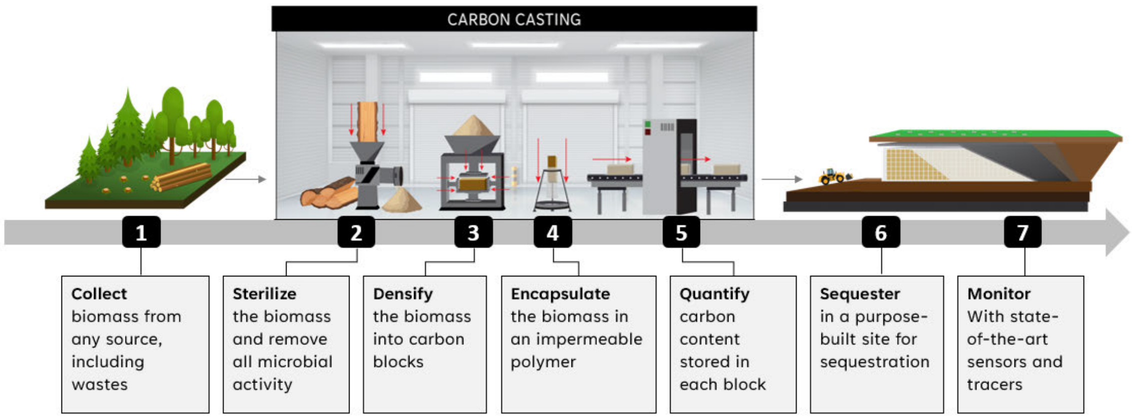
Table 1: *CDR Efficiency of Carbon Casting compared to other carbon removal approaches. CDR efficiencies for other removal approaches are provided by Chiquier et al, 2022. More detail is provided in the biomass supplement.*

The Carbon Casting Solution

The Carbon Casting process creates inert carbon blocks that are encased in an impermeable, long-lasting polymer material. These carbon blocks are then stored in a purpose-built sequestration site with a robust monitoring and verification system (outlined in Figure 1). This approach permanently halts biomass decomposition and ensures there are no changes in carbon content over time.

Graphyte leverages biomass sterilization techniques commonly used in the food safety industry to limit microbial activity in the biomass (Rezaei and VanderGheynst, 2010). The primary treatment step involves drying the biomass to a sufficiently low moisture content. Academic literature provides a strong basis for the water activity levels below which microbial activity is stopped (Yablonovitch and Deckman, 2022).

Once the biomass is sterilized, polymer encapsulation ensures that decomposition does not restart. The polymer encapsulation will occur immediately following the biomass sterilization and provide a hermetic seal so that no decomposing agent (e.g., oxygen, water) can re-enter the carbon block. The polymer will be made of a highly durable material to preclude biomass decomposition over the timeline required to permanently remove CO_2 from the atmosphere. Several studies (Chamas et al., 2020; Edge et al., 1991) have shown that commonly used polymers will last well over 1,000 years. The



sequestration site will be designed with an HDPE liner and water collection system to further preclude decomposing agents from interacting with the biomass.

Figure 1: *Introduction to the Carbon Casting process. Carbon Casting produces encapsulated carbon blocks that are permanently stored in a purpose-built sequestration site.*

Graphyte's Carbon Casting process overcomes several challenges associated with existing biomass burial approaches:

- **Potential methane releases:** Existing biomass burial approaches rely on "wood vaults" or burial chambers that create anaerobic conditions to slow the decomposition of buried wood (Zeng and Hausman, 2022). One challenge with this approach is that methane is generated from the decomposition of biomass in anaerobic environments (W. Li et al, 2018). Methane has a global warming potential of 27-30 times that of CO_2 (US EPA). Consequently, a methane leak from a wood vault could negate climate benefits associated with biomass burial. The Carbon Casting process eliminates the potential for methane generation by halting biomass decomposition altogether through sterilization and polymer encapsulation.
- **Precise carbon quantification:** Existing biomass burial approaches rely on statistically representative samples of the biomass material to infer decomposition based on flux measurements with soil characterization and monitoring. In contrast, the Carbon Casting process measures the carbon content of each block directly and ensures no decomposition of the blocks in the sequestration site. This provides a direct and highly accurate measurement of carbon sequestered.
- **Availability of feedstocks:** Existing biomass burial approaches are generally limited to use of lignin-rich wood as a feedstock given its natural resistance to decomposition (Towprayoon et al., 2006). Restricting biomass sequestration to woody materials precludes its application to 70% of the world's 2.5 gigatons of waste biomass produced annually. It also restricts the areas in which carbon sequestration may occur due to the cost of biomass transport. The Carbon Casting process can leverage both wood waste and agricultural residues, enabling the use of more widely available feedstock inputs in more geographies.

Ingredients to Reach Gigaton Scale

Carbon Casting takes a new approach that is uniquely suited to scale today. Graphyte has designed the Carbon Casting technology and our business model to align with four key criteria that are required to remove gigatons of CO_2 from the atmosphere:

1. **Ensure climate positive outcomes: permanence and MRV.** The sterilization and encapsulation steps described above ensure permanence of over 1,000 years. This addresses a key area of uncertainty for many biomass-based removal approaches including biochar and traditional biomass burial. Carbon Casting goes further and deploys a robust monitoring and verification system by using sensors and tracer substances. If the polymer layer is breached and the biomass starts to decay, the tracer substance embedded in the carbon block will be released and detected by the sensors. These sensors will also provide a location signal to identify the leakage area. In the event of a leak, the impacted blocks can be removed from the sequestration site and re-encased to prevent further decomposition.

2. **Leverage scalable inputs efficiently.** Carbon Casting relies on three main inputs – biomass, energy, and land – to remove CO_2. Ensuring efficiency of these constrained resources is paramount under the broader context of reaching net zero emissions.

   Biomass
   Carbon Casting has a CDR efficiency of 87% with the potential to reach up to 98% under optimal conditions. As described above, this is critical to maximize utilization of sustainably sourced biomass for climate objectives. In addition to CDR efficiency, Carbon Casting is feedstock agnostic. This means Graphyte can use virtually any type of biomass, including unutilized agricultural residues like rice straw. The combination of high CDR efficiency and feedstock flexibility makes Carbon Casting a uniquely attractive biomass-based CDR approach.

   Energy Input Requirements
   The Carbon Casting process requires less than 250kWh per ton of CO_2 removed, which is an order of magnitude less than direct air capture and many other engineered CDR approaches Soerhman et al, 2022). According to McKinsey's Global Energy Perspective, global power consumption will triple by 2050 to enable electrification of transportation, buildings, and manufacturing. To reach net zero emissions, clean electricity production will need to keep up with that demand. Clean electricity is a scarce resource, and we need to focus on carbon removal solutions that require as little energy input as possible.

   Land
   Land, like energy, is a scarce resource. Carbon Casting can sequester 1 million tons of CO_2 on 100 acres of land (10,000 tons/acre). When considering land needed to generate energy inputs for carbon removal, Carbon Casting offers an efficient solution compared to other approaches. Smith et al., 2015 estimates that 47 exajoules (10^{18} joules) of energy will be required per gigaton of CO_2 removed using direct air capture in 2100. Based on land requirements for wind and solar (estimated at 0.3-3 hectares/MW by Denholm et al, 2009 and Ong et al, 2013), deploying 1 gigaton of DAC would require roughly 3.7M acres of land for the renewable energy needed to power it. Carbon Casting can reach the same gigaton scale with land use of less than 175,000 acres after accounting for both the sequestration site and energy production. Leveraging land effectively will be increasingly important at gigaton scale.

3. **Build a ready-to-deploy project model.** Carbon Casting projects can be sited anywhere in the world. These projects do not require specific geologies, temperature and humidity conditions, or novel permitting regimes. This flexibility enables Graphyte to optimize project deployments around availability of biomass supply. Furthermore, the Carbon Casting process leverages

existing, off-the-shelf equipment. These components are already manufactured at scale and have robust supply chains that Graphyte can leverage to quickly deploy our solution.

4. **Meet the market need: low cost now and in the future.** Graphyte's levelized cost of production is $100/ton today. To our knowledge, no other permanent carbon removal approach has reached a cost target below that threshold. Other approaches that produce similar permanence claims project that their cost will decline to $100 per ton only after significant investment, deployment, and decades of time. Graphyte is able to deliver low-cost removals today by leveraging the natural photosynthesis process, using equipment already manufactured at scale, and minimizing biomass-related operational expenses including transportation.

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.

Graphyte can deliver permanent carbon removals at $100/ton today with ability to scale to 0.5Gt per year and beyond. Three key steps are required to reach gigaton scale: (1) Demonstrate our technology approach, (2) Build our first commercial project, and (3) Deploy units around the world.

Demonstrate Graphyte's Technology Approach

Graphyte's technology integrates existing commercial equipment in a novel way. Graphyte is partnering with academic universities and commercial labs to design experiments that will optimize the engineering and design of the Carbon Casting process. These experiments will focus on three key concepts:

- **Biomass sterilization:** In-field experiments will test biomass decomposition under various water activity levels. Biomass will be observed via microscopy and test variations in moisture, volatiles, and fixed carbon. The outcome of these experiments will inform the optimal engineering and design to achieve the necessary microbial load reductions. These experiments will also inform the compressive strength requirements for biomass to be stacked within the sequestration site.
- **Polymer impermeability:** Lab experiments will test the durability and mechanical properties of various composite polymer mixes. Polymers will be exposed to accelerated aging experiments (e.g., extreme temperatures, high humidity) to ensure they will not degrade over time. These tests will build upon academic literature to demonstrate (1) the ability of the polymer layers to block agents (e.g., water, oxygen) needed to fuel microbial decomposition of biomass, and (2) the effectiveness of these seals over 1,000 year time frames.
- **MRV and leak detection:** Graphyte is designing a novel monitoring and leak detection system, described in the MRV section below. Leak detection systems will be trialed to ensure high quality MRV, including use of tracers and sensors to detect leaks in the sequestration site.

Build Our First Commercial Project: The Loblolly Project

Graphyte's first commercial project will incorporate learnings from these experiments and provide the foundation for our growth toward gigaton scale. The Loblolly Project will be located in Pine Bluff Arkansas and sequester 50,000 tCO_2 per year. Loblolly will support economic development in central Arkansas and create jobs in the low-income community of Pine Bluff.

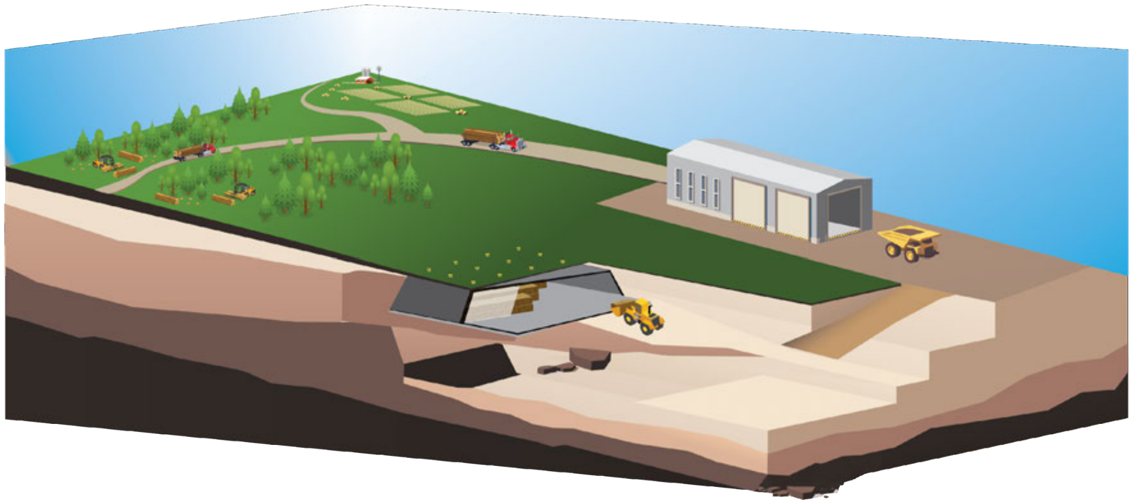


Figure 2: *The Loblolly Project. Graphyte is building a project in Pine Bluff Arkansas that will leverage Loblolly pine mill waste and agricultural residues. Encapsulated carbon blocks will be produced in a warehouse processing facility and sequestered in a co-located sequestration site.*

The Loblolly Project is strategically located in close proximity to significant agricultural and forestry activity. Graphyte is finalizing biomass supply contracts with three suppliers within a 55-mile radius of our project site. They will deliver mill residues (i.e., sawdust and bark) and rice husks (waste produced during the rice milling process) on a weekly basis to our processing facility. Graphyte will then produce encapsulated carbon blocks and sequester them in a co-located sequestration site. Graphyte's biomass feedstocks will be sourced in compliance with Sustainable Biomass Program standards. Mill residues and rice husks have limited alternative uses and are often left to decompose, generating methane emissions in the process. Both of these biomass feedstocks have limited nutrient removal risk because they are produced at processing facilities and are not otherwise left to provide nutrients back into the soil.

Graphyte will build the Loblolly Project in two phases. Phase 1 will process and sequester an initial volume of 5,000 tCO_2. Graphyte will then cap this portion of the sequestration site and begin the project monitoring period. Completing the end-to-end Carbon Casting process will give initial operational data that can inform operational improvements going forward. Phase 2 will involve scale-up toward the full operational capacity of 50,000 tCO_2 per year.

Carbon removal quantification for Carbon Casting is straightforward. The carbon content for bone dry biomass is typically 50% (Thomas and Martin, 2012). Roughly 3.67 tons of carbon dioxide are stored in biomass per ton of carbon, based on the molecular weight ratio of CO_2:C (44:12). This means that approximately 1.8 tons of CO_2 can be stored per ton of dry biomass. Graphyte will secure ~27,500 dry tons of biomass per year to support a CDR capacity of 50,000 tCO_2 per year.

Biomass (dry tons)	Carbon Content	Molecular Weight Ratio	Total CDR Capacity
1	50%	3.67	1.83
~27,500	50%	3.67	~50,000

A major benefit of the Carbon Casting approach is that each block can be weighed, and the carbon within that block measured, to quantify exactly how much carbon is being sequestered. Each carbon block is labeled and timestamped to provide a precise ledger for carbon accounting.

Deploy Carbon Casting Around the World

After building our initial 50,000 tCO_2 per year project, Graphyte will quickly deploy Carbon Casting to regions across the United States and around the world. We will expand the Loblolly Project to take advantage of the significant biomass resources in Arkansas and target other waste biomass supply sheds that present promising project development opportunities. Our future project development strategy is centered around the availability of biomass, the potential for revenue opportunities, and conditions for project financing.

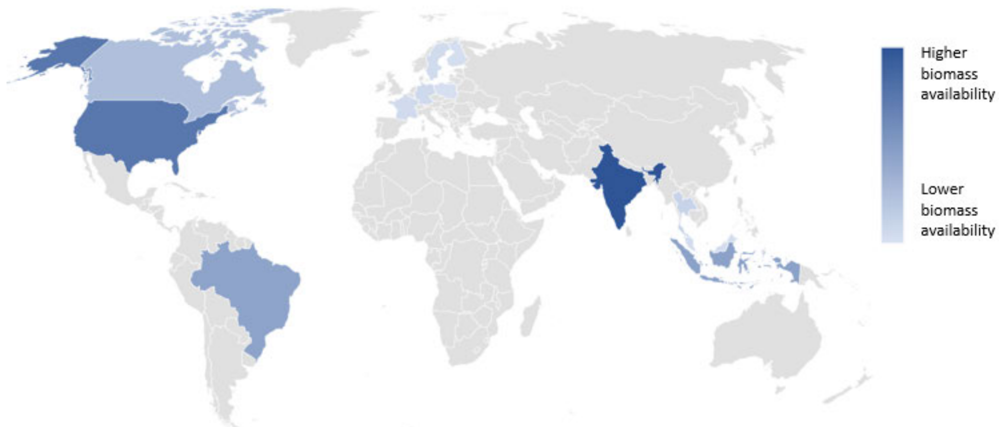


Figure 3: *A map of major producers of waste biomass. Graphyte will center its project development roadmap on availability of waste biomass in regions with favorable policy environments and development conditions.*

There are three primary components that enable Graphyte to reach gigaton scale:

- **Biomass Supply:** Graphyte will develop projects in areas with high availability of low-cost, sustainable biomass. Waste biomass production is highly concentrated in areas with high agricultural productivity and timber production. India, the United States, Indonesia, and Brazil produce 900M tons of waste biomass annually, translating to over 1GT of removal capacity. Graphyte is establishing relationships with suppliers to source waste biomass in these regions. Co-locating around biomass supply allows Graphyte to ensure the sustainability of the biomass source (e.g., using track and trace systems) and minimize transportation costs.
- **Revenue Opportunities:** Graphyte faces no fundamental technical hurdles to scale. As explained in the risk section below, the major constraint on growth is market demand for high-quality CO_2 removals. Graphyte will develop projects to meet demand as voluntary and compliance removals markets grow. Our target is to remove over 6 million tons of CO_2 per year by 2030.
- **Project Financing:** To most effectively deploy projects around the world, Graphyte needs access to low-cost capital. This means working in geographies with favorable conditions for development and project financing, including good labor practices, affordable clean energy production, and streamlined permitting processes. Graphyte's scale up plan ties closely

toward our ability to build a replicable model for developing and financing projects around the world.

Carbon Casting offers an affordable, permanent carbon removal solution that can scale today. With a sound technical foundation, a seasoned management team, and an effective commercialization strategy, Graphyte will remove gigatons of CO_2 from the atmosphere and help mitigate the worst impacts of climate change.

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.

The Graphyte team brings experience commercializing novel climate technologies and developing first-of-a-kind infrastructure projects. Graphyte is developing mitigation strategies to address the financial, technical, and project execution risks to scale our Carbon Casting solution.

Market Risk

The biggest barrier to deployment for Graphyte's solution is the nascency of the carbon removal market today. According to CDR.fyi, less than 37,000 tons of CO_2 removal were delivered in 2022, corresponding to ~75% of the annual volume of Graphyte's initial Loblolly Project. While recent offtake agreements announced by Microsoft, Frontier, and JPMorgan in 2023 represent big steps moving the market forward, there is a risk of insufficient demand to support CDR projects at larger volumes (the Loblolly Project will produce 1.25M tons of CO_2 over its lifetime). Graphyte will mitigate these market risks by securing offtake agreements prior to commencing project construction on the Loblolly Project.

Technology Risk

While Graphyte's solution involves technically mature components, the equipment is being integrated in a novel way and deployed in a unique context. Graphyte's experiments conducted in conjunction with academic and commercial labs will test key integrations between various parts of the Carbon Casting process prior to deployment.

Scale Up Risk: Building a 50,000 Ton Per Year Project

The Loblolly Project is projected to remove 50,000 tCO_2 per year, with operations starting in 2024. Building a project at this size enables meaningful progress toward the urgent objective to scale up CDR deployment. Research by the Systems Change Lab shows that 75M tons of CDR must be deployed annually by 2030 to keep warming under 1.5°C. Current planned production is not on track to meet that goal and Carbon Casting's solution is well suited to help accelerate deployment of durable removals today. Graphyte is confident that the technical risks of the Carbon Casting process are minimal due to the detailed design that combines existing off-the-shelf equipment. This project does not require R&D or invention of new scientific innovations. While there are engineering risks associated with building a first project at commercial scale (described below), Graphyte feels the benefits of demonstrating operational capacity at scale outweigh those risks.

Graphyte acknowledges that Frontier customarily uses the prepurchase process for smaller-scale projects. As described above, Graphyte intends to permanently seal an area within the broader sequestration site in which the first 5,000 tCO_2 will be stored. This initial pilot allows Graphyte to test the integrated Carbon Casting process and implement our MRV system, while concurrently developing the larger 50,000 tCO_2 per year project from which other buyers can purchase removals. In the event that Frontier is not drawn to this approach, Graphyte is interested in discussing the potential for a smaller pilot line at the 5,000 tCO_2 per year scale. Such an approach would help de-risk the overall project but would likely result in delays to reach scales of 50,000 tCO_2 per year and beyond.

Project Execution Risks

First-of-a-kind projects have inherent risk because they involve novel engineering and construction. No Engineering, Procurement, and Construction (EPC) firm has built a Carbon Casting project to date. Graphyte is establishing relationships with key partners to allocate risk across different counterparties and ensure the project is delivered safely, on time, and within budget. Graphyte will leverage best practices from adjacent industries and bring subject matter expertise across key components of the project. Below is an assessment of project execution risks.

Risk	Mitigation Strategy
Permitting	Permits are long lead-time items that often cause project delays. Graphyte's EPC firm, SCS Engineers, has in-depth experience permitting solid waste recover facilities in Arkansas. We have engaged the Arkansas Department of Environmental Quality early and often to ensure permits do not delay construction of the Loblolly Project.
Cost overruns	Cost overruns are a common problem in the engineering and construction of infrastructure projects. Graphyte will leverage best practices to manage costs. This includes use of conservative budget contingencies, conducting thorough front end-engineering and design (FEED) studies, and executing fixed price contracts where possible. Graphyte will cover any cost overruns from its own balance sheet.
Community Resistance	Graphyte is bringing the burgeoning carbon removal industry to an economically disadvantaged region. Graphyte has secured the support of the Economic Development Alliance for Jefferson County Arkansas. The Alliance will support Graphyte's community engagement approach, described in Section 7 below. Graphyte will hire locally and is developing a job sourcing initiative in coordination with the University of Arkansas at Pine Bluff, an HBCU land grant institution founded in 1890 (UAPB).
Novel Processing Facility Design	Graphyte will leverage process engineering approaches commonly used in other industries that utilize biomass as a feedstock, including wood pellet production and biomanufacturing.
Novel Sequestration Site Design	Graphyte's sequestration site involves many design elements common to the waste management industry. Graphyte's EPC firm, SCS Engineers, brings in-depth experience designing and constructing solid waste recovery facilities in Arkansas and around the world.
Physical Risks and Safety	Graphyte will implement best practices for managing fire risk (e.g., high capacity sprinkler systems) and designing the Project site to withstand natural disasters.

b. **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)*	5,000 tons
Delivery window *(at what point should Frontier consider your contract complete? Should match 2f)*	December 2024
Levelized Price ($/ton CO_2)* *(This is the price per ton of your offer to us for the tonnage described above)*	$100

** 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).*

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