Proto-Protocol for Carbon Removal from Waste Biomass

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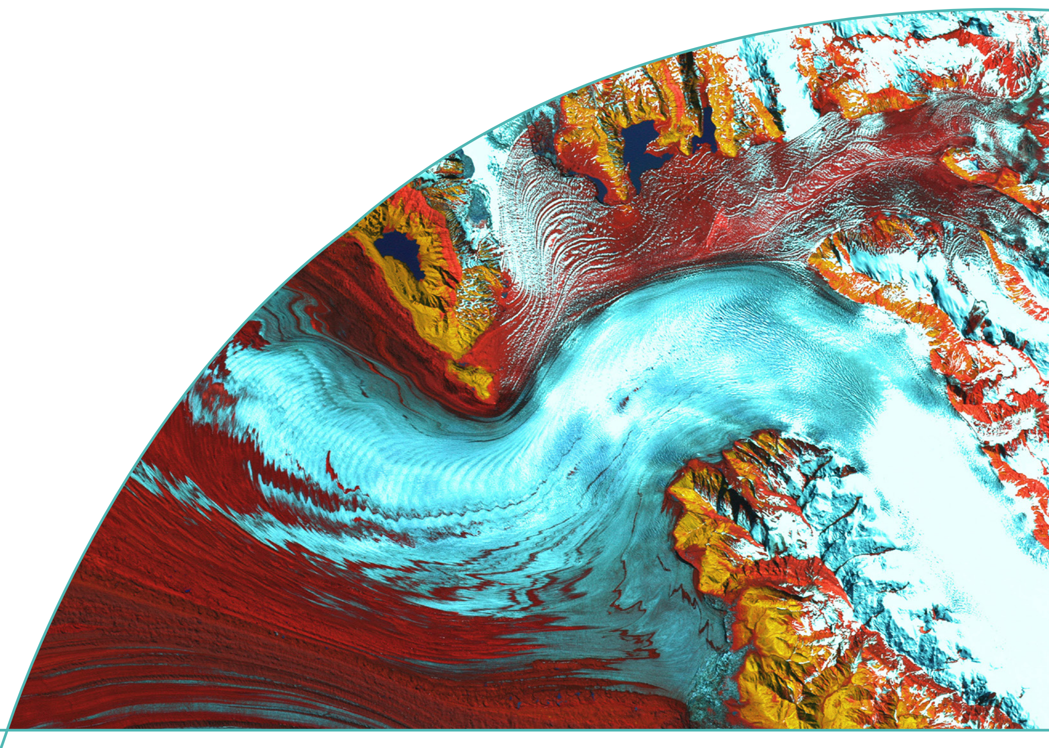

Background

Annually, more than 100 gigatons (Gt) of carbon dioxide (CO_2) is exchanged between the atmosphere and biosphere (terrestrial plants and algae) through photosynthesis, decomposition, and combustion.[1] Biomass Carbon Removal and Storage (BiCRS) is a type of carbon dioxide removal (CDR) technology that seeks to capture CO_2 temporarily stored within the biosphere and sequester that CO_2 before its return to the atmosphere. Sequestration can either be achieved through long-term storage of CO_2 in deep geological formations or through the use of a material to produce long-lived products. BiCRS contrasts with bioenergy with carbon capture and storage (BECCS) by prioritizing carbon capture over energy generation (as a byproduct of the capture process) through the appropriate selection of high carbon-content feedstocks that result in net CDR from the atmosphere.

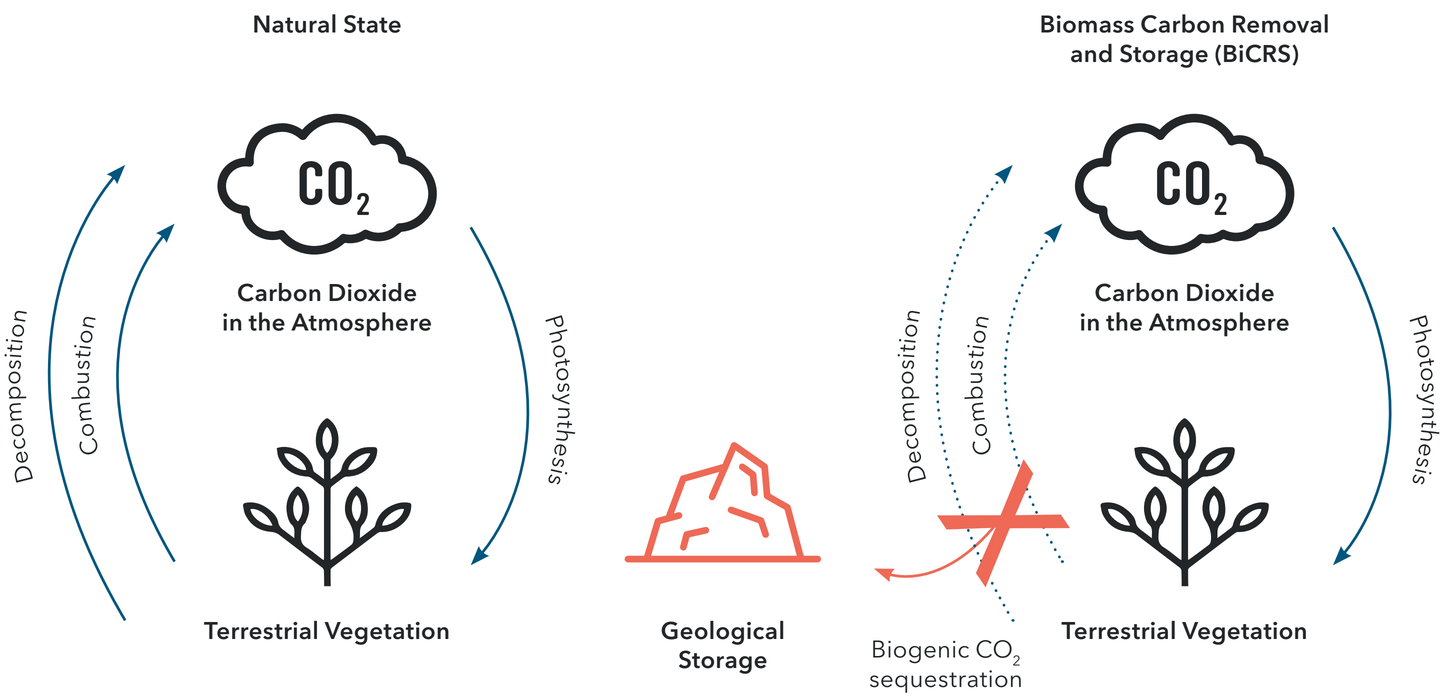

Figure 1. BiCRS directs part of the natural cycle of carbon dioxide into geological storage.

[1] Biomass: Impact on Carbon Cycle and Greenhouse Gas Emissions, Carly Green, Kenneth A. Byrne, in Encyclopedia of Energy, 2004.

Arbor, a carbon removal and storage company, has developed a next-generation BiCRS facility to extract biogenic CO_2 from forestry waste (biomass) with sequestration through geological storage. The facility additionally produces renewable electricity and slag as byproducts. The facility's processes have been designed to be self-sustaining upon initiation through utilization of internal waste heat and require only additional biomass to continue operating. Proprietary thermochemical conversion processes enable Arbor to use low-grade biomass as fuel and to capture nearly all released CO_2 with a net CDR efficiency target of ~1.8 metric tons of CO_2 per dry ton of biomass. The California Department of Forestry and Fire Protection (CAL Fire) recognizes the method to have a co-benefit of contributing to forest wildfire avoidance by creating a beneficial use for forestry waste collected from sustainable forestry management practices in California.

The stability of carbon markets and the achievement of international climate ambitions are threatened by project developers making uncorroborated claims of environmental benefit. In the case of BiCRS, biomass be derived from sustainable sources and do no additional environmental harm to build trust as a credible tool for achieving net CDR. Arbor is unequivocally committed to these principles. This protocol outlines a framework for transparent accounting of CDR credits generated through essential monitoring, reporting, and verification (MRV) of claims made using Arbor's BiCRS technology.

Process Flow

Arbor is developing an innovative facility that integrates four key processes for an optimal BiCRS-based energy generation system:

1. Torrefaction of biomass.
2. Compact entrained flow gasification of biocoal.
3. Oxy-fuel combustion of syngas.
4. Expansion of high-pressure gas in a turboexpander.

Torrefaction
Biomass is converted to biocoal under elevated temperatures in an inert low-oxygen environment. Conversion to biocoal has the following advantages:

- Biocoal can be finely pulverized to undergo gasification.
- Torrefaction releases volatiles such as tar and phenols entrained in the raw biomass.
- Biocoal has hydrophobic properties that allow it to be kept in storage for prolonged periods.

Compact-Entrained Flow Gasification
Biocoal is gasified under high pressures and temperatures with
a high carbon conversion efficiency to produce high-purity syngas consisting primarily of carbon monoxide (CO) and hydrogen (H_2). Additionally, the process has a high thermal conversion efficiency, and any waste heat is recovered to power other processes.

Oxy-Fuel Combustion
Syngas is combusted in an oxygen-enriched environment to produce a gas stream rich in CO_2. The process sources oxygen from a generator powered by the next process thus eliminating the need for an external power source and improving overall life cycle emissions. Additional post-processing removes impurities so that the gas is sufficiently pure in the CO_2 for injection into deep
geologic storage.

High-Pressure Expansion
CO_2-rich gas, still under high pressure, is sent through a supercritical CO_2 power cycle wherein the gas is allowed to expand in an expansion turbine, which provides torque to power a generator. This generator powers all onsite auxiliaries and surplus electricity is exported to either the grid or to an onsite customer. The process has high efficiency, reducing operating costs and emissions.
Upon completion of the cycle and post-processing, CO_2-rich gas is subsequently transported by truck to a geological storage site to be sequestered.

Applicable Feedstocks
A key tenet of BiCRS methods is to "do no harm." To meet this tenet, Arbor will source biomass collected through sustainable forestry management practices (i.e., thinning and logging residues, standing dead biomass resulting from tree die-off events) that will bring environmental benefits by helping to restore ecosystems and reduce the risk of wildfires. Sustainability requirements for the feedstock used will be in-line with the industry's best practices.

Generated Commodities:

- **CDR Credits**
  High-integrity carbon credits generated by captured CO_2 injected for permanent, geologic storage are the project's primary commodity.

- **Electricity**
  Renewable electricity generated as a byproduct of the high-pressure expansion phase will be commodified to help reduce operating costs. Arbor's BiCRS plant will be able to operate continuously and offer dispatchable power without the need for energy storage, unlike other renewables such as wind or solar. Additionally, the spatial footprint of the facility with respect to generated electricity is more compact compared to an equivalent amount of energy generation derived from renewable energy sources such as wind and solar.

- **Slag**
  Slag is a nutrient-rich residual byproduct generated during the gasification phase and will be commodified to help reduce operating costs through the appropriate sale of this waste stream for the beneficial use to concrete aggregators, chicken feed producers, and waste management facilities.

Carbon Accounting

A Life-Cycle Analysis (LCA) study must be conducted to accurately account for carbon captured and sequestered by the technology. An LCA study involves establishing baselines and conducting a thorough inventory of the energy and materials required by all the processes involved in the capture and sequestration of CO_2 and quantifying the corresponding greenhouse gas (GHG) emissions to the environment. An LCA quantifies the cumulative potential environmental impacts of processes within set boundaries.

The LCA baseline must conservatively estimate what would occur in the absence of Arbor's project to capture and sequester CO_2. Biomass in this case would release CO_2 to the atmosphere either through aerobic decomposition on the forest floor or through combustion at a forestry waste collection site. In the case of natural decomposition, the increasing frequency of forest and field fires in California accelerates this pathway of CO_2 released back to the atmosphere.

An LCA study for this technology should include measuring emissions resulting from the following sources:

- Loading and transportation of the biomass to the facility from the collection site.
- Processing of biomass and capture of CO_2 from the facility processes (torrefaction, gasification, combustion, expansion).
- Transportation of CO_2 to the sequestration facility.
- Injection of CO_2 into geological storage at the sequestration facility.
- Process auxiliaries such as external fuels used to initiate facility processes.

Fugitive emissions of CO_2 should be assessed throughout the entire process through proper estimation of baseline carbon stocks in the biomass and metering of extracted CO_2 at the injection points into transportation and geological storage to identify any significant losses that indicate an accelerated return of CO_2 to the atmosphere relative to the baseline. Any unaccounted-for carbon must be assumed to be fugitive and emitted as CO_2.

Analyses of life-cycle emissions, such as the one above, are measured and verified using various models. Once an LCA model is created, then the net CDR can be calculated as:

$$CDR_{Net} = \sum CO_{2\ sequestered} - \sum tCO_2\, e_{emitted}$$

where

$$\sum CO_{2\ sequestered} = \sum CO_{2\ captured} - \sum CO_{2\ fugitive}$$

and

$$\sum tCO_2e_{emitted} = \sum tCO_2e_{biomass\ transport} + \sum tCO_2e_{facility} + \sum tCO_2e_{auxiliaries} + \sum tCO_2e_{CO_2\ transport} + \sum tCO_2e_{CO_2\ injection}$$

and

$$\sum CO_{2\ fugitive} = \sum CO_{2\ facility\ fugitive} + \sum CO_{2\ transport\ fugitive} + \sum CO_{2\ injection\ fugitive}$$

Facility process emissions ($tCO_2e_{facility}$) will be reduced due to the internal recovery of waste heat to perpetuate the process. Emissions from facility startup and any auxiliary equipment powered by external sources ($tCO_2e_{auxilaries}$) must be accounted for fully.

Step	Biomass Transport	Biomass Processing	CO_2 Capture	CO_2 Transportation	CO_2 Injection
Measurement	Bill of lading, distances, calorific value	Input weight, energy use, output weight	Flow meter, biogenic component	Bill of lading, distance	Injected volume/ weight, energy use
Frequency	Per load	Daily	Continuous	Per load	Per operation

The mentioned principles will be embedded in a continuous LCA to estimate correct credit generation.

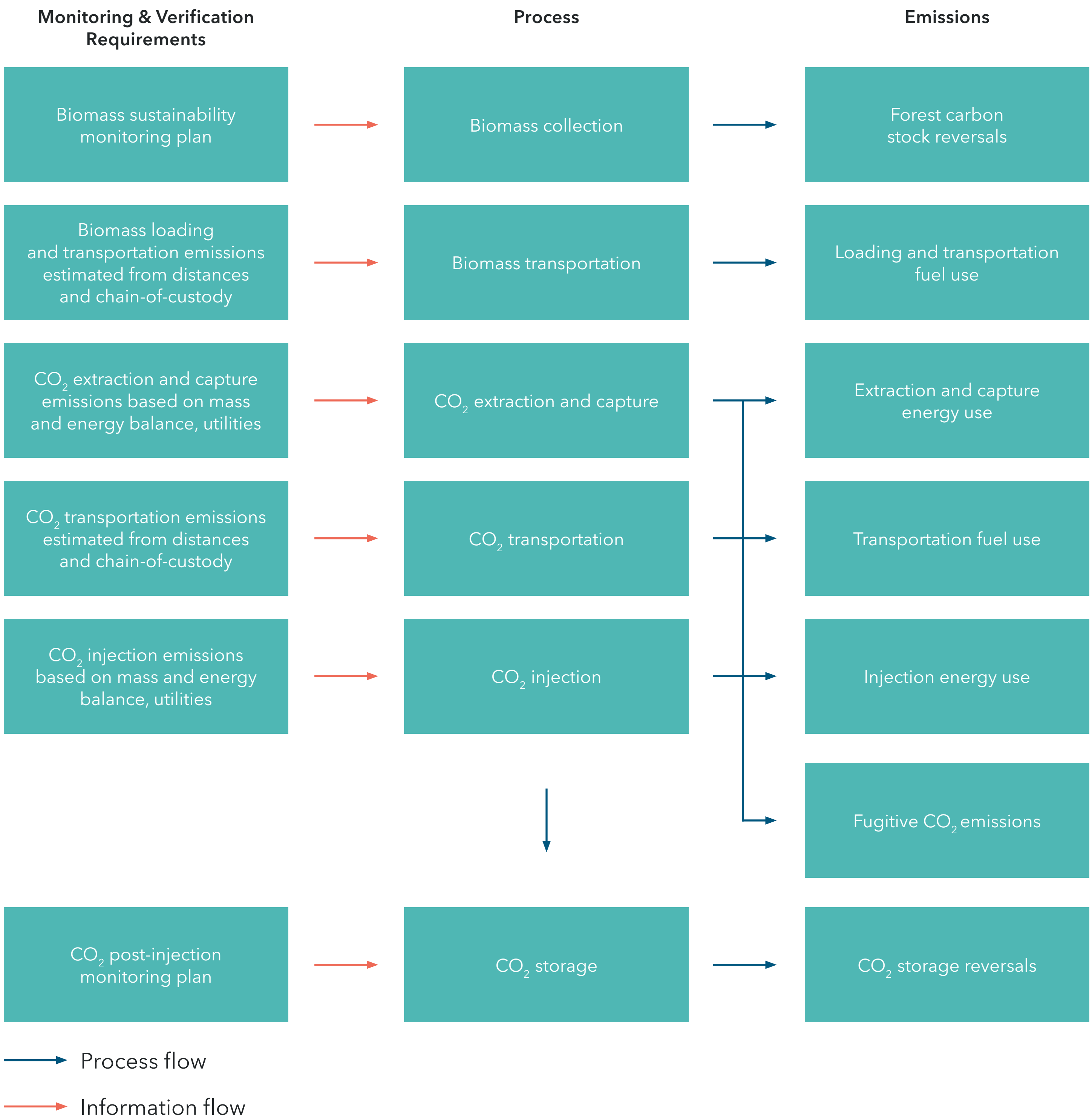

Figure 2. Illustration of LCA for Arbor's BiCRS process.

CO_2 Capture and Storage Monitoring Protocol

A monitoring plan provides a framework for verifiers to follow a project's activities to ensure proper, transparent, and complete assessment of CDR claims and generated credits.

The BiCRS monitoring plan must include but not necessarily be limited to the following:

- Operational protocol for testing to prove appropriate biomass is sourced for conversion to biocoal and estimation of total carbon stocks within the biomass.
- Measurement approaches for transportation (including loading) of biomass from the collection site to the BiCRS plant.
- BiCRS plant equipment measurement plan for biomass input and byproduct outputs (CO_2 capture, renewable electricity generation, slag production).
- Operational protocol for testing to prove biogenic fraction of captured CO_2.
- Measurement approaches for transportation of captured CO_2 from the facility to the injection site.
- A comprehensive description of the geological formation where CO_2 will be stored (U.S. Environmental Protection Agency, or USEPA Class VI[2]).
- A measurement plan to address fugitive emissions of CO_2 at locations of highest risk.
- Monitoring of meters' calibration to assure at least 95% confidence in reported claims.

The CO_2 injection site must be assessed before the initiation of injection activities to ensure permanent storage according to international best practices. CO_2 must be measured as it is injected, and subsequent post-injection monitoring must be completed to ensure that carbon reversals are avoided and properly reflected in credit issuance if they do occur.

Verification of Carbon Removals

Verification is needed to confirm that the project is properly fulfilling the requirements of the monitoring plan. Verification shall be performed by a recognized third-party auditor by inspecting relevant evidence and verifying procedures and calculations. The verification shall at a minimum be conducted according to the standards established by International Organization for Standardization (ISO) 14064-3:2019. Evidence provided to the auditor shall consist of data records, documents, and other relevant information that will allow for complete verification of the monitoring requirements to a reasonable level of assurance. The mass and energy balance of the facility should be calculated using data from actual metered inputs and outputs.

[2] https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-carbon-dioxide#:~:text=Class%20VI%20wells%20are%20used,atmosphere%20and%20mitigate%20climate%20change.

Metering must be shown to be accurate and reliable, and records for each CDR claim must be maintained for at least 10 years after the claim is made. Inputs should be audited regularly to assess injected carbon, and credits shall be issued only when the CDR quantity has been verified. Site visits should be required as part of the annual audit cycle.

Reversal Risks

Potential reversal pathways for CO_2 are as follows:

- **Geological Storage Reversals**
  The release of sequestered CO_2 back into the atmosphere poses a risk for all CDR projects that utilize geologic storage. This risk will be lowered by:
  a) Confirming that the storage site adheres to all regulatory requirements (USEPA or similar).
  b) Increased frequency of monitoring to allow early detection, if needed.
- **Forest Carbon Stock Reversals**
  Biomass sustainability poses a risk for BiCRS projects. Forestry waste collected beyond the sustainable yield will result in a net loss of carbon stored within the biomass of the forest compared to the baseline. This risk will be lowered by:
  a) Careful selection of biomass feedstock, focusing on slash and forestry waste, in coordination with local and national governmental bodies to ensure sustainability.
  b) Development of a biomass sustainability plan aligned with sustainable forestry management practices.
  c) Independent monitoring of regional forest stocks through time using satellite data.
  d) Confirming regional forest stock changes via U.S. Department of Agriculture (USDA) and Intergovernmental Panel on Climate Change (IPCC) forest stock change overlays.

A commonly used mechanism to mitigate reversals is to set aside a portion of credits generated into a buffer account. A buffer account could be assigned depending on the actual or estimated reversal risk for each deployment and injection site and could be up to 1% of total credit generation.

Conclusion

Carbon accounting, monitoring, and verification are well-understood principles applicable to high-integrity carbon crediting projects. Extending these principles to BiCRS will result in the removal of CO_2 from the atmosphere and lay the foundation for the creation of high-integrity CDR credits from such processes. Comprehensive monitoring systems must be required but should not require duplicative or overly burdensome procedures. Rapid atmospheric drawdown of CO_2 demands scalability. Arbor's technology will abide by the strongest standards of quantification and environmental quality while leveraging the vast stocks of waste biomass within California to generate CDR credits and clean electricity to propel the industrial transition.

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