CARBON DIOXIDE REMOVAL PROGRAM

NATIONAL ENERGY TECHNOLOGY LABORATORY

OVERVIEW

The National Energy Technology Laboratory's (NETL) Carbon Dioxide Removal (CDR) Program is advancing a diverse portfolio of CDR approaches that will aid in gigatonne-scale carbon dioxide (CO_2) removal from the atmosphere by mid-century. CDR is one method for carbon management as part of a comprehensive multi-pronged approach that involves the coupling of carbon capture methods (i.e., CDR technologies co-located with low-carbon energy sources, and point source capture for fossil fuel-based power generation and industrial sources) with long duration (at least 100 years) carbon storage in geologic, bio-based, and ocean reservoirs, or in long-lasting products (e.g., synthetic aggregates, biochar, concrete, durable carbon products). This diverse suite of technologies and solutions are integral to the U.S. goal of achieving a net-zero carbon economy by 2050. Furthermore, these efforts directly support the DOE's Carbon Negative Shot goal to remove CO_2 from the atmosphere and durably store it for less than \$100/net tonne CO_2-equivalent (CO_2e).

Research and development (R&D) for CDR is focused on areas such as direct air capture (DAC), biomass carbon removal and storage (BiCRS) and bioenergy with carbon capture and storage (BECCS), enhanced mineralization, and direct ocean capture to remove CO_2 that has accumulated in the atmosphere or oceans and durably store it (i.e., geological storage or subsurface mineralization) or convert it into durable products such as low-carbon concrete. NETL supports the robust analysis of life cycle impacts of various CDR approaches and has a deep commitment to environmental justice throughout the research, development, and deployment process.

The deployment of CDR methods can mitigate ongoing CO_2 emissions from difficult-to-decarbonize sectors (e.g., aviation, shipping and agriculture) to reduce "net" emissions, as well as to address legacy CO_2 emissions to achieve net-negative emissions goals.

DIRECT AIR CAPTURE

DAC involves technologies that separate CO_2 from ambient air and deliver extracted CO_2 in a pure, compressed form that can then be stored underground or reused. The major challenges for DAC technologies include extracting CO_2 from dilute concentrations in the atmosphere, large water and land-use requirements, carbon life cycle effectiveness, and impacts of process pressure drop on energy usage and system cost. To address cost barriers, DAC systems can be co-located with existing operational geothermal resources, nuclear plant facilities, or industrial plants to access thermal sources, such as waste heat and/or steam slip streams for regeneration of DAC materials, ultimately reducing the overall cost of capturing CO_2.

The CDR Program aims to leverage past research in materials, equipment, and process development for application to the conditions and process requirements of DAC. The program is also aiming to advance transformational materials that promote rapid CO_2 uptake, with high dynamic CO_2 capacity under DAC conditions, as well as modular scalable contactors to further reduce the costs for removal of CO_2 from air.

BIOMASS CARBON REMOVAL AND STORAGE

BiCRS processes use sustainably-sourced biomass (i.e., organic material or resource derived from plant or animal matter) to remove CO_2 from the atmosphere and store it underground or in long-lived products. The major challenges associated with BiCRS include water and land use requirements; cultivating, transporting, and processing microalgae at large scale; and difficulties in measuring, monitoring, and crediting carbon removal.

BECCS is a specific type of BiCRS in which biomass is converted to energy (in the form of electricity, liquid fuels, and/or heat) and the carbon emissions are captured and stored in geologic formations or embedded in long-lasting products. BECCS can result in net-negative CO_2 emissions, as the overall process involves carbon removal from the atmosphere via photosynthesis of the biomass source. Other types of BiCRS methods involve the use of biomass to capture and store carbon without energy production, such as using biochar to improve soil fertility.

ENHANCED MINERALIZATION

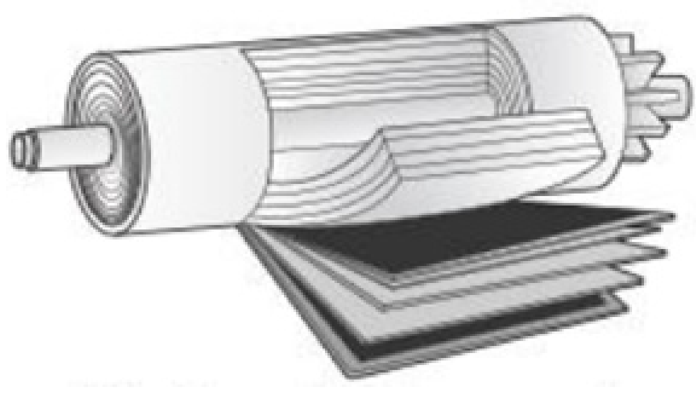
Enhanced mineralization is a CDR approach that aims to remove CO_2 from the air and store it in the form of carbonate minerals such as calcite or magnesite. Alkaline materials, such as naturally occurring rocks (e.g., basalts and peridotite), industrial waste material, or mine tailings, react readily with CO_2 to form carbonates that permanently store CO_2 as a solid. Mineralization processes include:

- *Ex situ* carbon mineralization—solid reactants are transported to a site of CO_2 capture and then reacted with CO_2-rich fluid or gas;
- *Surficial* carbon mineralization—CO_2-bearing fluid or gas is reacted with minerals distributed across land or coastal areas; and
- *In situ* carbon mineralization—CO_2-bearing fluids are circulated through geologic formations underground.

OCEAN-BASED CDR

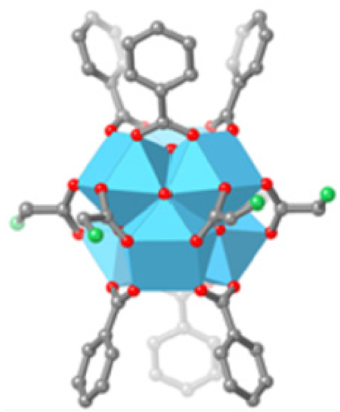
Direct ocean capture technologies aim to remove excess carbon from oceanwater, representing a direct reversal of ocean acidification caused by dissolved CO_2 in the ocean. Ocean-based CDR methods can promote a reduction of atmospheric CO_2 concentrations and complement land-based CDR activity to reduce CO_2 concentrations in the air and seas. Direct ocean capture can be implemented offshore, eliminating the challenge of competitive land use associated with alternative CDR approaches.

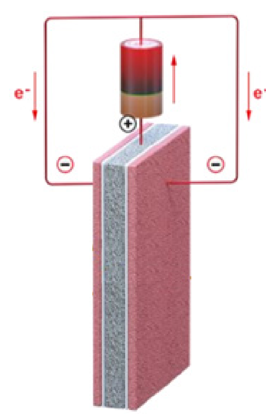
KEY TECHNOLOGIES



SOLVENT-BASED CO_2 capture is the chemical or physical absorption of CO_2 from air or a gas mixture into a liquid carrier. Research projects focus on the development of advanced, durable solvents that exhibit high CO_2 loading combined with low regeneration energy requirements for the separation of CO_2 from dilute gas mixtures. Advanced manufacturing methods can be applied to develop more economical materials for the construction of air contactors and packing. Research is also focused on approaches to mitigate solvent degradation and system advancements focused on heat integration and efficient mass transfer to reduce the cost of CO_2 capture.

MEMBRANE-BASED CO_2 capture utilizes permeable or semi-permeable materials for the selective transport and separation of CO_2 from gas mixtures or air. Membrane processes involve simple passive operation and the ability to incorporate membranes into a modular unit design with reduced equipment footprint and low pressure drop to minimize costs. Research is focused on the development of low-cost, stable membrane materials with superior permeability and selectivity for CO_2, high tolerance to excess concentrations of oxygen and nitrogen, and improved membrane lifetime.





SORBENT-BASED CO_2 capture is the chemical or physical adsorption of CO_2 using solid sorbents. Research is focused on developing low-cost sorbents with long-term stability, high selectivity for CO_2 in dilute gas mixtures, high CO_2 adsorption capacity, and resistance to oxidation. The development of structured supports (i.e., monoliths, laminates, or membrane bundles), design of advanced solid-gas contacting devices, and improvement of desorption processes are key R&D objectives that can lead to reduced pressure drop, heat and power requirements, and capital and operating costs.

ELECTROCHEMICAL-BASED CO_2 capture utilizes a pH swing cycle, which involves shifting a working fluid between basic and acidic pH to capture and recover CO_2. Electrochemical processes involve lower energy consumption compared to thermally driven separation and can be easily integrated with renewable power sources to reduce the cost and improve the efficiency of CO_2 capture systems. A major challenge is the design of electrochemical cell and gas-liquid contactors for large-scale applications. R&D objectives include the development of improved electrode materials and membrane contactors, and the scale up of systems for single-stack and/or multi-stack modular configurations.

The CDR Program utilizes life cycle analysis (LCA) to ensure the environmental viability of CDR technologies and approaches. NETL's LCA method utilizes the principles of life cycle assessment, life cycle cost analysis, and various other methods to evaluate the environmental, economic, and social attributes of energy systems, ranging from the extraction of raw materials from the ground to the use of the energy carrier to perform work (commonly referred to as the "life cycle" of a product).

ABOUT NETL

NETL is a U.S. Department of Energy national laboratory that drives innovation and delivers technological solutions for an environmentally sustainable and prosperous energy future. Through its world-class scientists, engineers and research facilities, NETL is ensuring affordable, abundant and reliable energy that drives a robust economy and national security, while developing technologies to manage carbon across the full life cycle, enabling environmental sustainability for all Americans, advancing environmental justice and revitalizing the economies of disadvantaged communities. Leveraging the power of workforce inclusivity and diversity, highly skilled innovators at NETL's research laboratories in Albany, Oregon; Morgantown, West Virginia; and Pittsburgh, Pennsylvania conduct a broad range of research activities that support DOE's mission to ensure America's security and prosperity by addressing its energy and environmental challenges through transformative science and technology solutions.

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