Carbon Utilization Infrastructure, Markets, and Research and Development

A Final Report

National and international plans for halting and reversing climate change focus on reducing and eventually ending the largest source of greenhouse gas (GHG) emissions: carbon dioxide (CO₂) released by fossil fuel combustion. For some materials, however, carbon is essential and cannot be removed or replaced: for example, in aviation fuel, chemicals, plastics, and some construction materials. For these systems, carbon will need to be managed and utilized effectively in a way that either prevents CO₂ from entering the atmosphere or reuses it through circular processes that do not contribute additional emissions.

In a net-zero future, CO₂ can be used to sustainably create products that require carbon (such as pharmaceuticals, fuels, and agrochemicals) or converted into products that durably store carbon (such as concrete), as shown in Figure 1. Coal waste also may be converted from a harmful legacy to a valuable feedstock for long-lived carbon products and critical materials. Use of CO₂ will have to be compared against other circular carbon feedstocks, such as biomass and carbon wastes (e.g., plastic wastes, municipal solid wastes).

To create a successful carbon utilization ecosystem, key technical, societal, and economic challenges must be addressed, including research, development, and demonstration of different carbon utilization pathways; techno-economic, environmental, and social life cycle assessments; and workforce development, environmental justice, and community engagement.

At the request of the Department of Energy (DOE) and Congress, the National Academies of Sciences, Engineering, and Medicine organized a study to identify market opportunities, infrastructure
needs, and future research priorities for carbon utilization. The study’s first report assessed the state of infrastructure for CO₂ capture, transportation, use, and storage, highlighting priority opportunities for further investment. Building on the first report, this report identifies potential markets and commercialization opportunities for CO₂- and coal waste–derived products; describes policy and assessment needs to support utilization; examines economic, environmental, and climate impacts of CO₂ utilization infrastructure; and puts forward a comprehensive research agenda for carbon utilization technologies.

**CO₂ AND COAL WASTE UTILIZATION IN A NET-ZERO EMISSIONS FUTURE**

Chemical or biological conversion of CO₂ can produce

- Short-lived products, including chemicals, pharmaceuticals, aviation fuels, and food and animal feed, which can participate in a circular carbon economy.

- Long-lived products, including concrete, aggregates, construction materials, carbon fiber, and other elemental carbon materials, which durably store carbon.

Coal waste utilization can produce sustainable carbon-based materials for construction, electronics, and other applications if the products are long lived and do not result in near-term CO₂ emissions. Coal waste is also a source of critical minerals and materials like cobalt, lithium, nickel, and rare earth elements.

Carbon utilization can complement other carbon management strategies like carbon capture and geologic storage by providing economic and societal returns from marketable products. Co-locating these processes can streamline operations, lower transportation costs, and enhance job opportunities, although it may require significant initial investment in new equipment and infrastructure development.

To better understand the benefits, opportunities, and challenges, DOE should prioritize research on co-located carbon capture and conversion, particularly for long-lived products that contribute to carbon sequestration. **DOE should also close information gaps on the environmental, market, resource, and jobs impact of CO₂ conversion** and support efforts to inform the public about carbon management.

**ASSESSING THE FEASIBILITY AND IMPACT OF CO₂ UTILIZATION TECHNOLOGIES**

CO₂ utilization is intimately tied to environmental, economic, and societal needs, and the attributes and feasibility of proposed technologies cannot be understood without assessment of their life cycles, societal impacts, and techno-economic status. The report evaluated technology assessment approaches, with a focus on what...
these assessments can and cannot do, how they are used to evaluate CO₂ utilization, and critical issues for improvement.

The report recommends that DOE require consistent methodologies for equity assessments of carbon utilization technologies to facilitate identification of critical locations where there could be significant environmental, cost, or equity problems. Additionally, DOE should support research into assessment approaches that enable circularity for CO₂-derived products and develop methods and tools for carbon traceability and custody.

**POLICY AND REGULATORY FRAMEWORKS NEEDED FOR SUSTAINABLE CO₂ UTILIZATION**

Realizing the climate and market benefits of CO₂ utilization technology and infrastructure will require fundamental changes to current policy, economic, and regulatory structures. The committee examined potential demand- and supply-side tools to increase the competitiveness of CO₂ utilization, such as procurement and deployment support, as well as noneconomic tools, such as common carrier status (i.e., open for use by all parties for a fee), clarity of standards and codes, and workforce development. It also evaluated business development mechanisms, especially for small businesses. The report emphasizes that a better understanding and intentional focus on environmental justice is needed.

The report recommends that the General Services Administration and DOE create growth opportunities for small businesses engaged in CO₂ utilization and that DOE collaborate with community-centered organizations to assess the impacts of CO₂ utilization projects. It suggests that non-governmental organizations and research entities identify gaps in societal acceptance of these projects and that DOE prioritize projects with strong community engagement throughout project timelines. Additionally, the report advises incorporating justice principles in the planning and design of new CO₂ utilization infrastructure to benefit, rather than harm, surrounding communities.

**CO₂ UTILIZATION INFRASTRUCTURE**

CO₂ utilization requires extensive infrastructure for CO₂ capture, purification, transportation, and conversion, as well as for enabling or related systems to provide hydrogen, electricity, water, short-term CO₂ storage, and product transport. Development of such infrastructure is under way, supported by both the private sector and government, but the planned capacity remains one or more orders of magnitude below projected requirements to achieve net zero. This report identifies opportunities and challenges for CO₂ utilization infrastructure planning at the regional or national scale.

A regional or national CO₂ pipeline system would enable low-cost transportation of large volumes of CO₂, incentivizing carbon management technologies and infrastructure, and promoting CO₂ utilization, especially if policies to support dual use of pipelines for utilization and storage are enacted. Multi-modal transport may be required to move CO₂, enabling inputs like H₂ and electricity, and products to or from a CO₂ utilization site. The committee recommends the development of a multi-objective optimization tool for infrastructure design and placement that accounts for costs, safety, and environmental impacts.

Addressing potential environmental and health risks associated with CO₂ utilization infrastructure will require additional research, as well as careful planning and public consultation. In particular, the report recommends that the Pipeline and Hazardous Materials Safety Administration perform research and testing to improve CO₂ pipeline safety.

**RESEARCH AGENDA FOR CARBON UTILIZATION**

The report presents a research agenda encompassing four pathways toward CO₂ utilization research, development, and demonstration (RD&D): (1) mineralization of CO₂ into inorganic carbonates, (2) conversion of CO₂ into elemental carbon materials, and (3) chemical and (4) biological pathways for CO₂ conversion into organic chemicals and fuels (see Figures 2 and 3).
The report also presents RD&D needs for coal waste utilization, both the use of carbon within coal waste to produce long-lived products and the extraction of rare earth elements, critical minerals, and other energy-relevant minerals.

**Mineralization of CO$_2$ to Inorganic Carbonates**
Carbon mineralization forms inorganic carbonates, which are materials with durable carbon storage potential. To bring carbon mineralization technologies to commercial readiness, the report recommends mapping alkaline resources, improving mineralization technology efficiency, optimizing infrastructure, understanding ocean- and land-based environmental impacts, developing protocols and testing platforms, advancing RD&D on electrochemically driven mineralization, integrating mineralization with metal recovery, and developing standards for CO$_2$-based construction materials.

**Chemical Conversion of CO$_2$ to Elemental Carbon Materials**
Elemental carbon materials are zero-, one-, two-, or three-dimensional structures composed of carbon alone, and include products like carbon dots, carbon nanotubes and wires, graphene and carbon nanolayers, and bulk carbon fibers, graphite, and carbon–carbon composites, respectively. Their structures yield properties like high conductivity and mechanical strength and can be used in a multitude of applications, including construction, transportation, microelectronics, and energy storage. CO$_2$ can be reduced to elemental carbon materials through thermochemical, electrochemical, photochemical, or plasmachemical reaction pathways. The report recommends developing foundational knowledge on the four reaction pathways, discovering and developing catalysts and low-energy processes that are selective for diverse elemental carbon materials, and developing tandem processes and integrated CO$_2$ capture and conversion for elemental carbon material production.

**Chemical Conversion of CO$_2$ to Fuels, Chemicals, and Polymers**
Chemical conversion of CO$_2$ can produce hydrocarbons and other organic products, including fuels, chemicals and chemical intermediates, and polymers. To enable scale up of chemical CO$_2$ conversion, the report recommends RD&D on catalytic selectivity, stability, and alternative heating methods for thermochemical processes; development of selective, active, and stable electrocatalysts and efficient membrane materials for electrochemical processes; fundamental understanding,
materials discovery, and reactor improvements for photo(electro)chemical and plasmachemical processes; and research on tandem catalysis, integrated CO₂ capture and utilization, and rapid, stereoselective polymerization with diverse monomers.

**Biological Conversion of CO₂ to Fuels, Chemicals, and Polymers**

Biological systems can convert CO₂ to fuels, chemicals, and polymers via photosynthetic, non-photosynthetic, and hybrid (e.g., electric–bio and cell–free biochemical) pathways. This report considered the direct conversion of CO₂ through autotrophic microorganisms, acetogenic microbes, or hybrid systems. Research needs for biological CO₂ conversion include improving metabolic design principles and genetic manipulation tools, integrating carbon capture with bioconversion, enhancing enzyme stability and efficiency, optimizing reactors, improving scalability of electrolytic technology, and developing biocompatible electrocatalysts and microorganism systems for efficient chemical production.

**Coal Waste Utilization**

Although production and consumption of coal have fallen substantially in the United States over the past several decades, there remains an immense amount of coal waste materials, including acid mine drainage, coal impoundment wastes, and coal combustion residuals. Coal wastes are both an environmental contaminant in need of remediation and a material containing potentially useful components. Coal waste can provide a source of carbon for long-lived, solid carbon products and contains a wide variety of critical minerals and rare earth elements with applications in clean energy technologies.

The report identified RD&D needs for coal waste utilization including mapping coal waste resources; improving separation methods and transformations to solid carbon products; conducting assessments of product performance, environmental impacts, and safety; and creating novel extraction and separation techniques for critical materials like lithium, nickel, cobalt, rare earth elements, and other energy–relevant minerals.

![Figure 3](https://example.com/figure3.png)

**FIGURE 3** Research themes for CO₂ and coal waste utilization RD&D needs, categorized by reaction- and systems-level understanding, as well as demonstration and deployment needs (columns).

**NOTE:** Icons in black (see legend lower right) indicate process(es)—mineralization, chemical conversion, biological conversion, and/or coal waste utilization—with RD&D needs in each theme.

**SOURCE:** Icons from the Noun Project, https://thenounproject.com. CC BY 3.0.
FOR MORE INFORMATION

This Consensus Study Report Highlights was prepared by the Board on Energy and Environmental Systems based on the Consensus Study Report Carbon Utilization Infrastructure, Markets, and Research and Development: A Final Report (2024).

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