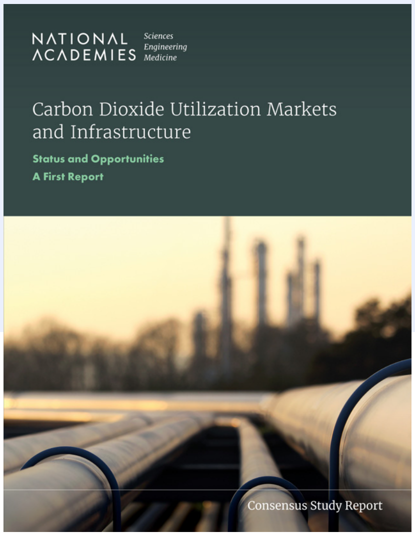
NATIONAL ACADEMIES *Sciences Engineering Medicine*

Consensus Study Report
Highlights

Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report



In the face of year-round wildfires, megadroughts, and massive flooding, exacerbated by the burning of fossil carbon, the global need to stop emitting gases to the atmosphere that warm the Earth is evident. Carbon dioxide (CO_2) utilization can play an important role in a net-zero greenhouse gas emissions future, taking CO_2 from the atmosphere, water, or waste gas streams and chemically transforming it into marketable carbon-based products.

In the Energy Act of 2020, Congress mandated that the U.S. Department of Energy (DOE) contract with the National Academies of Sciences, Engineering, and Medicine to analyze opportunities for and challenges to advancing CO_2 utilization technologies, developing the associated infrastructure, and establishing markets for CO_2-derived products, considering a future in which carbon waste streams participate in a circular carbon economy.

For this first report, the committee was tasked with assessing the state of the infrastructure for CO_2 transportation, use, and storage, and with identifying key opportunities to improve and expand on that infrastructure to enable future CO_2 utilization development. A second report, expected in 2024, will consider potential markets and commercialization opportunities for both CO_2 and coal waste–derived products; evaluate research, development, and demonstration needs for carbon utilization technologies; and examine economic, environmental, and climate impacts of CO_2 utilization infrastructure.

TRANSFORMING CO_2 INTO PRODUCTS

Carbon is the central element of many manufactured products, notably plastics, fuels, and commodity chemicals; however, current production relies predominantly on fossil sources of carbon and carbon-emitting inputs such as fossil fuel–powered heat, electricity, and transportation. In a future net-zero carbon economy, carbon-containing products will have to be produced sustainably, with no net emissions of CO_2 to the atmosphere.

This report examines CO_2 utilization as a sustainable approach[1] to manufacturing carbon-based products from CO_2 rather than fossil carbon. Products made on an industrial scale from CO_2 today include urea, organic carbonates, methanol, salicylic acid, and CO_2-cured concrete, though in general, these products are not net-zero on a lifecycle basis. Pilot-scale efforts are under way to generate additional commercial products but are limited by the lack of incentives to produce low-carbon products, the inherently higher cost and energy requirements to use CO_2 in place of readily available fossil carbon for hydrocarbon-based products, and the need for inputs of clean hydrogen, electricity, and heat.

Chemical transformations of CO_2 can result in both long- and short-lived products, which the report terms Track 1 and Track 2, respectively (see Figure 1). Long-lived products, such as concrete and aggregates, have lifetimes greater than 100 years. Their ability to durably store carbon means that these materials can be sustainably produced with fossil, atmospheric, or biogenic CO_2. Short-lived products, such as fuels, chemical intermediates, and many plastics, have lifetimes less than 100 years and remove CO_2 from the atmosphere only temporarily, because they decompose relatively quickly to CO_2 again at their end of life. Thus, short-lived products will have to be produced using atmospheric or biogenic sources of CO_2 such that their embodied carbon participates in a circular flow into and out of the atmosphere. Understanding the emissions impact of

[1] CO_2 utilization is the chemical transformation of CO_2 into a useful product. Other potential sources of sustainable carbon include biomass and carbon waste products.

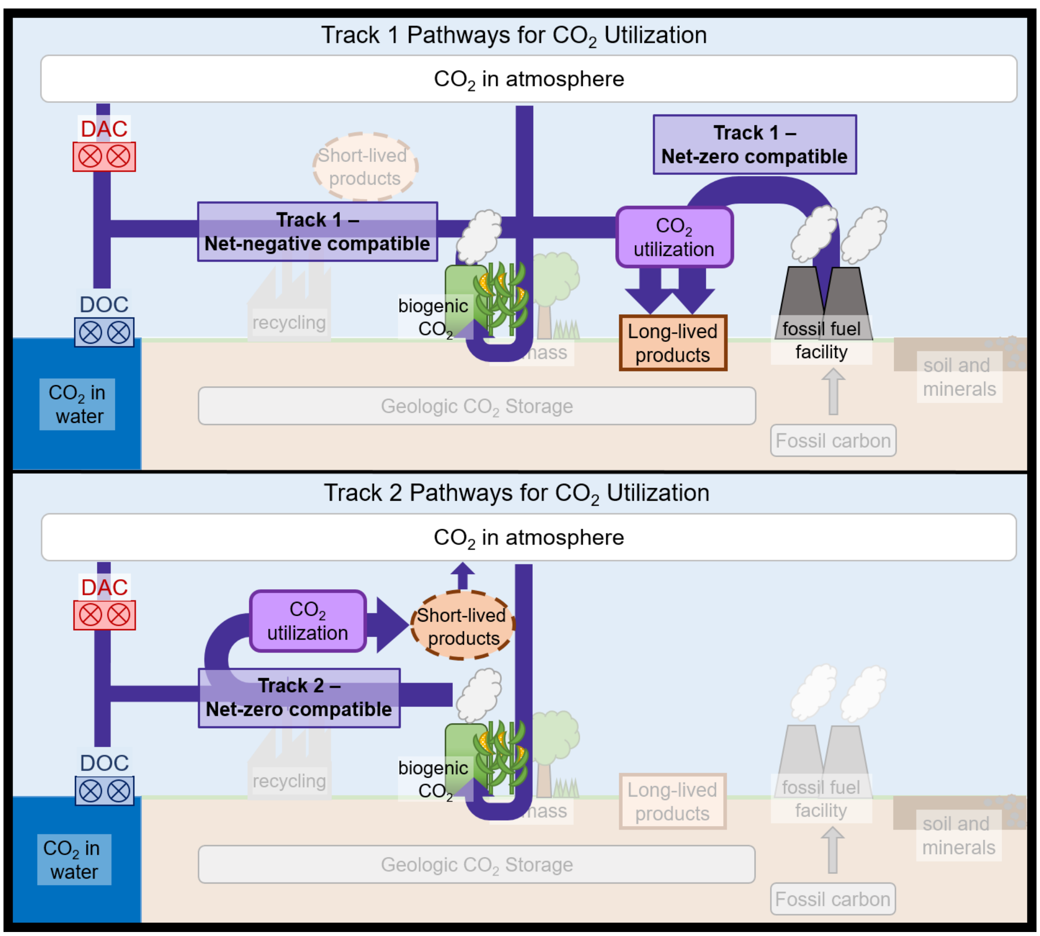


FIGURE 1 Schematic of Track 1 and Track 2 pathways for CO_2 utilization, resulting in long- and short-lived carbon-based products, respectively. Track 1 pathways enable carbon sequestration in products, and Track 2 pathways enable circular carbon flows.

CO_2 utilization products requires a full estimate of their lifecycle impacts, including all processes, feedstocks, and wastes. The report therefore recommends that DOE **build on ongoing efforts to harmonize and standardize lifecycle analysis for carbon capture, utilization, and storage projects.**

IDENTIFYING INFRASTRUCTURE OPPORTUNITIES

While CO_2 utilization may be an important part of a future net-zero emissions world, there are many challenges to its use at large scale today. The report finds limited opportunities to leverage existing CO_2 capture and transport infrastructure for future sustainable CO_2 utilization processes. However, significant CO_2 capture and transportation infrastructure for sequestration may be developed over the next decade, and such infrastructure also may serve utilization projects, depending on the type, purity, and location of the CO_2 source; utilization product; and other energy and feedstock requirements.

Once captured and purified, CO_2 can be transported by pipeline, rail, truck, ship, barge, or some combination of these. When accessible, CO_2 pipelines are the most cost-effective transportation option, as they can move the largest volumes of CO_2 and therefore benefit from economies of scale. There is a considerable level of understanding regarding the risks associated with pipeline transportation of CO_2 but limited practical experience. Given the unique thermophysical properties of CO_2, special consideration should be given to selecting pipeline materials with appropriate mechanical properties to resist ductile and brittle propagating fractures. The committee recommends **developing rigorous fluid-structure models validated by large-scale field tests to better understand the complex processes leading to propagating brittle fractures in CO_2 pipelines.**

Some CO_2 utilization processes, such as concrete production and biological CO_2 conversion to alcohols and hydrocarbons, are well suited for small-scale, distributed operations, with co-located CO_2 capture and conversion followed by the transport of the CO_2-derived product. Others, such as chemical synthesis, are better suited to large-scale, centralized production, and thus to using aggregated sources of CO_2. The economics of infrastructure placement will be dictated in part by the ease of transporting CO_2, hydrogen, electricity, and other inputs, versus the ease of transporting the carbon-based products. The report recommends that **DOE work with national laboratories, university researchers, and industry partners to conduct detailed studies that identify the most promising opportunities for CO_2 utilization infrastructure based on technological, environmental, economic, and societal factors.**

ENABLING INFRASTRUCTURE FOR CO_2 UTILIZATION

Infrastructure development decisions for CO_2 utilization depend not only on CO_2 capture, purification, and transportation requirements but also on the availability of infrastructure for inputs such as electricity, hydrogen, and water and for the CO_2-derived product. CO_2 utilization processes to produce fuels, commodity chemicals, and other hydrocarbon-based chemicals require more external energy and often more hydrogen inputs than generating the same products from fossil carbon sources.

In the long term, CO_2 utilization will fit into a larger system powered by net-zero carbon emissions energy, including decarbonized electric power for transportation, buildings, and other industrial activities. As the nation transitions to this net-zero future, significant increases in demand for zero carbon emissions electricity, including that required for CO_2 utilization, are expected and will influence transmission and distribution planning and load management. The committee recommends that **national policy should prioritize carbon emissions free energy as inputs to all aspects of a net-zero carbon emissions system, including growth in emissions-free energy to accommodate CO_2 utilization.** Additionally, given the complexities of transporting and storing the clean hydrogen needed to convert CO_2 to hydrocarbon products, the committee recommends that **project designers co-locate facilities for hydrogen production and CO_2 utilization when feasible.**

POLICY, REGULATORY, AND SOCIETAL CONSIDERATIONS

Policy, regulatory, and societal factors also play a significant role in enabling and expanding beneficial CO_2 utilization.

Efficient policies that disincentivize greenhouse gas emissions from all sources, such as carbon trading or taxes, will help create a level playing field for all industries, including CO_2 utilization. Certain incentives can enable knowledge creation and diffusion through research, development, and deployment of emerging technologies in nascent industries like CO_2 utilization. The report recommends **policymakers should take care that the policy regime does not create perverse incentives or excessively difficult regulatory environments.**

Navigating the regulatory framework and permitting processes are crucial for a project to move forward. The report recommends that **a single entity be appointed to coordinate the permitting and authorization process for CO_2 transportation and utilization projects, guiding developers through the process of dealing with the multiple states and localities to obtain the required permits.**

Meaningful community engagement is essential to ensure that the benefits and risks of CO_2 utilization projects are felt equitably as these technologies are implemented for a more sustainable future. Early and ongoing community engagement is important for a project's ability to move forward with community support, and without it projects are likely to fail, encounter delays, or require expensive reworking. The report recommends that **regulatory authorities account for distributional impacts of CO_2 utilization projects through a process that addresses equity for disadvantaged groups, engages impacted communities early and throughout project planning, and allows for the alteration of the project design and implementation.**

INVESTING IN NEAR-TERM OPPORTUNITIES

The report identified two priority near-term opportunities for CO_2 utilization infrastructure investment: (1) combining CO_2 off-gas from bioethanol plants with clean hydrogen to make synthetic aviation fuel and (2) mineralization using fossil or non-fossil CO_2 sources to generate mineral carbonates for construction materials, including concrete.

In both cases, locating the CO_2 utilization facilities near enabling infrastructure such as clean electricity or clean hydrogen could prove cost effective. Additionally, recognizing that infrastructure to capture and transport CO_2 for storage will likely be developed over the next decade, the report recommends **favorable consideration of flexible infrastructure that can integrate long-term CO_2 utilization needs.** Specifically, the committee recommends **DOE consider co-location of at least one each of the hydrogen and direct air capture hubs authorized in the Bipartisan Infrastructure Law of 2021.**

Moving forward, the best deployment and investment opportunities for CO_2 utilization should be identified using techno-economic, lifecycle, and integrated systems analyses, while considering relevant regulatory and policy frameworks and factors that may influence societal acceptance. All infrastructure siting and development decisions should include best practices for substantive community engagement to ensure equitable outcomes.

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FOR MORE INFORMATION

This Consensus Study Report Highlights was prepared by the National Academies' Board on Energy and Environmental Systems based on the report *Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report* (2022).

This study was sponsored by the U.S. Department of Energy. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of the sponsors.

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