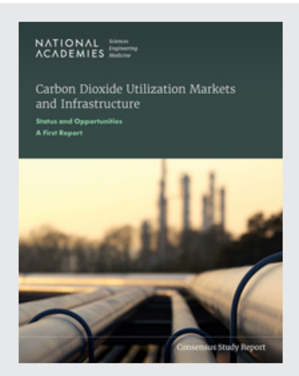

Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities: A First Report (2022)

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6 Priority Infrastructure Opportunities for CO_2 Utilization

Building on the analyses of carbon dioxide (CO_2)-derived products, infrastructure requirements, and policy, regulatory, and societal considerations discussed in Chapters 2 through 5, this chapter presents a summary of priority infrastructure opportunities to enable CO_2 utilization. The chapter begins by describing options for CO_2 utilization infrastructure funding based on current policy and regulatory regimes, and considering successful examples in related industries. It then examines near-term opportunities for CO_2 utilization infrastructure investments, as well as near-term actions to enable longer-term deployment options. A primary consideration for these opportunities is the ability of CO_2 utilization to participate in a future circular carbon economy, which depends on the type of CO_2 source, CO_2-derived product lifetime, and life cycle emissions of other process inputs. The chapter ends with findings and recommendations focused on implementing these identified opportunities.

6.1 INFRASTRUCTURE FUNDING AND INVESTMENTS

When thinking about infrastructure funding, the first consideration is to understand what is allowed or incentivized by policy or law, and then to understand the economic implications of different options. Minimization of cost per unit mass CO_2 mitigated is an important metric of success to motivate CO_2 capture and utilization development broadly and marketable products specifically. Credible, product-level demonstration of cost minimization using captured CO_2 has proven the basis for demand for such a product in a carbon-constrained world. Provided with this framing, the next considerations at a most basic level are the total unit cost to fabricate a product utilizing captured CO_2 and obtaining sufficient revenue to cover such costs (and a fair return).

The most resource-efficient approach to building infrastructure for CCU is to consider the entire value chain at the same time, given the need to align many of the individual links along the chain. A successful example of this approach is the Alberta Carbon Trunk Line (ACTL) located in Canada, which mapped out CO_2 supply, transportation, and disposition as part of an integrated project (Alberta Government, 2020). The ACTL links together capture from industrial sources in one part of the province, conveyed along an (initially oversized) pipeline to geologic sequestration and enhanced oil recovery sites in another. One impetus for the project, among others, was the downstream demand for the CO_2 and the revenue that it would generate. This framing is useful when considering the context for CCU.

To assess the entire value chain of carbon utilization projects, one would begin by estimating revenue from demand for the products created by CO_2 conversion and the expected selling price for such products. Total input costs include the cost of capture and transportation of CO_2 and any other costs associated with enabling infrastructure. Project finance will be enabled when revenues are sufficiently large, consistent, and of long enough duration to pay down all capital and provide a fair return on top of the cost of ongoing operations. Incentives and contracting tools can serve as remedies where revenues fall short of these dimensions, either due to initial weak market demand or revenues insufficient to make the project of rated investment quality. For example, the 45Q or 45V tax credits would lower the input costs of CO_2 and hydrogen, respectively, thereby increasing the possibility of revenue sufficiency. Moreover, a procurement mechanism using a take-or-pay contract mechanism set at a sufficient price would guarantee the revenue irrespective of market fluctuations, thereby lowering the cost of capital associated with the project, since the probability of capital repayment is enhanced. Liquefied natural gas terminal project development uses this type of contracting mechanism. In either case—reducing input costs through tax incentives or other support mechanisms or enhancing revenue through procurement mechanisms or contracting terms that reduce volatility and/or offset required sales premiums—while public policy may provide the incentives, it is fully within the realm of the private sector to build, own, and operate the conversion facility. The same is true for a capture facility, provided there is sufficient infrastructure to move the CO_2 from capture to the point of utilization.

As articulated in Section 4.3, the most cost-effective transportation option is via pipeline, depending on the distance and volume of CO_2 to be moved. Setting aside the need to obtain right-of-way, easement, and other relevant permits, developing a pipeline is predicated on securing adequate commodity flow via throughput agreements. However, there is a trade-off between constructing a pipeline that can handle immediate volumetric needs versus a larger pipeline that is otherwise overbuilt, given current market volumes compared to potential future demands. For cases that can credibly demonstrate that future demand will exceed current transportation needs, public-sector support of pipeline buildout may be advantageous. Public funding would remove the volume and timing risk associated with uncertain market developments and serve as an important catalyst for driving supply of and demand for captured CO_2. Although within the scope of the electricity industry, the Texas Competitive Renewable Energy Zone (CREZ) is a good example of public-sector vision, planning, and development of infrastructure at a scale meant to support an expanding market (Cohn and Jankovska, 2020). In this case, the Public Utility Commission of Texas planned and brokered the financing for the development of CREZ, where transmission developers earned return through payments from electricity ratepayers. In the case of CO_2 pipelines, similar to what occurred in the ACTL example, the public entity can finance the project development and retain the right to sell off the asset to a private entity once a specified portion of the volumetric capacity has been attained. As discussed in Section 5.2.4, Section 40304 of the Infrastructure Investment and Jobs Act (IIJA) authorizes grants and loans for building CO_2 common carrier infrastructure through the Carbon Dioxide Transportation Infrastructure Finance and Innovation Program. The loans aim to help eligible projects attract investment and begin earlier than would otherwise be possible, while the grants target the costs of constructing a facility that can accommodate future growth in demand for CO_2 transport. The IIJA calls for the Secretary of Energy to prioritize projects that are large-capacity, common-carrier infrastructure, have demonstrated demand for infrastructure from CO_2 capture facilities, represent geographic diversity, and site infrastructure within existing corridors to minimize environmental disturbance and other siting concerns (IIJA, 2021, § 40305).

Of course, where practical, the capture and production facilities could be both “behind the fence,” such that any kind of CO_2 transportation could proceed over short distances and minimize disturbances to surrounding lands. In this case, need for any direct public investment is unlikely; however, this kind of point-to-point pipeline may be limited in volume and perhaps may be less cost-efficient in the event that there needs to be an expansion. An example of this kind of layout may be that of a fertilizer production facility, which operates a steam methane reforming process to make hydrogen and captures some of the emitted CO_2 for use in the production of urea. Two obvious opportunities to deploy CO_2 utilization facilities are within the hydrogen and direct air capture (DAC) hubs designated to receive significant funding via appropriations associated with the IIJA (§§ 40308, 40314). Another opportunity stemming from the IIJA is DOE’s Carbon Dioxide Transport/Front-End Engineering Design Program, which aims to “design regional carbon dioxide pipeline systems to safely transport CO_2 from key sources to centralized locations” and for which DOE issued a notice of intent for funding in July 2022 (DOE, 2022).

Finally, in fashion similar to pipeline transportation, geologic sequestration sites benefit from economies of scale, where it would be cost-efficient to construct a large repository (and necessary monitoring, reporting, and verification infrastructure) that could receive injections from multiple sources. Therefore, it would be beneficial for a public entity to lead in sponsoring site selection, characterization, and construction, in anticipation of greater volumes of CO_2 needing sequestration ultimately materializing. IIJA § 40305 includes authorization and funding that expands an existing DOE program for carbon storage validation and testing to include commercialization and associated CO_2 transport infrastructure. The commercialization program intends to facilitate new or expanded CCS and associated CO_2 transport infrastructure, including funding for feasibility, site characterization, permitting, and construction, giving priority to those storing substantial amounts CO_2, or those collecting from multiple capture facilities (IIJA, 2021, § 40305). Depending on demand projections, the revenue model that supports the project finance could be based on either a capacity payment or a tolling/tipping fee payment arrangement. The latter of these two approaches is similar to the municipal waste model; however, the waste model is based on relatively stable usage rates (i.e., number of trucks entering and tipping waste to the landfill per unit of time).

6.2 NEAR-TERM VERSUS LONG-TERM INFRASTRUCTURE STRATEGIES

Expanding infrastructure to meet climate goals and carbon management objectives will be a major challenge requiring deliberate, long-term planning. Given the smaller potential scale of CO_2 utilization relative to other CO_2 emissions reduction and carbon management opportunities, it will not be a driving factor in large infrastructure development, but rather additive to ongoing infrastructure projects that capture CO_2. In the near term, opportunities for investable projects in CO_2 utilization that align with a future circular carbon economy are limited (see, e.g., Bazzanella and Ausfelder, 2017; Centi et al., 2020; Gabrielli et al., 2020; Hepburn et al., 2019; Soler, 2020). Sources of CO_2 are likely to change significantly over the next 30 years, with many point sources of CO_2, such as fossil fueled power plants, being phased out, and new sources, such as DAC, developing. This will complicate investments that require 20+ year facility lifetimes to yield returns. Currently, the cost of manufacturing hydrocarbon products from CO_2, hydrogen, and electricity exceeds that of existing manufacturing processes significantly due to the high hydrogen consumption required and capital intensity of conversion steps (Frontier Economics, 2018; Huang et al., 2021). Costs can be even higher if net-zero emissions CO_2 utilization is attempted such as through use of clean hydrogen, clean electricity, and CO_2 from DAC, and premiums for "green" products or CO_2 abatement costs are not universal. For these reasons, opportunities for CO_2 utilization need to be considered on a project-by-project basis, and addition of any necessary infrastructure considered as part of the project cost.

Two product pathways are prime targets for early CO_2 utilization infrastructure investments. First is use of biogenic CO_2 for hydrocarbon production, particularly sustainable aviation fuels. CO_2 sourced from bioethanol plants is highly concentrated and biogenic, with a low cost of capture. The scale is small per bioethanol plant, but, when aggregated via pipelines, could produce a sustainable CO_2 source at a scale that can allow production of synthetic aviation fuel or sustainable chemicals when combined with clean hydrogen. Synthetic aviation fuel, a prime product target, can be transported to market via truck or rail, given the scale of manufacture, and may not require a dedicated liquid pipeline. If synthetic natural gas is the CO_2 utilization product, then existing natural gas pipelines can be used for product transportation. The current market for bioethanol production is blending with gasoline for liquid transportation fuels. In a decarbonized future, this market my decrease substantially; however, bioethanol's use may pivot to other needs for sustainable substitutes for fossil carbon, such as for heavy-duty transportation, as a seasonal store of energy, or as a feedstock for ethylene used in chemical synthesis, potentially maintaining these sources of high-quality CO_2.

A second prime CO_2 utilization opportunity is generating mineral products for construction. Fossil CO_2 point sources can be used in this case, since the mineral products entail long-term sequestration, often into building products. The other required feedstock is mined minerals, which can be high cost if transported over long distances, such that co- or near-location of mining operations with CO_2 capture options is a key consideration. Otherwise, CO_2 pipelines would be required to couple mineral and CO_2 feeds, or mineral transport will be needed (trucks or rail). Similarly, the product (e.g., aggregate for concrete) is a solid and requires transport by truck or rail to the end-use location, so location near demand centers such as urban areas is preferred.

For both of these near-term use cases, infrastructure needs and siting must be considered on a project or hub basis with input and buy-in from local communities. There is no one-size-fits-all infrastructure model. Nonetheless, locating enabling infrastructure such as clean hydrogen and clean electricity in the proximity of both fossil-derived (i.e., unsustainable) and DAC, DOC and/or biogenic (i.e., sustainable) CO_2 sources could prove cost-effective, as it would enable the manufacturing of sustainable products in both the near and long term.

In addition to the near-term opportunities described above, additional steps may be taken to position CO_2 utilization for future viability. For example, focusing in the near term on decarbonizing the grid and scaling up clean hydrogen production will benefit CO_2 utilization in the long term. Concurrently, continued research and development to reduce the costs and improve the energy and material efficiency of CO_2 capture and conversion technologies, as well as to demonstrate scale-up and establish the commercial viability of new products developed, is needed to position CO_2 utilization for successful deployment as a sustainable option for mitigating climate change. Furthermore, although initial markets for CO_2-derived products may be small, they provide an opportunity for learning on regulatory and institutional issues related to the development and deployment of new products and processes. Net CO_2 emissions across the energy system can be reduced via combinations of learning by doing, reduced carbon intensity of energy and supply chains, and public and commercial acceptance of new technologies and products. The emerging potential of CO_2 utilization needs to be considered in siting of pipelines and infrastructure for carbon capture and storage, renewable energy, and hydrogen production. Also important to consider is the overlap of existing industrial chemicals and materials manufacturing facilities and workforce skills, which in many cases could be repurposed for CO_2 utilization deployments. Identification and support of commercial hubs to enable CO_2 utilization experimentation, development, and de-risking will be critical for successful leveraging of CO_2 utilization opportunities.

In the longer term, DAC or biogenic CO_2, biomass carbon, and chemical circularity (recycling), are anticipated to be the primary sources of carbon for manufacturing. Of these, only biomass carbon and biogenic CO_2 sources (i.e., bioethanol plants) exist today at commercial scale. Planning for future deployment of CO_2 utilization processes requires considering a variety of infrastructure options and requirements. For example, siting for DAC is more likely to need to incorporate infrastructure to transport the CO_2-derived product rather than the CO_2. Optimization of enabling infrastructure is a function of the scale of the manufacturing plant, and there are requirements for constant operation and capacity factor in meeting target economics. Given the large amounts of electricity and/or hydrogen required to upgrade CO_2 to hydrocarbon products, co-locating hydrogen generation with the manufacturing plant utilizing CO_2 as feedstock may be desirable. These decisions will have to be made strategically as integrated hubs are designed, and by following best practices for community engagement as discussed in Chapter 5. In doing so, it must be recognized that the use of CO_2 as a feedstock for future synthetic fuels or chemicals is not a given; bio-based feedstocks and/or chemical recycling may compete with CO_2 capture and utilization pathways.

Specific end uses and projects for CO_2 utilization may be unsustainable relative to better use of renewable or clean electricity, or alternative means for providing energy services to society. CO_2 captured from point sources requires more energy and/or hydrogen to reform to fuels than replacement of those fuels by direct electrification (via clean energy) or hydrogen, where the latter are "zero emission"[24] and do not contribute to local air pollution and equity issues in human health (de Kleijne et al., 2022; Mac Dowell et al., 2017; Serdoner and Whiriskey, 2017; Soler, 2020; Yugo and Soler, 2019). Reuse of fossil CO_2 to make fuels or other short-lived chemical products, which re-releases CO_2 upon combustion, degradation, or incineration,[25] at best results in a 50 percent reduction in CO_2 emissions per unit of energy service for the use of the fuel originally and again with one-time recycling. In reality, the net emissions reduction is much less (20 percent) due to conversion inefficiencies.[26] The GHG reduction benefit can be improved by using biogenic CO_2 from bioethanol fermentation or CO_2 from DAC or DOC as the carbon

[24] Hydrogen combustion can lead to criteria pollutant thermal NO_x if not done in a judicious manner.

[25] Hydrocarbon products derived from CO_2 have an average effective sequestration of less than 100 years despite the fact that they do not chemically degrade for hundreds or even thousands of years. This is because product lives are shorter than 100 years, and a substantial portion of end-of-life waste is incinerated—20–80 percent today, and likely a higher percentage in the future given space constraints, environmental runoff issues, and a desire for energy recovery.

[26] The combustion of a hydrocarbon fuel yields the lower heating value of energy release and the associated CO_2 emissions. If renewable energy is used to capture the emitted CO_2 and convert it back into a hydrocarbon fuel, and then the fuel is combusted again, the same net emissions result but with twice the energy output. However, that 50 percent reduction in CO_2 footprint assumes that capture and conversion are 100 percent efficient, so in reality, the CO_2 footprint will be reduced by less than 50 percent compared to the "no recycling" case.

feedstock for synthesizing fuels or short-lived chemicals. However, particularly for the case of fuels, if used for local transport in urban areas, they still create the same air pollution inequities that arise from use of fossil fuels today. Synthetic aviation fuel is one sustainable and equitable option for biogenic CO_2 use, given that aviation's primary deployment is distant from population. Chemical and fuel production pathways must compete with the use of bio-based feedstocks (e.g., biomass) to make chemicals for a future circular chemical economy, where the added energy and unit costs may be lower (Lange, 2021). For these reasons, a full life cycle assessment of any proposed CO_2 utilization project is critical to ensure effective use of capital and renewable or clean energy resources for addressing climate change and avoiding propagation of air pollution stresses on communities.

6.3 FINDINGS AND RECOMMENDATIONS ON PRIORITY INFRASTRUCTURE OPPORTUNITIES FOR CO_2 UTILIZATION

Finding 6.1 Near-Term Opportunities for CO_2 Utilization. Options for near-term deployment of CO_2 utilization exist and can be identified via a combination of techno-economic and life cycle analysis. One example is low-cost capture of highly concentrated biogenic CO_2 fermentation exhaust gas from ethanol production, which, when combined with low- or zero-carbon-emission hydrogen, can produce sustainable chemicals or fuels for heavy duty transportation such as shipping and aviation. Another example is the exothermic reaction of minerals with CO_2 to form mineral carbonates for the building/construction industry. However, it is also possible to utilize CO_2 in costly and unsustainable ways that will result in increased fossil CO_2 emissions, environmental damage, and societal injustice relative to competing options, if the appropriate systems-level analyses are not considered.

> **Recommendation 6.1.** The U.S. Department of Energy should support its national laboratories, academia, and industry to leverage their competencies in techno-economic and life cycle analyses, as well as integrated systems analysis, to identify the best deployment and investment opportunities from the myriad of utilization options, avoiding those that are technically feasible but not sustainable or economically attractive. These assessments should consider relevant regulatory and policy frameworks and environmental justice impacts, as well as factors that may influence societal acceptance of the technologies.

Finding 6.2 Flexible Infrastructure for CO_2 Capture, Utilization, and Storage. Carbon dioxide capture and transportation infrastructure for sequestration also may serve utilization projects, depending on the type, purity, and location of the CO_2 source; the utilization product; and the other energy and feedstock requirements. For example, fossil CO_2 sources are only sustainable in a net-zero future for utilization into durable products, for example, concrete, aggregates, and carbon fiber, unless utilization into a short-lived product is paired with a separate, verifiable negative-emissions process (e.g., direct air capture plus storage). In general, the ability to divert some of the CO_2 destined for storage to a utilization process provides an economic driver for infrastructure development, exploiting economies of scale where possible and economies of numbers where needed, and may in some cases improve public perception of carbon management practices.

> **Recommendation 6.2.** The U.S. Department of Energy (DOE) should favorably consider the ability to connect to future CO_2 utilization processes and technologies when reviewing CO_2 capture, transport, and storage demonstration projects. Designing such flexibility into the initial infrastructure development could provide long-term benefits, since CO_2 utilization likely will be required to produce carbon-based products in a net-zero emissions future. DOE should document and share learning from such demonstrations with CO_2 utilization and carbon capture and storage project developers to facilitate future CO_2 utilization opportunities.

Finding 6.3 Industrial Clusters for CO_2 Capture, Utilization, and Storage. Industrial clusters that co-locate capture, utilization, and storage (CCUS) of CO_2 provide the capability for managing large volumes of CO_2 without the need for extensive pipeline networks and have the flexibility to incorporate different utilization processes if market trends change or new technologies are developed over time. Additionally, locating such CCUS clusters in regions that already have a large industrial presence would maintain jobs, knowledge, and workforce, allowing know-how to be recycled into a new, related industry. However, the CO_2 sources in *current* industrial clusters are primarily fossil-carbon based, which is not desirable or sustainable for all utilization applications.

> **Recommendation 6.3.** As part of its industrial decarbonization efforts, the U.S. Department of Energy should provide technical and financial support for the development of industrial clusters for carbon capture, utilization, and storage (CCUS) that capture CO_2 in large amounts and include the necessary infrastructure for both utilization and storage of CO_2. CCUS cluster development should involve best practices for community engagement and allow for flexibility in utilization scenarios over the long term, for example, by incorporating hydrogen production, chemical and fuel manufacturing, and low-carbon electricity generation. To achieve sustainability goals, these clusters should route the majority of CO_2 captured from fossil sources to long-term geologic storage or production of durable CO_2 products (e.g., mineralization products, carbon fiber, and other solid carbon materials). Infrastructure for producing nondurable CO_2-derived products (e.g., chemicals and fuels) should incorporate CO_2 from direct air capture or biogenic sources where possible, or be paired with verifiable negative-emissions projects to offset fossil CO_2 use.

> **Recommendation 6.4.** When evaluating proposals for the hydrogen and direct air capture hubs authorized in the Infrastructure Investment and Jobs Act, the U.S. Department of Energy should consider rewarding through their selection process projects that co-locate hub types to take advantage of shared infrastructure needs and facilitate CO_2 utilization applications that require hydrogen.

Finding 6.4 Near-Term Opportunities for Maximum Climate Benefit via Strategic Co-location to Minimize Transport. Strategic co-location that considers the features of CO_2 sources and utilization products can maximize climate benefits and minimize transportation requirements for near-term CO_2 utilization opportunities. In particular, CO_2 utilization facilities making durable, solid carbon products co-located with fossil, biogenic, or direct air capture CO_2 sources near urban demand centers could enable net-zero or net-negative manufacturing of building materials like cement and aggregates while minimizing transport of heavy, high-volume products. Likewise, co-location of direct air capture or biogenic CO_2 sources with utilization facilities making liquid products like sustainable aviation fuels near existing infrastructure for enabling inputs and product transport could produce net-zero emissions fuels while minimizing transport of the CO_2 feedstock.

> **Recommendation 6.5.** The U.S. Department of Energy should work with its 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. These studies should examine opportunities to (1) co-locate sources of CO_2, utilization facilities, and product users to minimize transport; and (2) site utilization facilities in proximity to existing transport and delivery infrastructure. The studies should determine the value of co-locating specific CO_2 utilization activities with specific source types of CO_2, as well as the value of minimizing transport, identifying those that maximize climate benefits, either net-negative or net-zero.

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