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Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities

A First Report

Committee Chair: Emily Carter (NAS/NAE), Princeton University

Study Director: Elizabeth (Beth) Zeitler

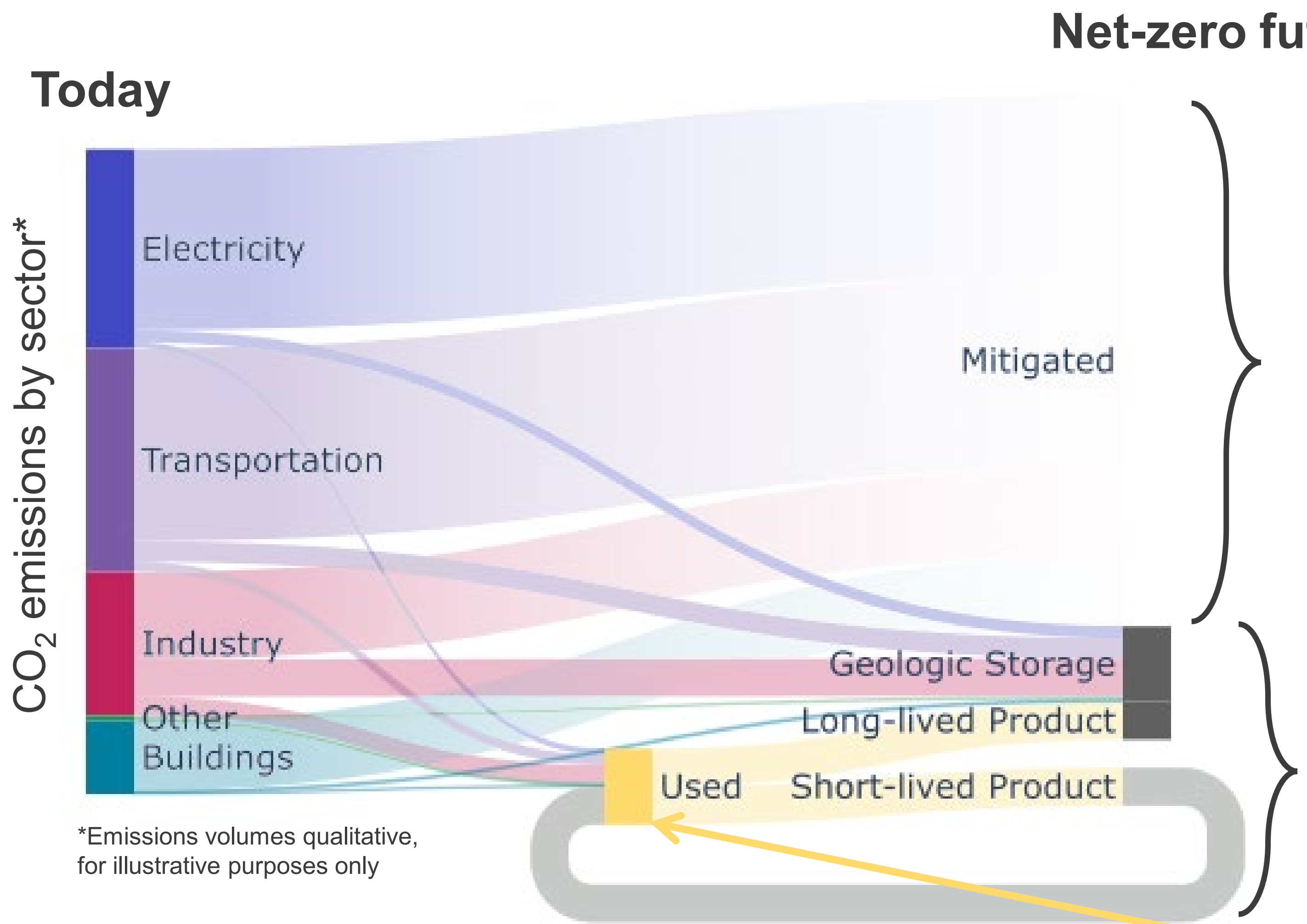
Study Co-Director: Catherine Wise

CONSENSUS REPORT BRIEFING

What is carbon dioxide utilization?

How could it fit into a net-zero emissions future?

Targeting a Net-Zero CO_2 Emissions System



*Emissions volumes qualitative, for illustrative purposes only

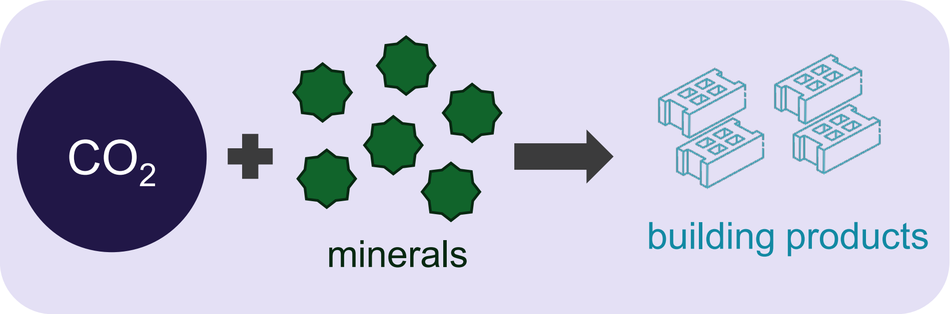
Energy transition eliminates many carbon-based processes (primarily fossil fuel combustion)

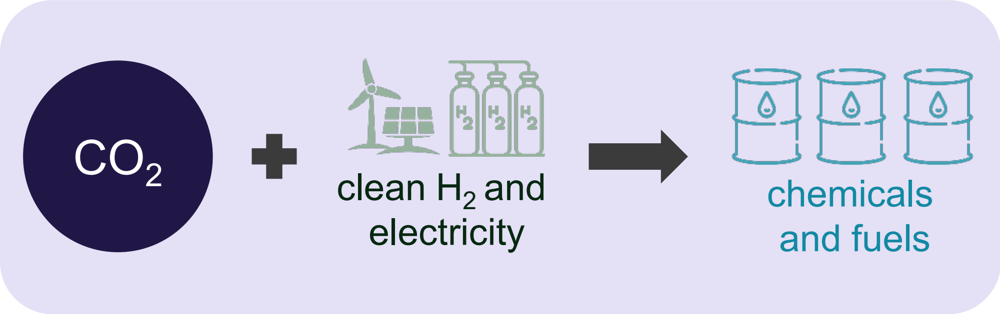
Carbon management addresses remaining emissions

CO_2 utilization is one component of carbon management

What is Carbon Dioxide (CO_2) Utilization?

- Chemical transformation of CO_2 from the atmosphere, water, or waste gas streams into a marketable product



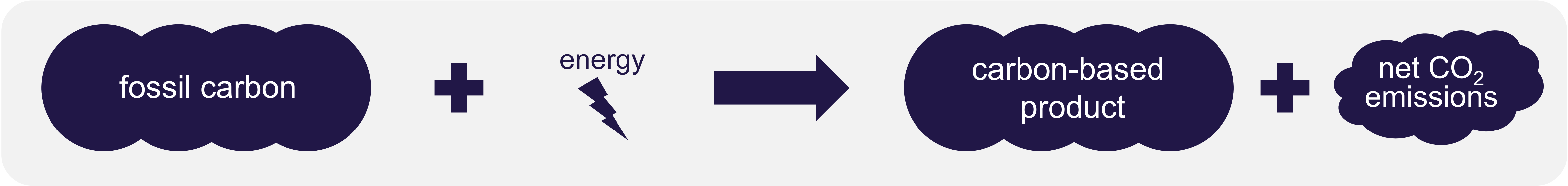


- In this report, CO_2 utilization does **not** include:
  - uses of CO_2 that do not involve a chemical transformation (e.g., enhanced oil recovery, fire suppression, beverage carbonation)
  - chemical transformations of CO_2 resulting in non-traded products and goods (e.g., soil carbon, ocean mineralization)

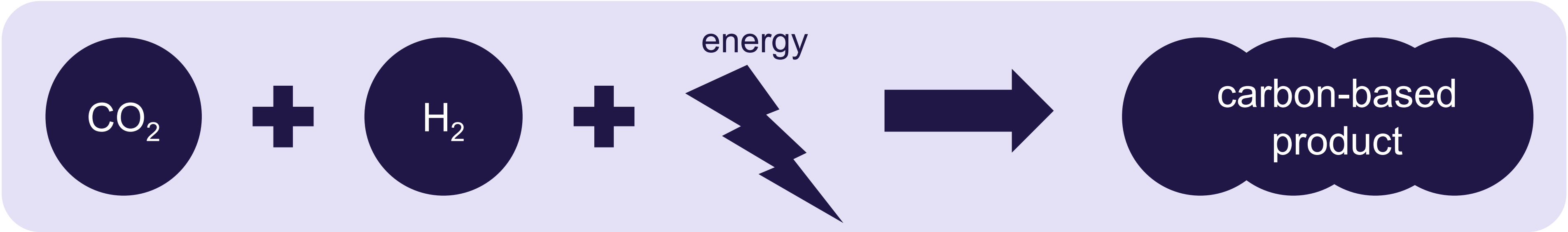
CO_2 Utilization in a Net-Zero Emissions System

Enables sustainable production of carbon-based products that are currently derived from fossil resources

Today



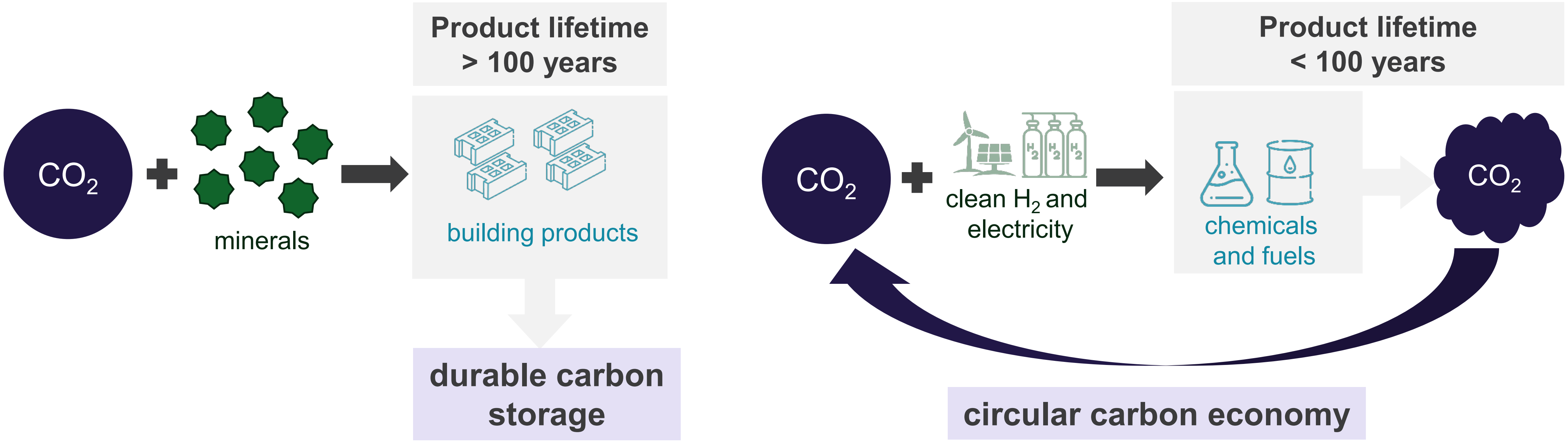
Net-zero future



CO_2 Utilization in a Net-Zero Emissions System

Climate and emissions impacts of CO_2 utilization processes depend on product lifetime, CO_2 source, and emissions associated with other inputs

- Long-lived products provide durable carbon storage
- Short-lived products participate in circular carbon economy



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About the Study

About the Study

Origin: Congressional mandate in the Energy Act of 2020; follow up to 2019 National Academies study *Gaseous Carbon Waste Streams Utilization: Status and Research Needs*

Sponsors: DOE's Offices of Fossil Energy and Carbon Management, Energy Efficiency and Renewable Energy, and Science

Report : Consensus study with 44 findings and 19 recommendations

This briefing shares the results of the first of two reports from the committee (a second report will be released in 2024).

About the Study – Committee

Emily Carter (NAS/NAE), Princeton University, Princeton Plasma Physics Laboratory, *Chair*

Shota Atsumi, University of California, Davis

Makini Byron, Linde

Alayna Chuney, Carbon 180[1]

Stephen Comello, Stanford Graduate School of Business, Energy Futures Initiative

Maohong Fan, University of Wyoming, Georgia Institute of Technology

Matthew Fry, Great Plains Institute

Haroun Mahgerefteh, University College London

Emanuele Massetti, Georgia Institute of Technology

Ah-Hyung (Alissa) Park, Columbia University

Joseph Powell (NAE), ChemePD LLC, Formerly Shell

Andrea Ramírez Ramírez, Delft University of Technology

Volker Sick, University of Michigan

[1] Until May 2022

About the Study – First Report Task Statement

The committee will provide a first report which:

1) assesses the state of infrastructure for carbon dioxide transportation, use, and storage as of the date of the study; including pipelines, freight transportation, electric transmission, and commercial manufacturing facilities.

2) identifies priority opportunities for development, improvement and expansion of infrastructure to enable future carbon utilization opportunities and market penetration. Such priority opportunities will consider how needs for carbon utilization infrastructure will interact with and capitalize on infrastructure developed for carbon capture and sequestration.

What is the status of infrastructure for CO_2 utilization?

Existing Processes and Facilities Utilizing CO_2

Products currently produced from CO_2 on a commercial scale

- Oxygenated chemical products
- CO_2 cured ready-mix concrete
- Ethanol from biological CO_2 utilization

Pilot-scale CO_2 utilization efforts

- Mineralized CO_2 products from waste materials
- Some commodity chemicals and plastics
- Some biological CO_2 utilization processes

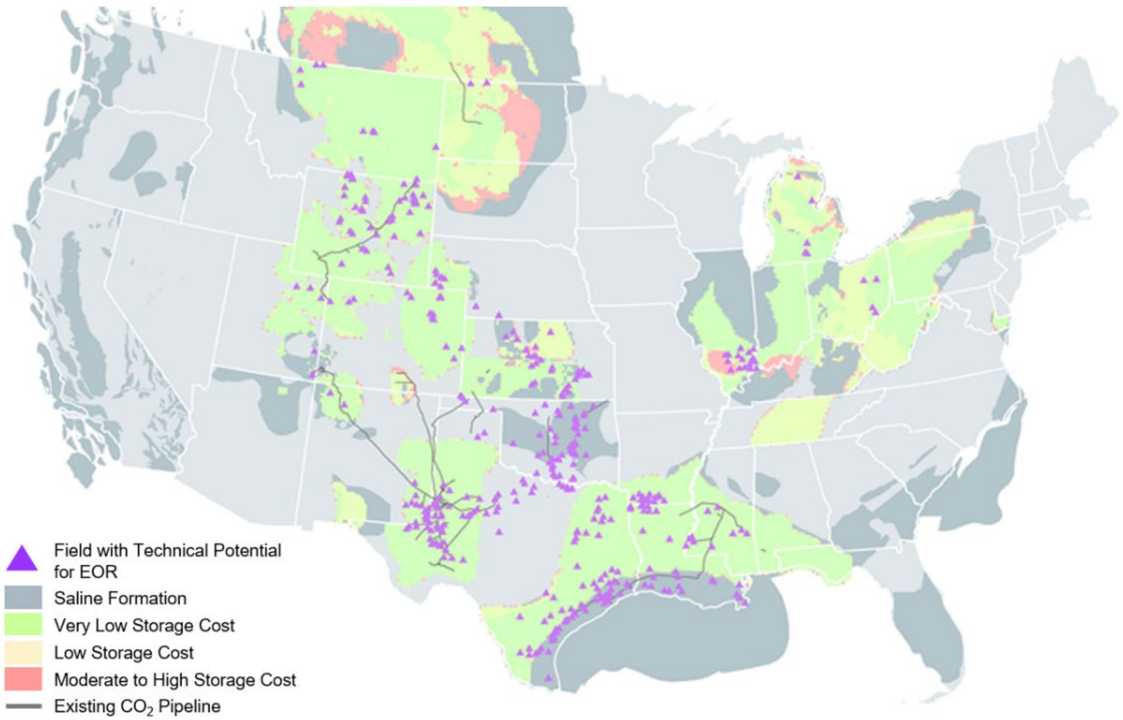
Barriers to Commercialization (from Finding 2.1)

(1) Higher cost than incumbent fossil-fuel-derived products

(2) Limited incentives to produce certifiable net-zero-emissions products

(3) Limited availability of net-zero emissions inputs, such as clean electricity, hydrogen, and heat

Existing CO_2 Transport and Storage Infrastructure



Existing CO_2 pipelines (gray lines) and potential CO_2 storage sites (green, yellow, and red shading).

Figure adapted from Abramson et al. (2020).

- ~5000 miles of CO_2 pipelines in the U.S., mostly for enhanced oil recovery
- CO_2 transport also occurs by truck and rail and, less often, by ship and barge
- U.S. has significant capacity to store CO_2 underground in various geologic formations

Leveraging Existing Infrastructure?
(from Finding 2.3)

Existing CO_2 pipeline transport infrastructure not well-aligned with sustainable CO_2 utilization opportunities in a net-zero future

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What commercial products can be made from CO_2?

Major Potential CO_2 Utilization Opportunities

Product Class	Chemical or Material	Product Lifetime
Construction Materials	Concrete Aggregates	Long-lived
Chemicals and Fuels	C1 Compounds ● Methanol ● Formic Acid ● Formaldehyde ● Methane ● Carbon Monoxide C2 Compounds ● Ethanol and Ethylene ● Dimethyl Ether ● Oxalate and Oxalic Acid C2+ Compounds ● C2+ Carboxylic Acids and Carboxylates ● Hydrocarbon Fuels ● Protein ● Pigments	Short-lived
Polymers and polymer precursors		Some short-lived, some long-lived
Elemental Carbon and Engineered Products	0-3D products	Some short-lived, some long-lived
Niche Products	Diamonds, vodka, etc.	Some short-lived, some long-lived

Adapted from Table 3.2

Market Potential for CO_2 Utilization
From Finding 3.10

- Global utilization potential for CO_2 to make products: up to several gigatonnes per year, or about 5% of current global emissions
- Volume of CO_2 utilized in a net-zero economy driven by market value of carbon-based products and the competitiveness of CO_2 as a feedstock, as well as:
  - demand for services provided by carbon-based products
  - relative cost compared to fossil-based products and other alternatives
  - availability of required inputs like clean hydrogen and clean electricity
  - policy incentives and regulatory frameworks

What factors need to be considered when developing infrastructure for CO_2 utilization?

Overview of Infrastructure Needs for Utilization

Safety, Environmental, Equity, and Cost Impacts

point source
atmosphere
water

CO_2 capture

- Solvents
- Sorbents
- Membranes
- Looping cycles

CO_2 purification

- H_2O
- NO_2
- H_2S
- O_2
- N_2
- Ar
- H_2
- CO
- SO_3

CO_2 transport

- Pipeline
- Truck
- Rail
- Ship/Barge
- Multi-modal

CO_2 purification

Other inputs

- Electricity
- Hydrogen
- Water
- Land
- Energy Storage

CO_2 utilization

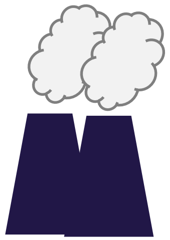
- Mineralization
- Biological conversion
- Thermochemical conversion
- Electrochemical conversion
- Photochemical conversion

Product transport

- Pipeline
- Truck
- Rail
- Ship/Barge
- Multi-modal

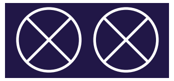
CO_2 Capture

CO_2 Sources



Fossil Source CO_2

Biogenic CO_2



Direct Air or Ocean Capture CO_2

- Currently 12 commercial carbon capture facilities in the United States
- As of June 2022, 60 carbon capture projects under development

CO_2 Capture Costs (from Finding 4.1)

- Capture cost a deterrent to more widespread implementation of CO_2 utilization
- Cost of CO_2 capture depends on:
  - concentration of CO_2 in the source
  - type of CO_2 capture technology

CO_2 Purification for Transport and Utilization

Different CO_2 utilization pathways have different purity requirements

increasing purity needs

CO_2 utilization route	Required purity
Mineralization	Low
Biological conversion (anaerobic)	Low to medium
Thermochemical conversion	High to very high
Electrochemical conversion	Very high

CO_2 Purification Requirements (from Findings 4.2 & 4.3)

- Capture, transport, utilization, and storage all have different CO_2 impurity tolerances
- Technologies for purifying CO_2 waste streams are commercially available but costly

CO_2 Transport Safety

Properties of CO_2

- colorless, odorless gas
- heavier than air
- asphyxiant
- non-toxic
- non-flammable

Risks associated with CO_2 transport

- Asphyxiation from CO_2 displacing oxygen in air
- Physical damage from rapid expansion of CO_2 from supercritical to gas phase upon pipeline rupture

Safety Considerations (from Finding 4.7)

- Difficult to draw meaningful conclusions on CO_2 pipeline failure statistics:
  - relatively small number of existing CO_2 pipelines
  - location of existing pipelines in remote areas
- No major safety issues envisaged with appropriate mitigation steps in place

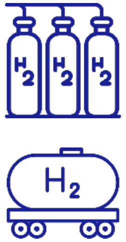
Clean Electricity Infrastructure

Electricity for CO_2 Utilization (from Finding 4.11)

- Higher demand for zero-emissions electricity
- Most CO_2 utilization processes require 24/7 operation
- Impacts optimal power generation mix, load management, transmission and distribution planning

Recommendation 4.4. 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. In the near term, the U.S. Department of Energy should coordinate efforts to advance CO_2 utilization with carbon-emissions-free energy projects, especially those with intermittent characteristics, such as solar and wind energy systems that offer opportunities to capitalize on production capacity that would otherwise be curtailed.

Clean Hydrogen Infrastructure



Hydrogen for CO_2 Utilization (from Finding 4.12)

- Many CO_2 utilization processes require hydrogen as an input
- Hydrogen difficult to transport and store
- On-site, on-demand production of hydrogen favored where feasible

Recommendation 4.5. Given the complexity of transporting and storing the hydrogen required for upgrading CO_2 to hydrocarbon products, project planners should **consider co-location of hydrogen generation with manufacturing plants utilizing CO_2 as a feedstock**. Given that most utilization projects will require 24/7 plant operation to be economically viable, project planners should also incorporate energy storage into the facility design.

Opportunities for Co-Location to Minimize Transport

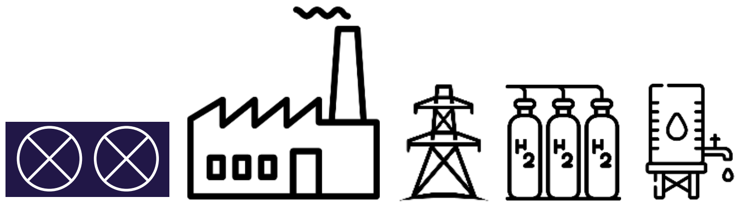
Strategic Co-Location (from Finding 6.4)

Consider features of CO_2 source and utilization product(s) when developing infrastructure:

- To maximize climate benefits (e.g., emissions reductions)
- To minimize costly transportation requirements

Examples Include

Building material product manufacturing sited near existing point sources and product uses



Direct air capture facility sited near existing chemical manufacturing plant and energy/hydrogen/water inputs

What policies and regulations would facilitate future CO_2 utilization projects?

Policy Considerations to Support CO_2 Utilization

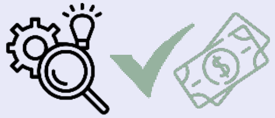
Cost-Effective Economic Tools (from Finding 5.1)

Most cost-effective ways to promote adoption of CO_2 utilization technologies:

- Disincentivize emissions (via, e.g., carbon tax or emissions trading scheme)

AND

- Incentivize research and development in CO_2 utilization technologies



Limitations and Challenges (from Findings 5.2 & 5.3)

- Unlimited subsidies can create perverse incentives
  - to continue operating inefficient technologies
  - to create emissions that would not otherwise exist
- Policy uncertainty over the long term can hinder investments and technology adoption

Regulatory and Permitting Considerations

Regulatory Considerations and Permitting Landscape (from Findings 5.4 & 5.5)

- Complex regulatory frameworks are necessary to define markets, protect public safety, and achieve societal goals such as environmental justice
- As a result, there are many permits and approvals necessary for CO_2 utilization projects, which have to be processed through multiple federal, state, and local agencies
- This can slow down the diffusion of CO_2 utilization technologies needed to support a net-zero future

Recommendation 5.2. All states should craft regulation that is efficient and clearly communicated to **achieve public policy goals while providing a usable framework for participation in CO_2 utilization markets** without unnecessarily penalizing the deployment of CO_2 utilization projects across the value chain.

What are strategies to ensure community engagement and equitable development?

Societal Acceptance and Environmental Justice

Cost-benefit Analysis (CBA) (from Finding 5.8)

- CBA can provide appropriate framework for:
  - choosing how to invest public resources to maximize total societal benefits
  - estimating distributional impacts
- CBA *cannot* be used to judge fairness of an action
- Regulators may choose not to invest in projects that would generate a net societal benefit but have unavoidable and unacceptable equity implications

Community Engagement (from Finding 5.9)

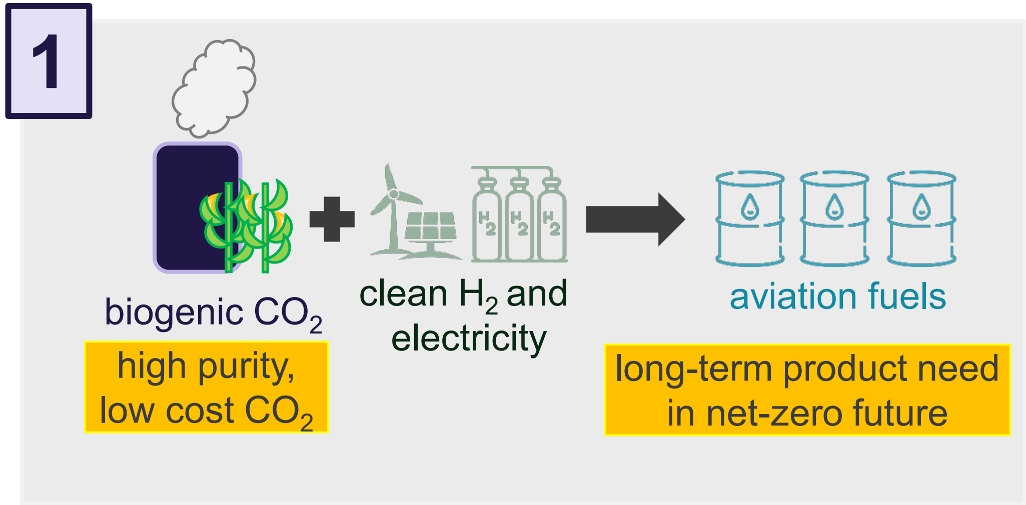
- Disadvantaged communities have not had substantive agency in affecting development of infrastructure that often negatively impacts them
- Early and ongoing community engagement can enable just and equitable outcomes for those populations
- Without community support, infrastructure projects are likely to fail, encounter delays, or require expensive reworking

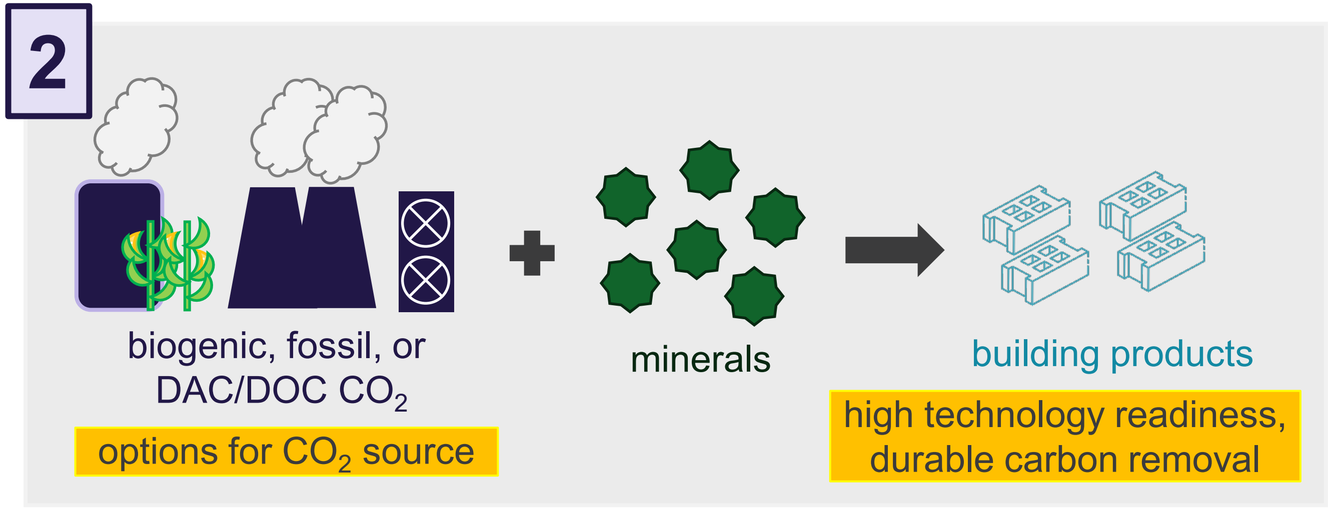
Recommendation 5.6. Regulatory authorities in charge of siting infrastructure should **account for distributional impacts of CO_2 utilization projects** through a process that considers equity and justice for disadvantaged groups, engages impacted communities early and throughout the project planning and allows for alteration of project design and implementation.

What are near-term opportunities for investment in CO_2 utilization infrastructure?

Near-Term Opportunities for Infrastructure Investment

From Finding 6.1





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.

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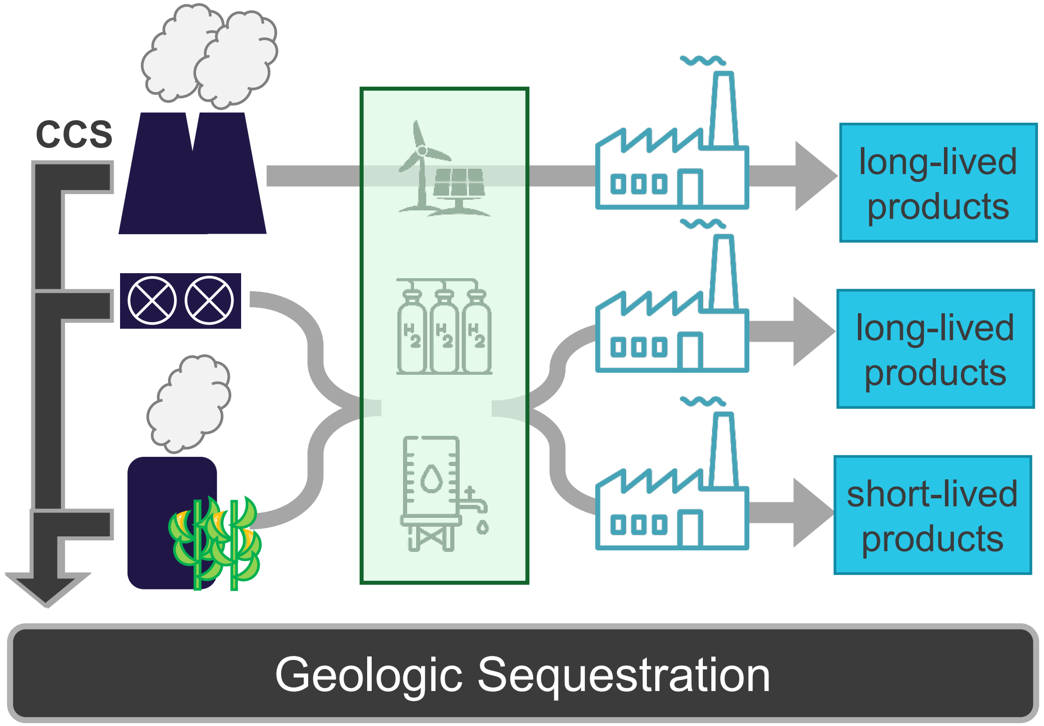
CO_2 Utilization in Industrial Clusters

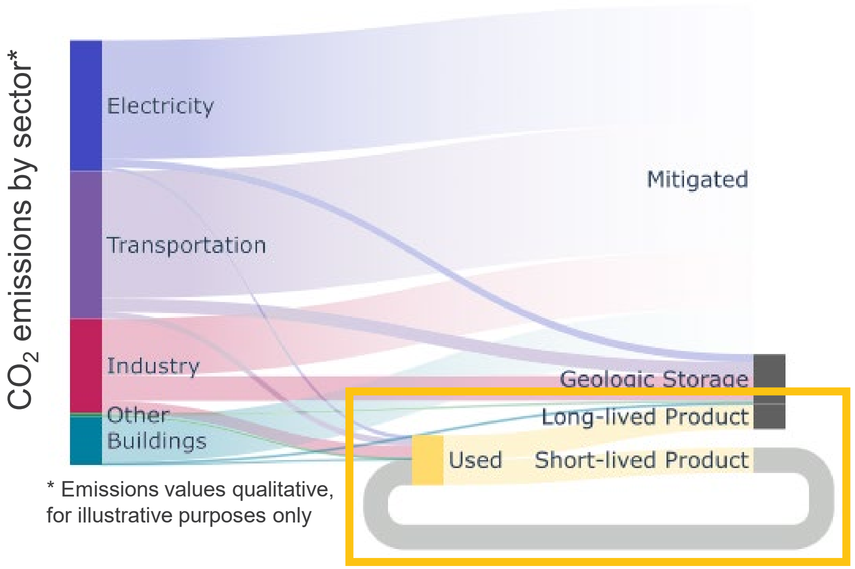


Attributes of Industrial Clusters (From Finding 6.3)

- Ability to manage large volumes of CO_2 without extensive pipeline networks
- Flexibility to incorporate new CO_2 utilization opportunities over time
- Co-location with enabling infrastructure
- Maintain jobs in regions with large industrial presence

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**.

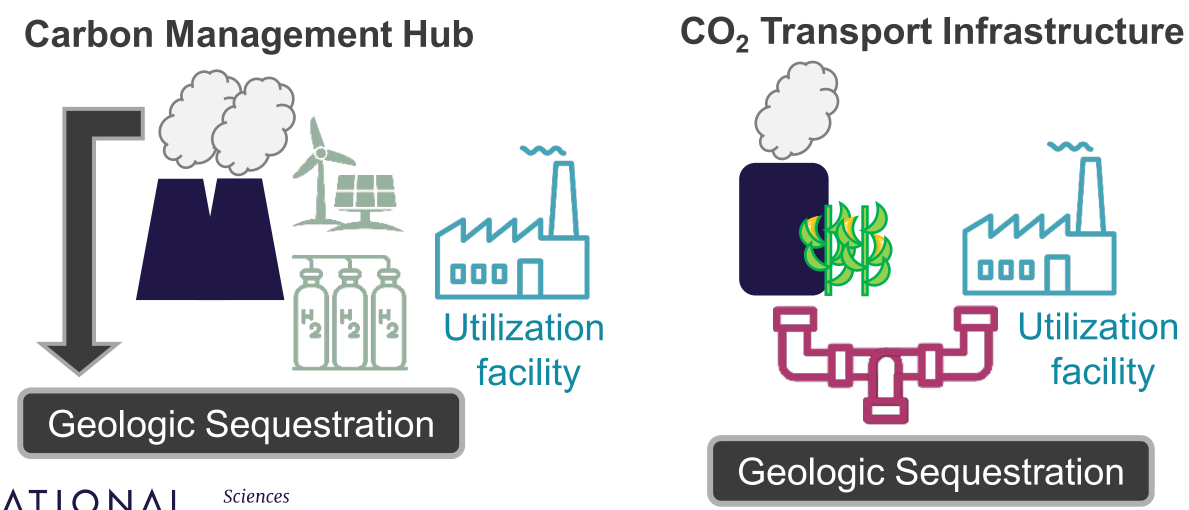
Conclusions



* Emissions values qualitative, for illustrative purposes only

CO_2 utilization can play an important role in a net-zero future

- Enables continued production of carbon-based chemicals and materials
- Provides durable carbon storage in long-lived products



Near-term infrastructure planning and design considerations:

- Co-location of utilization with clean electricity, clean hydrogen, other carbon management infrastructure
- Ability to connect CO_2 transport with future utilization opportunities

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Thank you!

Questions?

Download the report here:
http://nap.edu/26703