# $CO_2$ Sources and Sinks Matrices

**Fred Mason[1], Gerald Stokes[2], Susan Fancy[3], Volker Sick[3*]**

[1] Retired, Greenland, NH, USA

[2] Retired, Philadelphia, PA, USA

[3] Global $CO_2$ Initiative, Department of Mechanical Engineering, University of Michigan, Ann Arbor, Michigan, USA

*** Correspondence:**
Volker Sick, vsick@umich.edu

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## Abstract

Carbon dioxide capture, utilization, and sequestration (CCUS) is a collection of approaches needed to supplement other efforts to achieve net zero carbon emissions. The specific combination of $CO_2$ sources and sinks (a "usage pathway") determines the environmental impact, economic viability, overall role in climate change mitigation and continued availability of carbon-based products. Optimal deployment requires a clear understanding of the nature of carbon sources and the durability and economic value of downstream processes and materials. Rigorous life cycle and techno-economic assessments (LCA and TEA) are critical. This paper presents a $CO_2$ sources and sinks matrix as the high-level basis for assessing a usage pathway's climate relevance and economics.

## Introduction

Atmospheric and oceanic carbon dioxide concentrations are at an all-time high and causing well-documented damage to climate, habitats, and communities [1]. Stabilizing the climate, and providing equitable access to carbon-based materials, is an urgent societal challenge. The use of fossil carbon (coal, oil, natural gas) needs to be phased out as quickly as possible, but without jeopardizing access to energy and carbon-based materials while alternatives are being developed and deployed. Business-as-usual, that continues to add $CO_2$ to the atmosphere and oceans, is simply unsustainable. Rapid de-fossilization of the world's energy and materials systems is imperative. During the transition, $CO_2$ from fossil carbon point sources must be eliminated or captured to prevent additional carbon from entering the atmosphere. However, this will not be adequate. At least some fraction of the $CO_2$ that has already accumulated in the atmosphere and oceans must be removed. [1–5] Once $CO_2$ has been captured from air or water, it needs to be handled in a manner that has no further adverse effect on climate, ecosystems or human health.

Connecting $CO_2$ sources with sinks creates "usage pathways" that are often collectively called CCUS. Each pathway has a specific potential impact on the climate, ecosystems, economics, and communities. However, outcomes are uncertain and may be conflicting, leaving decision makers in a difficult position for action. [6,7] Region-specific, multifactorial assessments are needed for any proposed usage pathway to determine the appropriate solutions, and these will differ from one location to another [8].

In considering CCUS, it is important to understand the salient features of carbon capture, carbon sequestration, and carbon utilization:

> **Carbon Capture** is the process by which carbon oxides (CO and $CO_2$) are isolated from dilute mixtures, such as air, water, or flue gas. Direct Air Capture (DAC) processes isolate $CO_2$ from ambient air, Direct Ocean Capture (DOC) extracts $CO_2$ from water, and flue gas capture removes $CO_2$ from a point source emitter in a place such as a cement plant, natural gas plant, or ethanol fermentation plants.
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> **Carbon Sequestration** entails storage in geological, mostly underground reservoirs with or without mineralization to carbonates. Key attributes of $CO_2$ sequestration include carbon removal at geological time scales and potential volumes exceeding 100,000s of gigatonnes of $CO_2$. [9]
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> Sequestration from point sources of direct fossil $CO_2$ emissions currently requires societal subsidies in the form of tax credits, or penalties, such as a tax on carbon, or increased prices for e. g., electricity from power plants to cover the expenses of operation.
>
> Sequestration could generate revenue from the sale of carbon credits if the $CO_2$ is taken from air or water.
>
> **Carbon Utilization** takes the carbon oxides as a raw material to convert them to products. This conversion into useful products could offer several advantages over sequestration in geologic formations. However, it is essential to note that not all utilization processes will constitute net-negative carbon performance as will be detailed in the remainder of this perspective. The framework that is described shows how the source of the carbon and the lifetime of the resulting products are amongst the key factors to determine the net impact on carbon balances. [10] A clear understanding of these connections will help decision makers to select best options.
>
> Conversion of $CO_2$ creates products that generate revenue from their sales to help cover the increased cost of production from capturing and using $CO_2$. Some carbon utilization products can simultaneously generate revenue from the sale of carbon credits. While of lower $CO_2$ storage capacity than sequestration overall, the annual utilization potential is sufficient in the long term to more than adequately handle inevitable $CO_2$ emissions from hard-to-abate industrial sectors and the use or decomposition of short-lived $CO_2$ products at the several gigatonne/year level. [5,11–14]
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> Enhanced oil recovery without $CO_2$ recycling could be a path to remove some $CO_2$ while oil production is still necessary during the transition to a fossil-free future.

Some technologies for $CO_2$ capture and conversion are ready for deployment, while others will require substantial R&D investments. [15] However, cost of installation and operation can be a significant barrier to rapid market introduction even for more mature technologies. As a result, projections for the $CO_2$ utilization potential and the associated revenue cover a substantial range as summarized in Figure 1. [16,17]

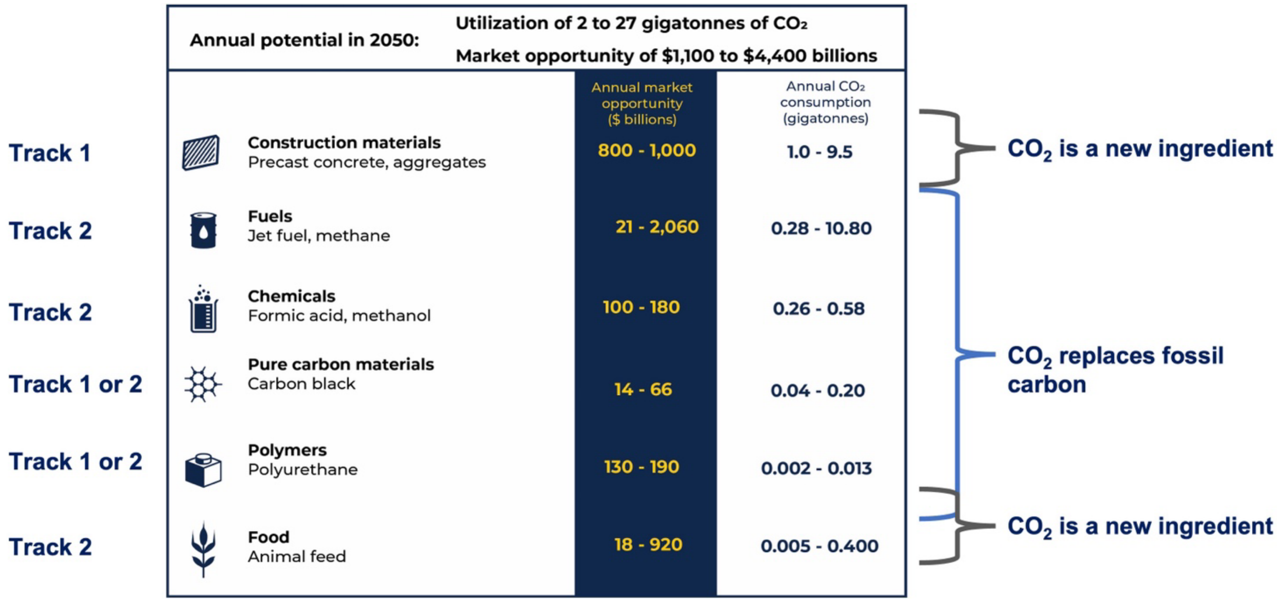


*Figure 1: The environmental and economic potential for $CO_2$-based products is very large.*

Understanding the potential climate impact of $CO_2$-based products is aided by the concept of Track 1 and Track 2 products [10]. The distinction between Track 1 and Track 2 is in the anticipated product lifetime and associated time during which the underlying $CO_2$ is removed from the environment. Track 1 products have lifetimes of at least 100 years, with potential lifetimes of thousands of years for some polymer materials and some construction materials. In contrast, Track 2 products are consumed or decompose in less than 100 years. They thus re-release $CO_2$ on a time scale that has different climate implications [10].

Figure 1 also indicates the role of $CO_2$ for a particular product category. For example, traditionally, concrete or aggregates production did not entail mineralization of $CO_2$. $CO_2$-based concrete and aggregates are therefore a new carbon removal opportunity that durably stores the carbon similar to geologic storage, but with the benefit that these products have intrinsic commercial value. The financial viability of this pathway is thus not solely dependent on revenues from tax credits and/or the sale of carbon credits. $CO_2$-based construction materials must overcome several market entrance barriers, as product costs and material properties will differ from the incumbent products. In contrast, material properties for Track 2 products (e.g., chemicals, fuels and other materials) will be identical to the incumbent products. Market adoption will thus likely be a function of availability and price competitiveness. Food and other agricultural products represent a new set of opportunities for $CO_2$ use. [18–22] Competitive costs and satisfactory performance (e.g., taste) will be key to market acceptance. $CO_2$-based food for human consumption may face additional challenges. [23]

**$CO_2$ Sources and Sinks Matrix**

CCUS technologies include a wide range of options, and this creates a complex and confusing situation even for experts. Tools such as life cycle assessments (LCA) and techno-economic assessments (TEA) are available and are essential for evaluating the climate impact, technical feasibility, and economic viability of these technologies. Enhancements of these tools are under development and will permit rigorous assessments and guidance for societal acceptance. [8,24–26] Apart from the technologies, specific combinations of sources and sinks play a key role in determining the effects on climate, ecosystems, economics, and communities. Therefore, it is useful to compile a higher-level matrix that provides insights into figures of merits at a qualitative level. The key figures of merit in this discussion are climate benefits, i.e., the impact on ambient $CO_2$ levels, and the economic outcomes. The matrix provides a starting point for technology considerations, clarity in terms of maximum potential or risk, and a common framework for decision makers. It must be noted that the matrix assumes fossil-free energy will ultimately be available for any of the processes or products. During the transition to fossil-free energy, the potential favorable climate impact might not be fully achieved. This assumption highlights the need to rigorously apply LCA to guide research, development, and deployment, and to preclude greenwashing. [15,27]

Sources of $CO_2$ that relate to human activity can be grouped into four categories: 1) Emissions from the use of fossil fuels[1] (oil, natural gas, coal); 2) process emissions from other (non-fuel) fossil carbon sources (limestone); 3) $CO_2$ that is bio-captured via plants; and 4) $CO_2$ taken from ambient air or water. The former two categories will always lead to additional carbon in the atmosphere unless the $CO_2$ is captured and sequestered in underground formations, or converted into long-lived (Track 1) products. $CO_2$ from the latter two categories can lead to net-negative carbon fluxes via sequestration, or conversion to long-lived products. For underground sequestration, it is assumed that the geological storage security exceeds 10,000 years. [28]. It is essential in this context to highlight that the matrix overview of $CO_2$ source and sink combinations will showcase the best possible outcome but that success is not guaranteed unless a detailed lifecycle assessment shows the overall environmental impact. [29] Here it will be important to conduct a cradle-to-grave assessment unless the prod cuts are drop-in replacements for incumbent materials. It is not sufficient to simply investigate how much carbon is bound in a product, but it is critical to analyze any potential carbon emissions at any step of the production process since these could negate the removal function of the product. For commercial products made with $CO_2$, such as inorganic carbonates ($CaCO_3$, $MgCO_3$), as natural rock formations demonstrate, the lifetime could exceed the 10,000-year timeframe that is projected for geological sequestration. For many polymer materials, the lifetime can exceed 1,000s of years equaling the $CO_2$ removal time they can provide. [30,31] The Track 1 categorization of $CO_2$-based materials uses a minimum lifetime of 100 years, consistent with UNFCCC estimations. [32] Short-lived (Track 2) products with lifetimes below 100 years due to decomposition during use or by natural processes will end up as $CO_2$ emissions that can be recaptured and reused as part of a circular carbon economy.

Figure 2 illustrates the relationship between sources and sinks of $CO_2$ for CCUS and the resulting best-case scenario for $CO_2$ removal. Color-coded pathways illustrate the desirability of the various capture-use combinations from the combined perspective of contribution to net-zero greenhouse gas emissions and economic value created independent of taxes and sales of credits.

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[1] It is noted that fossil fuels category includes their use as the raw materials, e.g., for chemicals and polymer production.

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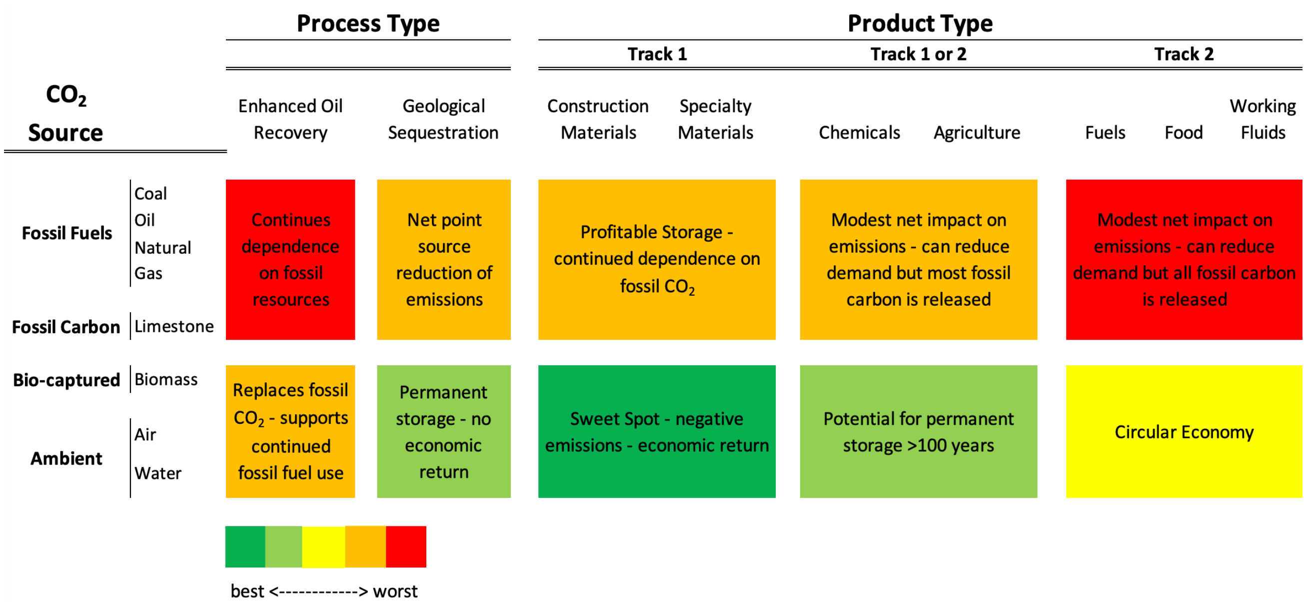


*Figure 2: The value or risk of capturing and utilizing or sequestering $CO_2$ strongly depends on combination of source and downstream process or product.* [2]

The impact of $CO_2$ source-sink combinations on atmospheric $CO_2$ levels – which are the ones that matter for global temperatures – can be illustrated by looking at three process and product categories as examples for the use of this source- sink matrix: Geological Sequestration, Construction Materials, and Aviation Fuels.

Geological Sequestration: Captured $CO_2$ from direct fossil origin is sequestered, i.e., durably removed by underground storage, underground mineralization, or above-ground mineralization where the resulting material is not used as a commercial product. Since $CO_2$ capture rates are below 100%, and due to some $CO_2$ leakage during handling and transport, the theoretical upper limit for geological sequestration cannot be achieved. The result is a net amount of new $CO_2$ is inevitably added to the atmosphere. In contrast to this, geological sequestration can result in a durable net removal of $CO_2$ when $CO_2$ is captured from biological materials processing (e.g, biomass combustion or corn fermentation to produce ethanol), air or bodies of water. It is required, though, that any process involved in the capture and sequestration effort does not lead to $CO_2$ emissions that are greater than the amount that is being sequestered. Any such emissions would count against the overall carbon balance and reduce the carbon removal rate in practical terms until we have a fully carbon-emission-free energy system. The end result constitutes net-negative carbon dioxide removal (CDR) [9]. This creates the potential to produce verifiable, meaningful carbon offsets that can be used to increase the economic viability and in the long run should allow financial sustainability without public subsidies.

[2] Note that no $CO_2$ capture process captures 100% of the emissions and therefore the implications shown in Figure 2 are upper theoretical limits.

Construction Materials: Mineralization of fossil $CO_2$ via curing of concrete and the production of carbonated aggregates offers opportunities akin to geological sequestration in terms of durability of the storage as well as the near-neutral but not negative carbon balance. As these processes that use fossil $CO_2$ do not create carbon offsets, revenue generation is dependent on tax incentives (e.g., 45Q in the United States), procurement mandates for low-embodied carbon products, and sales of the materials. Using bio-captured or ambient $CO_2$ and converting it to construction materials fundamentally offers the best option for carbon removal. Again, it must be shown in rigorous life cycle assessments, that peripheral $CO_2$ emissions do not counter the removal in the mineralized product. Potential volumes are substantial, e.g., by 2050 over 100 gigatonnes of aggregates will be needed annually. [17]

Aviation Fuels: Compared to concrete and aggregate production for which $CO_2$ utilization is a new use case for carbon, the production of sustainable aviation fuels (SAF) is not creating a new product rather it replaces a fossil-based incumbent. Although SAF is energy-intensive to produce from $CO_2$, it is necessary because biomass-based SAF cannot meet global demand. In contrast to ground vehicle propulsion, electrification and hydrogen cannot meet technical requirements for long-haul flights in the foreseeable future. [15] $CO_2$ from direct fossil origin should not be used in SAF production since it will simply be passed through to the atmosphere with no reduction in atmospheric $CO_2$. In contrast to this, bio-captured and ambient $CO_2$ will lead to a circular fuel economy that can become carbon-neutral within the constraints of potential fossil $CO_2$ emissions, e.g., embodied in the materials that are used to build the production facilities.

## Discussion

Under the premise of, and with the understanding that carbon-negative processes or products are those that durably remove $CO_2$ from air or bodies of water, a matrix was developed to help understand how the combination of a $CO_2$ source, and the disposition of the $CO_2$ once it is captured, determines a set of outcomes. It is then apparent that the often-used term "carbon capture" alone is not a useful term - the combination of $CO_2$ source type and downstream fate is critically important, and thus must be clearly presented and discussed. Key takeaways are as follows.

1. Fossil and non-fossil sources of $CO_2$ need to be viewed differently. For non-fossil sources the critical consideration is the cost of $CO_2$ delivered to the point of disposition. While cost of capture from fossil point sources is important, from the perspective of climate impact, the critical consideration is the fraction of emitted $CO_2$ that is captured.

2. Track 2 (short-lived) materials are very important due to the dependency of modern society on carbon-based materials. The success of a circular economy based on non-fossil carbon capture may well depend on its ability to use existing fossil-carbon infrastructure and meet volume needs. For fossil $CO_2$, Track 2 usage simply delays the release of fossil $CO_2$ into the atmosphere and should be avoided.

3. Geologic sequestration is unavoidable but much more work is needed to ensure suitable storage space is available and acceptable.

4. LCA and TEA, standardized and rigorously executed, are essential for all use cases. The carbon credit markets and governmental policy makers need to be absolute in requiring that they be done.

5. Useful and profitable products based on capture of non-fossil $CO_2$ are an obvious contributor to $CO_2$ management, but only if they can be delivered at scale and in the near term.

Figure 2 presents a view of climate relevance and economic opportunities for $CO_2$ source-sink combinations. Similar approaches can be taken to highlight the respective cost, dependence on subsidies, potential revenue, $CO_2$ removal or $CO_2$ utilization potentials, and more.

**Data Availability Statement**

The data used to produce figure 1 are available for download as referenced.

**Conflict of Interest**

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Author Contributions**

FM developed the initial idea of organizing sources and sinks of $CO_2$ into a matrix. All co-authors contributed equally to the development of the matrix presented in this perspective. VS led writing of the paper and integrated contributions from the co-authors. All authors approved the submitted version.

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