DOE | UNDERSTANDING THE MARKET FOR CARBON CONVERSION

October 2024

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1.0 Introduction

Potential applicants to the Carbon Utilization Procurement Grant include states, local governments and public utilities looking to procure CO_2-derived products.

In 2023, the U.S. Department of Energy (DOE) released under the Bipartisan Infrastructure Law (BIL) Section 40302 – the **Carbon Utilization Procurement Grant** which enabled applicant states, local governments, and public utilities to purchase products derived from converted carbon emissions. Procurement of CO_2-derived products could help to create early markets for CO_2-derived products with verifiable climate benefits. It is anticipated that this Grant will incentivize states, local governments, and public utilities and other organizations to purchase products made from carbon emissions and drive emissions reductions. Indeed, the ultimate goal is to speed up adoption of advanced carbon management technologies, creating a market for environmentally sustainable alternatives in fuels, chemicals, and building products sourced from captured emission.[1]

The primary purpose of this report is to see what information is available to size the current and future market for CO_2-derived products that could potentially be purchased by states, local government and public utilities – i.e., those entities which might apply for a Carbon Utilization Procurement Grant. In addition, this report explores other questions of interest to the Office of Fossil Energy and Carbon Management (FECM) regarding opportunities for inorganic carbonate products (CO_3^{2-}), chemicals and fuels derived from CO. The last section of this report addresses an additional request of FECM - information on the market for CO_2 derived products in the chemical industry.

In looking at the market for CO_2-derived products that could be procured using funds from the **Carbon Utilization Procurement Grant** , eligible entities are defined as states, units of local governments, or public utilities and agencies.[2] However, there are several stakeholders involved in the procurement process including:

1. Carbon conversion product manufacturers that provide the commercial or industrial products,
2. States, units of local governments and public utilities, and
3. Contractors which provide the services utilizing CO_2-derived products.

Nearly all operations of local government and state entities require the purchase of goods and services from the private sector. This is true when building and/or maintaining roads or when one requires general infrastructure work. This work is completed by contractors. A recent review article identified several challenges when purchasing net-zero products that relate to the contractors, for example:

i. "Financing net-zero procurement to obtain goods and services for construction activities may be more expensive,
ii. Low stakeholder involvement in decisions surrounding net-zero purchasing strategies for construction projects,
iii. Project teams within construction firms were often found to be lacking expertise, for example in the procurement of net-zero materials for construction activities."[3]

None-the-less market analysts suggest that the use of captured CO_2 used to make high value products such as fuels and chemicals could grow to scales of multiple billions of tons of CO_2 per year. However, in practice this would compete with products currently in use that may be more cost effective in most applications. This begs the question; will local governments and municipalities continue to purchase higher premium products as opposed to the lower cost counterparts after grants have expired? The answer to that question will affect true market growth.

2.0 Carbon Dioxide to Useful Products – Background

New opportunities to use captured CO_2 to develop new products is capturing the attention of governments, industry and the investment community interested in mitigating climate change. Please note that throughout this discussion, we will differentiate between industrial CO_2 and captured CO_2.

2.1. Transforming CO_2 into Valuable Commodities

In 2023, CO_2, the most abundant greenhouse gas, reached a record high concentration in the Earth's atmosphere. The industrial sector accounted for 23 percent of U.S. greenhouse gas emissions in 2022, excluding indirect emissions from electricity end-use. If indirect emissions from electricity use are distributed to the industrial end-use sector (e.g., powering equipment and industrial buildings), industrial activities account for 30 percent of U.S. greenhouse gas emissions (GHG).[4]

> **"Industrial carbon dioxide (CO_2) is an incombustible gas that's collected as a byproduct of industrial processes. Most CO2 that's sol as a commercial product is recovered and purified from industrial plants, usually as the result of large-scale chemical production."**
> **–*Oxygen Service Company***

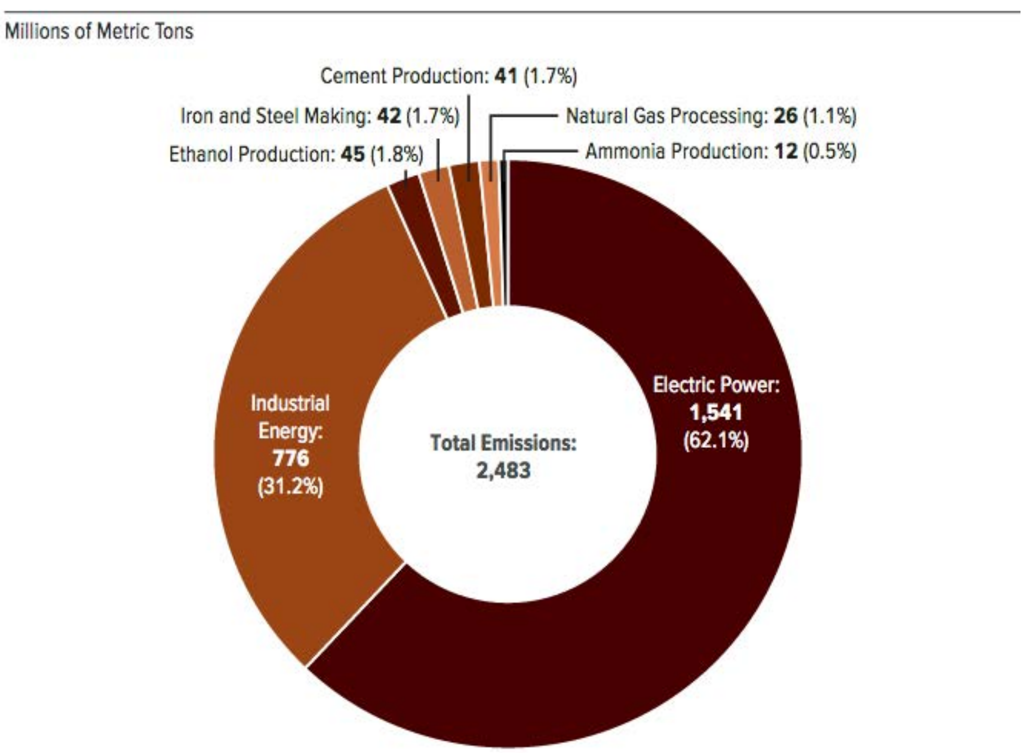

Figure 1: CO_2 Emissions in the United States in 2021 from Sources that are Potential Candidates for Carbon Capture and Storage
Source: Congressional Budget Office (December 2023)[5]

Carbon capture and storage is seen by many experts as a tool in combating climate change. CCS technologies are considered important in industries described as "hard-to-abate" including fertilizers, chemicals, steel, and cement, which account for 20% of global

CO_2 emissions, creating greenhouse gases from the waste generated. Mitigating these emissions through carbon storage strategies only offers a partial solution, leading stakeholders to actively work on sustainable approaches to repurpose CO_2. The ability to repurpose (sell or convert) CO_2 into useful products such as CO also leads to carbon neutrality.[6]

2.2. Captured CO_2 Capacity

Assuming all current and planned projects become operational, the global carbon capture capacity is projected to increase from ~107.2 mtpa in 2023 to ~1574 mtpa in 2030 (Figure below). The majority of CO_2 is currently captured and stored from industrial facilities, with natural gas processing plants accounting for around 65 percent of global capture capacity.[7]

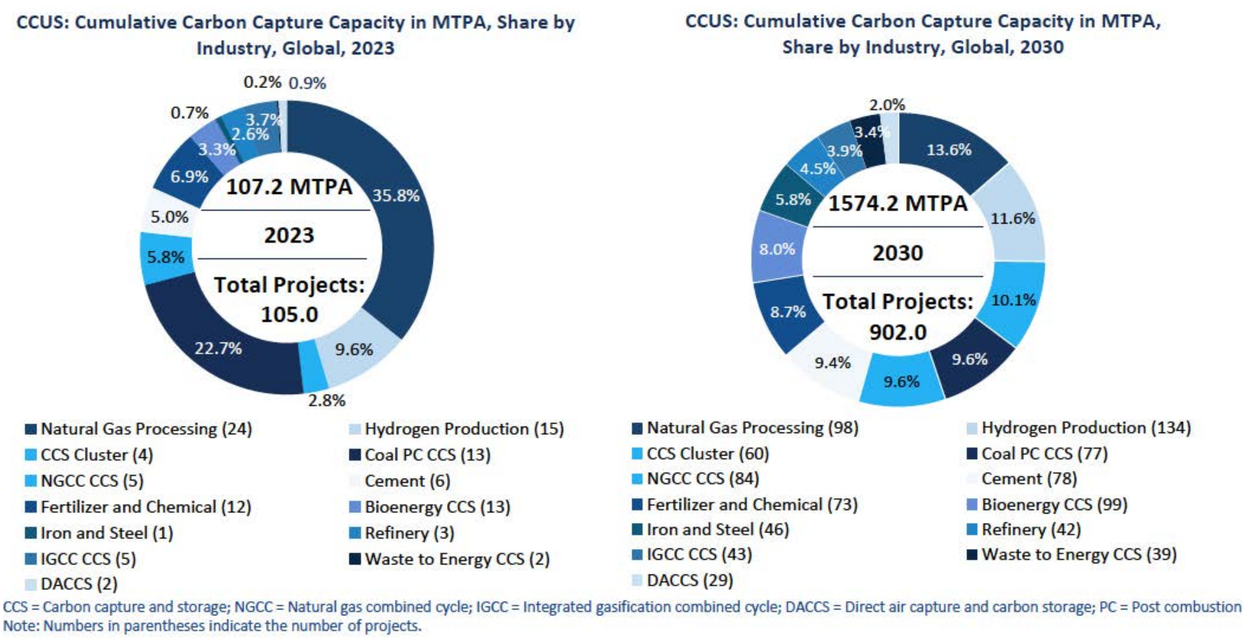

Figure 2: Global CCUS Project Type and Capacity – 2023 and 2030

Source: Reprinted with Permission from Frost & Sullivan (June 2024)[8]

As of 2023, the United States had approximately 231 CCS projects in the pipeline in various stages of development, 17 of which were operational. These carbon capture and storage facilities have the capacity to capture 2 million metric tons of CO_2 per year, or 0.4 percent of the total annual CO_2 emissions in the United States. If all CCS projects were completed and become operational, they would increase the nation's CCS capacity to 3 percent of current annual CO_2 emissions. Further, Congressional Budget Office suggests that the percentages are small in “part because CCS is generally used in sectors that have the lowest costs for capturing CO_2—such as natural gas processing and ammonia and ethanol production—and those sectors account for a small share of total U.S. CO_2 emissions.”[9]

Table 1: Carbon Capture and Storage Facilities in the U.S.

Status of Facility	Number	Total CO_2 Capture Capacity (Millions of metric tons per year)
In Construction	6	10
In Development		
Advanced development*	69	79
Early development	46	45
Total	121	134

**Projects at the stage of advanced development are ones for which front-end engineering and design are underway or have been completed; projects at the stage of early development are ones for which a feasibility or prefeasibility study is underway*

Source: Congressional Budget Office (December 2023)[10]

In the next few years, it is anticipated that several large-scale CCUS projects will be operational. These projects will assure the supply of CO_2, the raw material that can be converted into high-end applications.[11]

2.3. Supporting Policies and Regulations

Direct tax credits that could support the deployment of CCS and carbon dioxide utilization is the 45Q tax credit via the Inflation Reduction Act (IRA), which is anticipated to boost investments in new projects which can earn $60/ton of CO_2 companies use to enhance oil recovery and $85/ton of stored CO_2.[12] 45Q includes other add-ons such as the 45V tax credit for clean hydrogen production and the 40B and 45Z tax credits for sustainable aviation fuels and low-carbon transportation fuels.[13] The 45Q tax credit can be claimed when an eligible project has for example, reused the captured CO_2 or carbon monoxide as a feedstock to produce low embodied carbon products such as fuels, chemicals, and building materials.[14] The following Table shows Maximum value of the credit for carbon capture and storage under 45Q.

Table 2: Maximum Value of The Credit for Carbon Capture and Storage Under 45Q

Application	Approved Uses		
	For dedicated secure geologic storage of CO2 in saline or other geologic formations	For carbon reuse projects to convert carbon into useful products (e.g., fuels, chemicals, products)	For secure geologic storage of CO2 in oil and gas fields
Industry & Power	\$85/metric ton	\$60/ metric ton	\$60/ metric ton
Direct Air Capture	\$180/ metric ton	\$130/ metric ton	\$130/ metric ton

Source: Congressional Budget Office (December 2023)[15]

Studies vary widely in their estimates of the impact that the carbon capture and storage tax credit programs (such as 45Q) will have over the next decade. Some studies suggest an associated CO_2 capture capacity of at least 100 million tons per year will be installed by the early 2030s with a value of anywhere from \$30 billion to well over \$100 billion.[16] Other studies have also attempted to estimate the potential for carbon capture by determining the number of facilities that could utilize the 45Q tax credit, for instance, a 2020 analysis by Elizabeth Abramson, et al, from the Great Plains Institute, identified 1,517 45Q-eligible facilities across the United States (following Table) that emit a total of 2,352 million metric tons of CO_2 annually, accounting for 89 percent of the CO_2 emissions from those sectors.

Table 3: 45Q-Qualifying Facilities and Emissions by Industry

Industry	Number of Facilities	Share of 45Q-Eligible Facility Emissions	CO_2	Biogenic CO_2	Methane	Nitrous Oxide
Coal Power Plant	308	53.8%	1,269.6	0.3	3.0	6.2
Gas Power Plant	571	23.8%	565.4	0.7	0.4	0.4
Refineries	78	6.9%	163.3	-	0.6	0.4
Cement	135	3.7%	88.8	0.9	0.1	0.2
Hydrogen	57	2.7%	64.3	-	0.1	0.1
Steel	31	2.3%	54.0	-	0.2	-
Ethanol	173	1.3%	31.0	8.97	0.1	0.1
Ammonia	21	1.2%	25.1	0.0	0.0	4.1
Petrochemicals	30	1.1%	26.0	0.1	0.4	0.1
Metals, Minerals & Other	37	0.9%	19.5	-	0.4	-
Gas Processing	40	0.9%	19.9	-	0.7	-
Chemicals	16	0.8%	8.7	-	0.0	10.4
Pulp & Paper	18	0.4%	7.8	25.5	2.4	0.1
Waste	2	0.1%	0.8	1.2	0.6	-
Grand Total	**1,517**	**100%**	**2,344.2**	**29.3**	**9.1**	**22.1**

Source: Elizabeth Abramson et al, Great Plains Institute (2020)[17]

3.0 Carbon Dioxide Utilization Products

Captured CO_2 utilization technologies have the potential to enable decentralized carbon management while generating secondary raw materials that can be used in several high-end applications. The use of raw materials derived from carbon utilization technologies creates an additional benefit of being carbon negative, a contributor to achieving long-term emission reduction targets.

The following analysis considers products derived from both industrial CO_2 and captured CO_2, with a focus on the former. The key here is to identify products from captured CO_2 currently on the market that could be purchased by large entities.

3.1. Where is Industrial CO_2 Being Used

Carbon dioxide can be produced using various processes such as combustion of fossil fuels, fermentation, natural gas processing, and as a by-product of certain chemical processes. It is a by-product of the combustion of fossil fuels, such as coal, oil, and natural gas. This method is widely used in power plants and other industrial settings.[18] In the U.S., the commercial CO_2 industry is composed of about 111 plants, largely sourced from ethanol, with 49 plants. CO_2 is also a by-product from industrial plants, specifically, from the production of anhydrous ammonia, hydrogen reformers in oil refineries, natural sources from deep within the earth are a source type, not by-product based, which require purification only. Other miscellaneous facilities include by-product from flue gas, ethylene oxide, natural gas processing and syngas.[19]

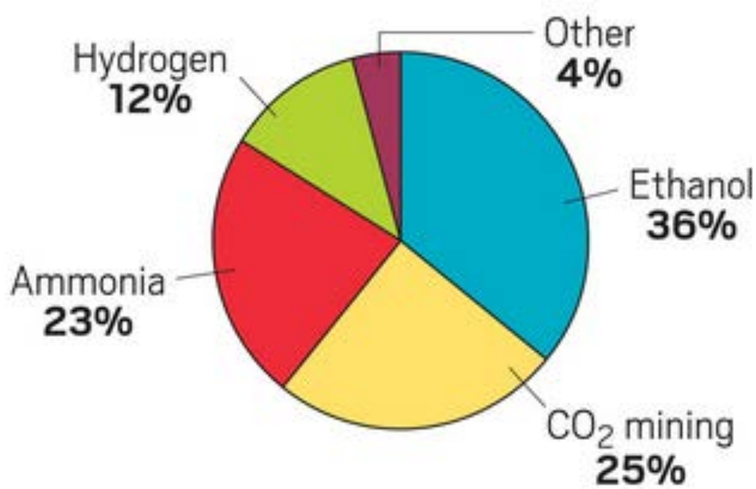

Figure 3: CO_2 sources

Source: Craig Bettenhausen, *Chemical & Engineering News* (2023)[20]

Globally, the demand of carbon dioxide was around 263 million tons in 2023 and has been increasing since 2018 from $14.5 billion in 2018 to $18.4 billion in 2023 with a CAGR of 4.9%. The market is projected to increase from 263 million tons in 2023 to 290.4 million ton in 2028 with CAGR of 2.0% between 2023 - 2028. illustrate the global demand (volume and value) for carbon dioxide during last 5 years and projected demand through 2028.

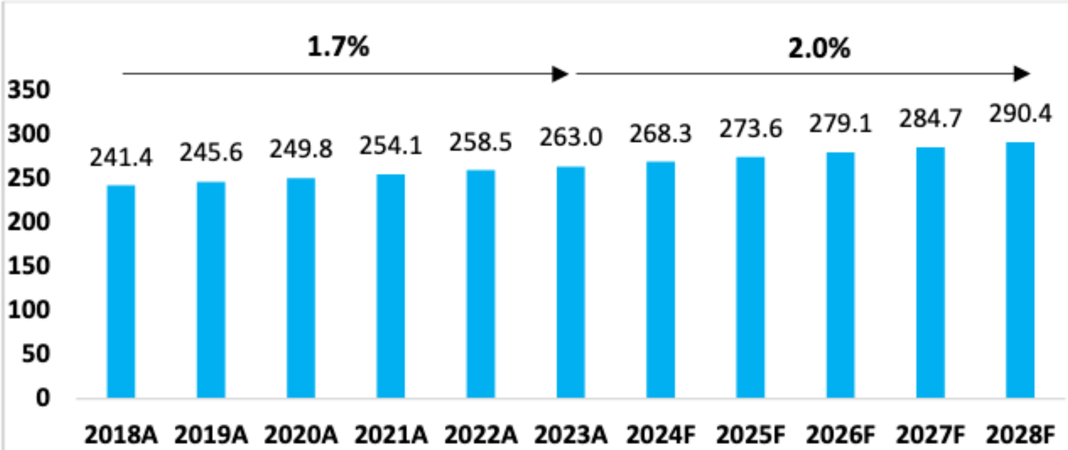

Figure 4: Global CO_2 Market, by Volume (Million Tons), 2018-2028

Source: Frost & Sullivan (2024)[21]

Industrial CO_2 is used in several industries, such as food & beverage, chemicals, refining, etc. In the food & beverage industry, it is used in carbonated soft drinks, beers, and wine and helps prevent fungal and bacterial growth. It also finds application in welding processes in manufacturing, contributing to enhanced stability and efficiency. Carbon dioxide is crucial in the oil and gas industry for enhanced oil recovery, where it is injected into reservoirs to facilitate the extraction of remaining oil.[22]

Frost & Sullivan suggest that the global demand for CO_2 at industrial scale is driven by its use for the manufacturing of urea and enhanced oil recovery (EOR), with a consumption of 130 $MtCO_2$ per year and 70 $MtCO_2$ per year, respectively, and the production of food and beverage, metal fabrication, cooling, and fire suppression. The following Figure shows approximately 55 percent of all industrial CO_2 is directed to the food and beverage sector. Non-food uses for CO_2 range from metallurgy to health care and others.

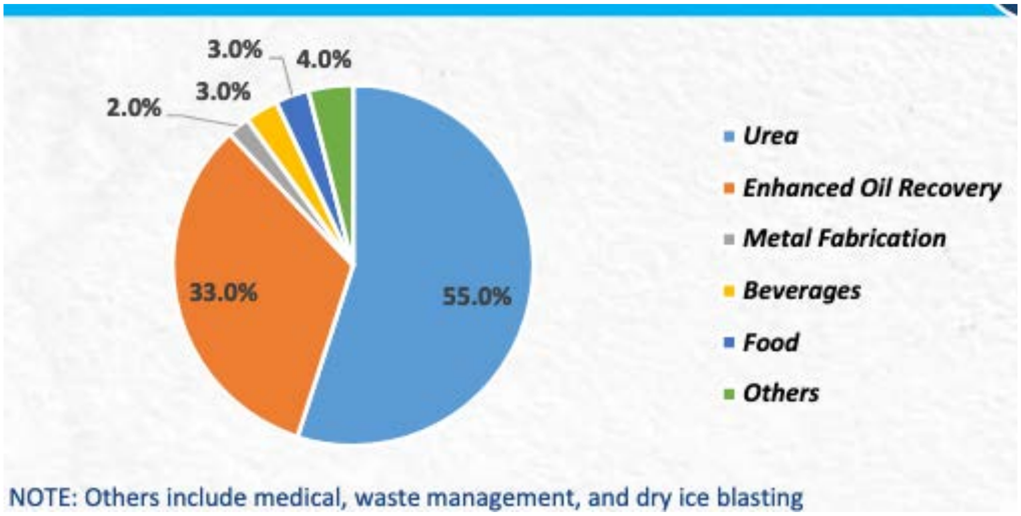

Figure 5: Primary uses of CO_2 globally

Source: Frost & Sullivan (2024)[23]

At present, except in enhanced oil recovery (EOR), captured CO_2 is not being used in the industry applications listed in the Figure above in meaningful quantities.

3.2. Products from Captured CO_2

Industrial CO_2 is used in applications such as EOR, production of food and beverage, metal fabrication, cooling, and fire suppression. CO_2 at a commercial scale from CCS is mostly used today for enhanced oil recovery. However, the industry is beginning to develop novel applications for captured CO_2 that can also allow for the synthesis of high-value-added products such as chemicals, pharmaceuticals, and fuels among others.[24]

Companies are beginning to commercialize technologies that convert captured CO_2 into valuable products including fuels (such as ethanol, sustainable aviation fuel), chemicals, and building materials, which have generated global interest.[25] All these categories could individually be scaled-up to a market size of at least 10 $MtCO_2$/yr.[26] Much of current CCS technology is used for enhanced oil recovery. Goldman Sachs observes that the majority of the CCS facilities (85%) capture CO_2 from O&G operations, which are then either sold to industrial facilities or injected into the subsurface to boost oil recovery. Goldman Sachs expects captured CO_2 volumes to increase to ~100 million tons by 2032 and 780 million tons by 2050, primarily driven by carbon-capture technology adoption in power generation, blue hydrogen production and industry.[27] A Congressional Research Service report notes that in the near term, most CCS projects will continue to be for sequestering CO_2 by injecting it underground solely for sequestration purposes or as part of "tertiary" oil recovery from oil fields.[28] The following Figure provides an overview of the CO_2 utilization pathway. Captured CO_2 can be transformed into many products through various processes, depicted in the following Figure. The range of potential applications for CO_2 utilization is extensive, from construction aggregates to chemicals.

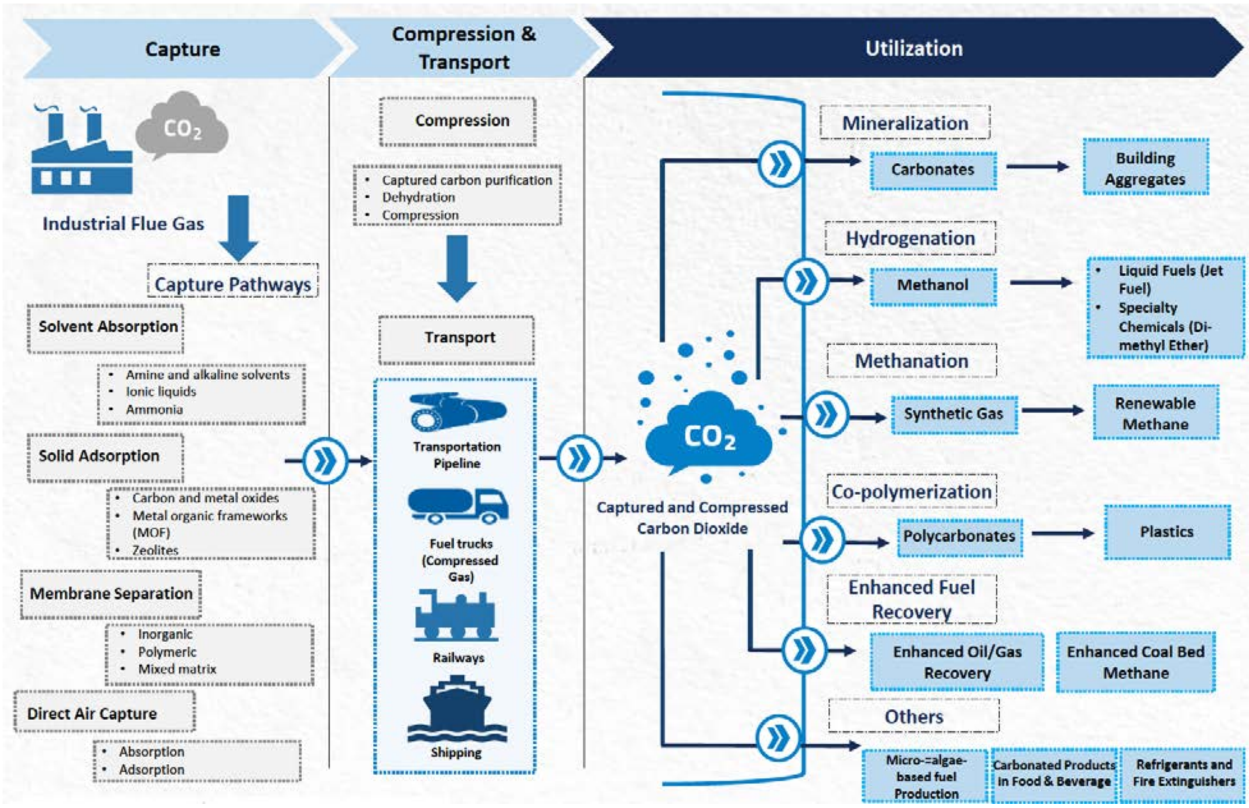

Figure 6: Carbon Utilization Value Chain

Source: Reprinted with permission from Frost & Sullivan (July 2024)[29]

The range of product categories accessible from CO_2 feedstock is very large. A 2024 study on captured CO_2 utilization by the National Academies of Sciences summarized the scope of technologies and products from captured CO_2 utilization (see following Figure). The report deemed mineralization processes to be the most highly developed potential growth areas for utilization. Products from mineralization include inorganic carbonate products such as CO_2 cured concrete, precast concrete and aggregate materials. These materials find use in many industries including construction.[30]

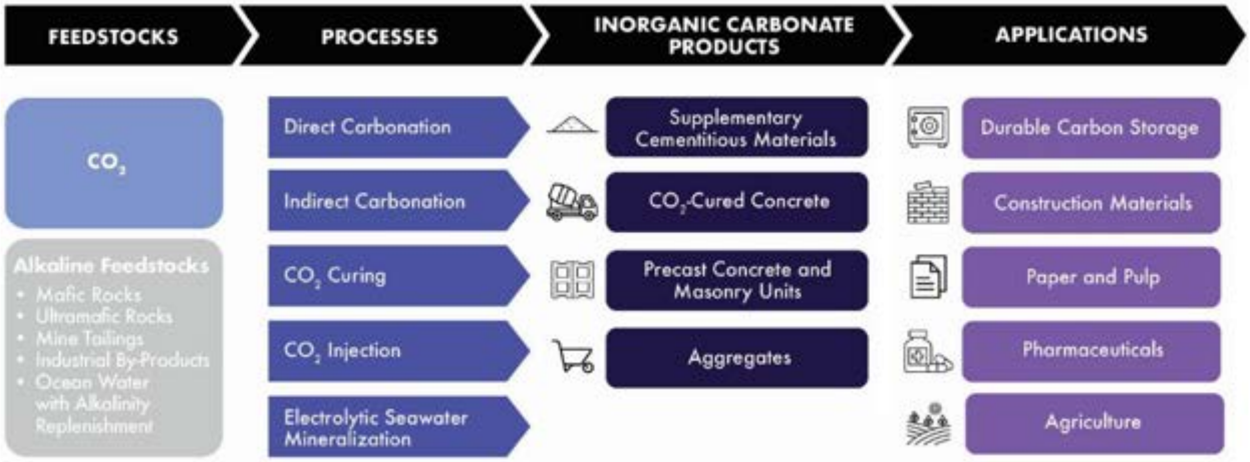

Figure 7: Summary of the Feedstock Inputs, Processes, Products, and Applications for Mineral Carbon Utilization Processes to Form Inorganic Carbonates

Source: National Academies of Sciences (2024)

With respect to chemical and biological processes, the National Academies of Sciences notes that there are a myriad of chemicals and materials that can be produced directly from CO_2. These chemicals include carbon monoxide, formic acid, urea, and many others (see following Figure).[31]

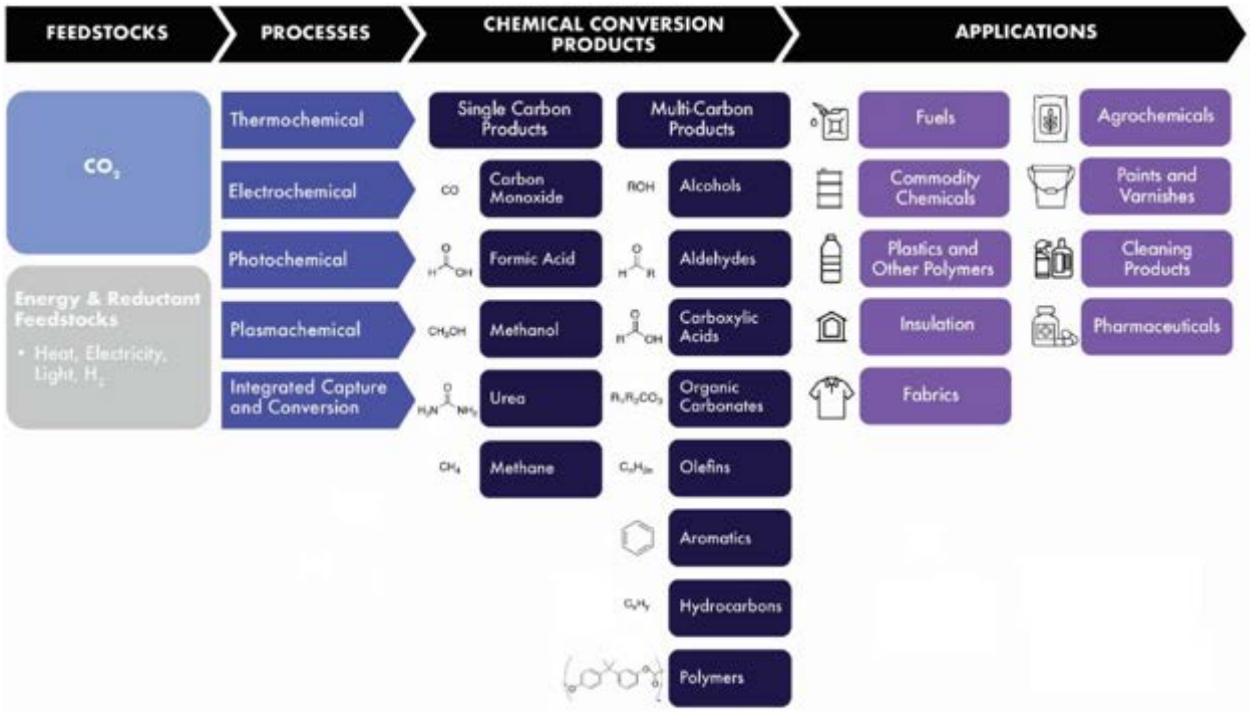

Figure 8: Feedstocks, Processes, Products, and Applications for Carbon Utilization to Make Chemical Products

Source: National Academies of Sciences (2024)

An earlier National Academies of Sciences report, published in 2023 estimates that by 2030, the potential annual use of captured CO_2 to make products to be between 2 and 8 gigatons, generating an annual revenue stream between \$0.5 trillion and \$2 trillion. The following figure provides an estimate of the anticipated market opportunity. Construction materials provide the largest market opportunity, followed by fuels such as replacement of natural gas.[32]

$0.5 – $2 trillion / year opportunity	2 – 8 Gigatons of CO_2 / year		
	Annual Market Opportunity (Billion USD)	Annual CO_2 Consumption (Million Tons)	
Construction Materials Concrete, aggregates	165 - 550	900 - 5000	CO_2 is a new ingredient
Fuels Natural gas replacement, gasoline, diesel fuel, jet fuel	10 - 250	700 - 2100	CO_2 replaces fossil carbon
Chemicals Solvents, detergents	200 - 750	135 - 565	CO_2 replaces fossil carbon
Engineered Materials Carbon fiber, carbon nanotubes, graphene, carbon ceramics	140 - 400	30 - 84	CO_2 replaces fossil carbon
Polymers Plastic foils, containers, furniture, plastic housings, toys	2 - 25	1 - 20	CO_2 replaces fossil carbon
Agriculture and Food Fertilizer, protein for human consumption, animal feed	> 25	> 40	CO_2 is a new ingredient

Figure 9: Estimated Annual CO_2 Utilization and Revenue Potential by 2050
Source: National Academies of Sciences, Engineering, and Medicine (2023)[33]

The Figure below provides an estimate of the anticipated market opportunity of major product categories on a global scale. Products that could use high volumes of captured CO_2, include aggregates and high-volume circular carbon uses such as jet fuel and methane. [34]

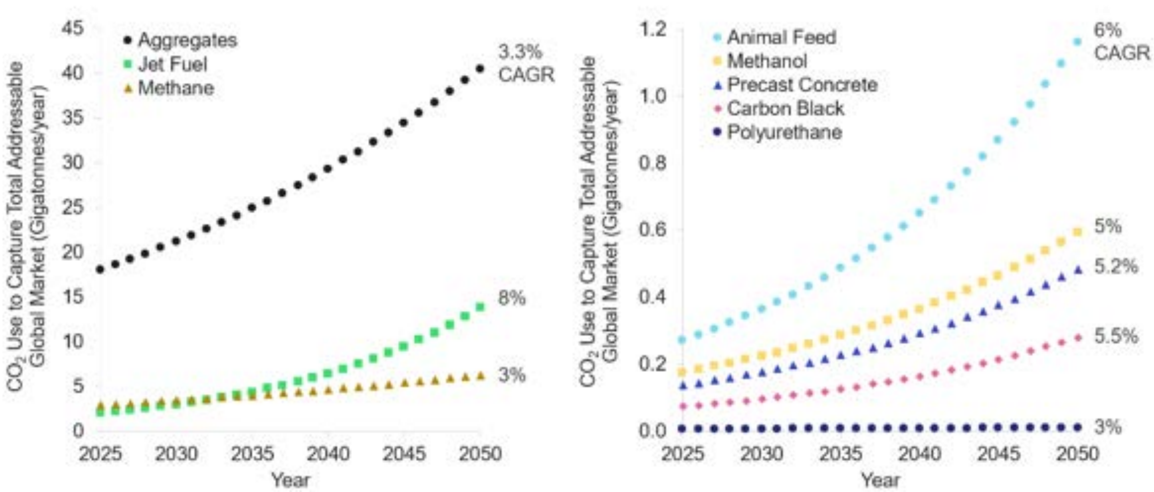

Figure 10: Estimated Annual CO_2 Utilization and Revenue Potential by 2050
Source: National Academies of Sciences, Engineering, and Medicine (2024)[35]

Other consulting groups such as the Oil and Gas Initiative and Boston Consulting Group estimates concur with the National Academies of Sciences study. A white paper by the Oil and Gas Initiative and Boston Consulting Group suggests the captured CO_2 utilization market will vary widely between 10 percent and 33 percent of total captured carbon. The Boston Consulting Group suggests several pathways that will lead to the utilization of CO_2 to ~430-840 million tons per annum (Mtpa) by 2040. Products with the largest market potential identified by the group include:

1. "Construction aggregates make up the largest potential market in terms of CO_2 volume (estimated at ~0.5Gt CO_2 per year), however, low product value makes it challenging to compete with low-cost conventional aggregates.
2. CO_2 cured concrete is a small market in terms of overall CO_2 required (estimated at 40-70 Mtpa CO_2 per year). The technology is almost ready for scaling.
3. E-kerosene is a medium-sized market (estimated at 50-150 Mtpa CO_2 per year) and technology is nearly ready for scaling. However, overall cost is expected to stay well above conventional and other bio-based kerosene prices without significant regulatory incentives.
4. E-methanol is a medium-sized market (estimated at 130-280 Mtpa CO_2 per year) and technology is nearly ready for scaling. However, given that high energy requirements drive the bulk of production cost, the business case is likely to be negative without financial incentives."[36]

The range of products that can be derived from CO_2 utilization in the chemical sector is broad. The Oil and Gas Initiative and Boston Consulting Group suggest that some earlier stage CO_2 uses are in the chemical sector such as green methanol to olefins, dimethyl ether, and formic acid) and some developing uses such as polymers. These markets could become small to medium-sized markets. Other markets that are gaining traction also include leveraging CO_2 to create proteins for animal feed and producing ethanol using CO_2-based microbes.[37] The following Figure summarizes potential classes of chemical products for future captured CO_2 utilization.

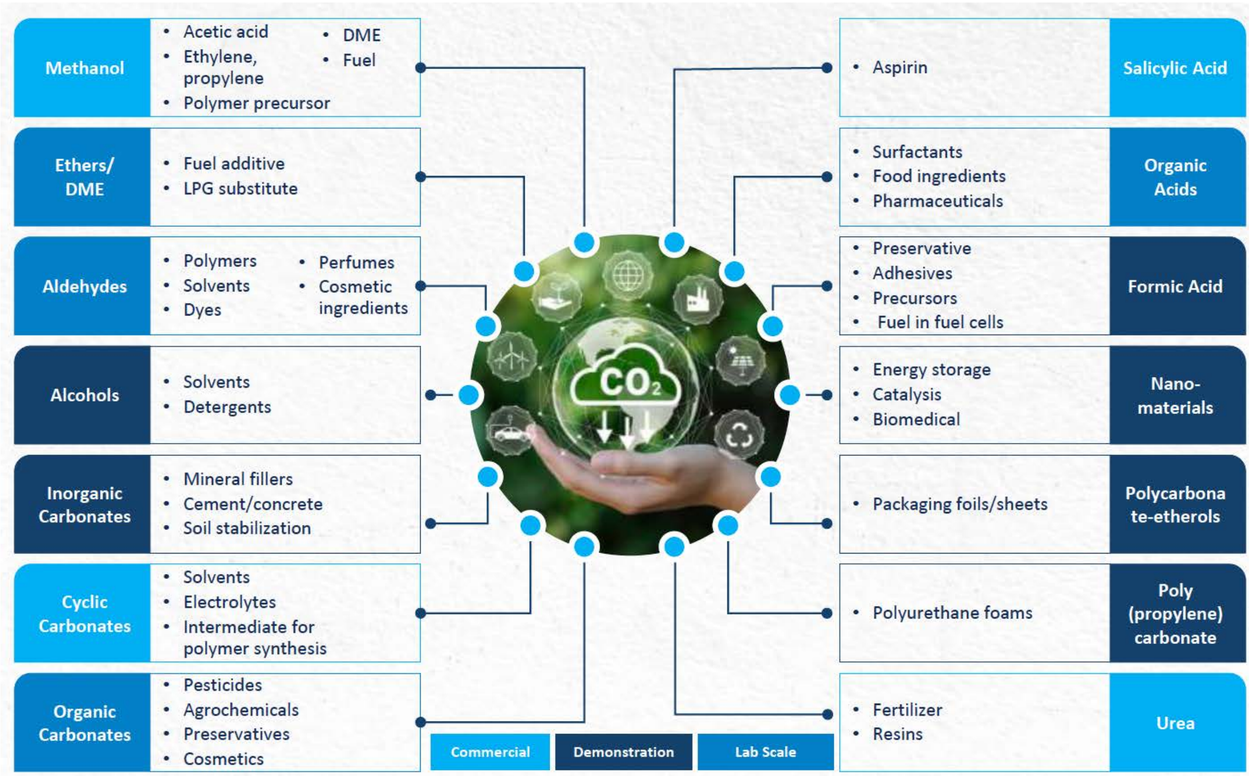

Figure 11: Chemicals Products Derived from Captured CO_2

Source: Reprinted with Permission from Frost & Sullivan (April 2024)[38]

4.0 Carbon Monoxide

As a greenhouse gas, CO_2 contributes to climate change as it accumulates in the atmosphere. One way to reduce the amount of unwanted CO_2 in the atmosphere is to convert this gas into a useful form of carbon that can be used to generate products. One area of interest to FECM is inorganic carbonate products (CO_3^{2-}) and chemicals and fuels derived from carbon monoxide (CO). This section provides background on the CO market, followed by a discussion on opportunities for products and chemicals derived from carbon monoxide.

4.1. Carbon Monoxide Production

The U.S. carbon monoxide market size was valued at $0.51 Billion in 2022. The carbon monoxide industry is projected to grow from $0.54 Billion in 2023 to $0.83 Billion by 2032, exhibiting a compound annual growth rate (CAGR) of 5.50% during the projected period (2023 - 2032).[39]

CO is produced on an industrial scale by the partial oxidation of hydrocarbon gases from natural gas or by the gasification of coal and coke. The majority of CO produced is used immediately downstream and at the plant site for chemical synthesis or steel manufacturing. Other methods of manufacture include incomplete combustion of carbonaceous materials, dehydration of formic acid with sulfuric acid, reduction of carbon dioxide over hot coke and by reacting carbon and oxygen at elevated temperatures. It has been suggested that CO gas streams are currently produced by energy intensive processes such as steam methane reforming or autothermal reforming of methane, and consecutive purification. Carbon monoxide is used by the chemical industry for the synthesis of many compounds such as acetic anhydride, polycarbonates, acetic acid, and polyketones among other uses.[40]

Industrial gas manufacturers that supply CO include Axcel Gases, Sipchem Company, American Gas Products, ATCO Atmospheric and Specialty Gases Private Limited., Messer, Linde plc, Middlesex Gases & Technologies, Inc., Air Products and Chemicals, Inc., Celanese Corporation, Air Liquide and others.[41]

4.2. Carbon Monoxide Uses and Market Drivers

Carbon monoxide is a widely used chemical in the industry especially in the form of syngas.[42] Over 90% of carbon monoxide is used for the production of ammonia, hydrogen, and methanol. The rest is consumed directly as carbon monoxide for the production of phosgene, acrylic acid, acetic acid, dimethyl formamide, propionic acid, pivalic acid, and many other copolymers.[43] The chemicals and ore processing and extraction are the largest segments. CO is consumed in the manufacturing process of several inorganic as well as organic chemicals, including metal carbonyls, titanium dioxide, and benzaldehyde.[44] Carbon monoxide also used as a reducing agent in metals refining and other applications such as food packaging electronics and pharmaceuticals.[45] Metal fabrication is the largest end user of CO (Figure below). In this application, CO is used in fuel gas mixtures with hydrogen and other gases for industrial and domestic heating. The high demand for the product in metal extraction, purification, and fabrication applications is anticipated to propel the growth of this segment. The chemicals and ore processing and extraction are the largest segments. CO is consumed in the manufacturing process of several inorganic as well as organic chemicals, Including metal carbonyls, titanium dioxide, and benzaldehyde.[46]

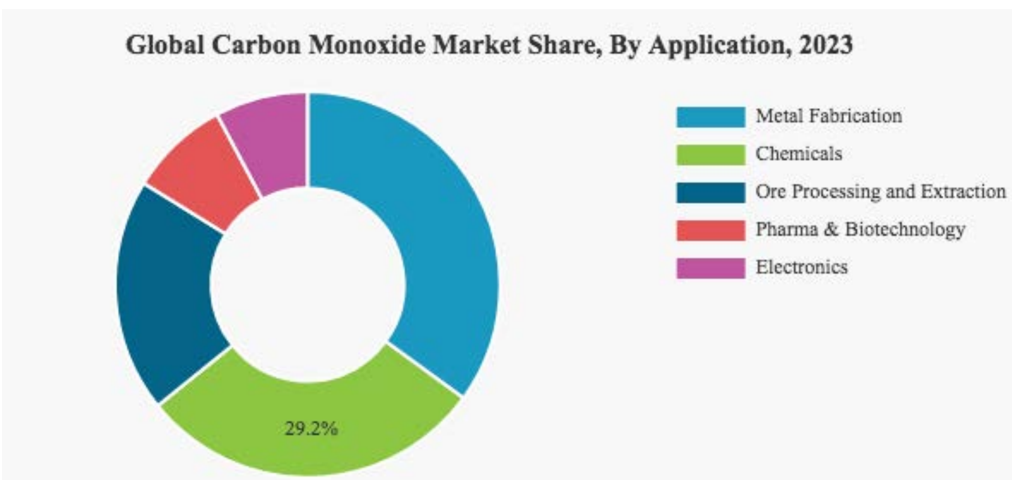

Figure 12: Carbon Monoxide End Uses

Source: Fortune Business Insights (2024)[47]

The demand for CO is expected to rise globally, mainly due to the increasing investment in developing advanced and technical products. This rise in demand is also creating opportunities for market players. The carbon monoxide market is expected to grow even further with more research and development activities.[48] Allied Markets suggests market for carbon monoxide is significantly driven by the rise in demand for both organic and inorganic compounds. Demand for both organic and inorganic chemicals is further driven by an increase in use of these chemicals in manufacturing, construction, and consumer goods, that reflects a growing global economy and technological advancements, as well as the expansion of industrial sectors such as pharmaceuticals, plastics, and textiles. Furthermore, the demand for innovative materials in industries like electronics, automotive, and renewable energy technologies contribute to the growth. Additional market growth is from end use industries including:

1. "Mining and metal extraction activities drives the growth of the carbon monoxide industry. The increased demand for metals globally, fueled by the growth of infrastructure, and innovations in technology.
2. CO is an essential reducing agent in metallurgical operations that helps remove metals from their ores to produce steel and iron. Demand for steel is driven by the growth of infrastructure and industrial expansion.
3. CO is used and reducing agent in many chemical reactions involved in the extraction of non-ferrous metals including copper and lead. The need for these metals in industries such as electronics, automotive, and renewable energy is driving up the use of CO in metal extraction processes."[49]

4.3. CO_2 Derived Carbon Monoxide Products

CO is one of the products derived from CO_2.[50] Before being transformed into a useful product, CO_2 must be chemically converted into CO. The problem is that achieving the CO_2-to-CO conversion requires large energy inputs — and even then, CO makes up only a small fraction of the products that are formed.[51] The following Figure shows the variety of chemicals that can potentially be derived from CO_2, including inorganic carbonates. In the following Figure, CO is also an end product in itself.

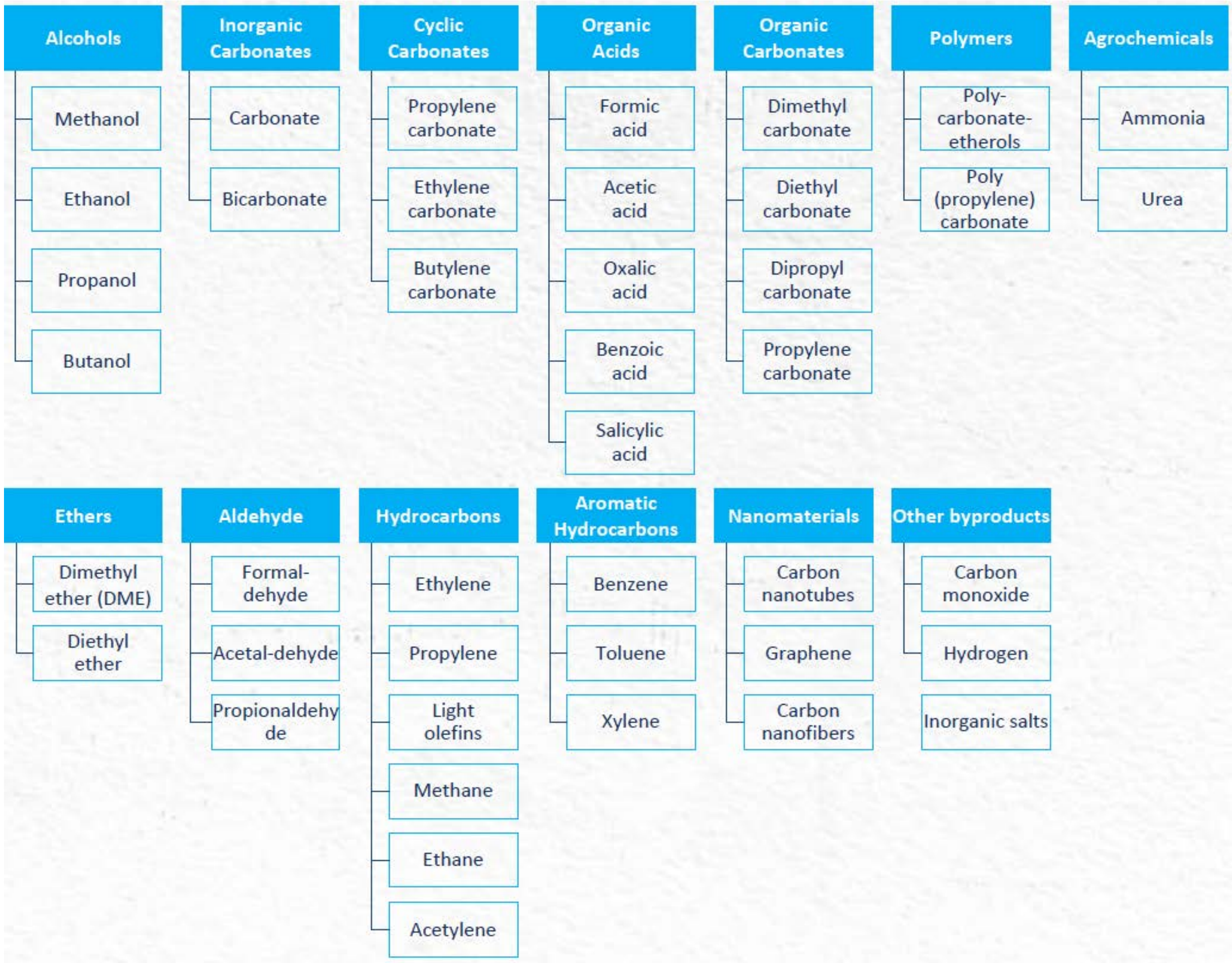

Figure 13: Chemicals Derived from CO_2

Source: Reprinted with permission from Frost & Sullivan (April 2024)[52]

Using various processes, CO_2 can be converted into various carbon-based chemicals and/or fuels. CO_2 could be converted into CO, which often serve as feedstocks for other chemical synthesis. The market will depend on factors such as (1) demand for services provided by carbon-based products; (2) their relative cost compared to fossil-based products, non-carbon-based alternatives, and products derived from carbon sources other than CO_2, such as biomaterial carbon and recycled waste carbon products; (3) availability of inputs that enable net-zero product status, and (4) policy incentives and regulatory frameworks, including CO_2 abatement incentives.[53]

The balance of this section provides an overview of products derived from CO that originate from CCS as DOE expressed an interest in knowing more about inorganic carbonates which are used in the mineralization process of CO_2.

4.3.1 Inorganic Carbonates

CO_2 mineralization has emerged as a novel approach to CO_2 resource utilization. "Mineralization presents significant carbon removal potential but has lacked sufficient research and demonstration funding that could eventually bring it into wider use."[54] This method involves the use of solids containing calcium and magnesium, such as fly ash, gypsum, calcium CO_2, steel slag, waste cement, various magnesium and calcium ores and waste streams to sequester CO_2. The resulting solid carbonates can store CO_2 for an extended period, yielding high value-added chemical products such as magnesium carbonate.[55, 56] Magnesium carbonate is obtained from magnesite ore. It is insoluble in water and any inorganic solvent. Carbonate is used in flooring, fire extinguishing, cosmetics, pharmaceuticals, personal care products, as filler, smoke suppressant, reinforcing agent and other. The global magnesium carbonate mineral market is worth $241.5 million by 2024 and is set to acquire a valuation of $386.7 million by 2034, reflecting a CAGR of 4.8% between 2024 and 2034.[57]

Inorganic carbonates include disodium carbonate, lithium carbonates, calcium carbonate, carbonates of metals, sodium bicarbonate, potassium carbonates, barium carbonate, strontium carbonate, ammonium carbonate (including commercial), and lead carbonate, among others. The global carbonate market, segmented into dimethyl, propylene, ethylene, glycerol, 1,2-epoxydodecane, 1,2-hexadecene, styrene, epichlorohydrin, and others had a market value of $3.5 billion in 2020, and is projected to reach $7.1 billion by 2030, growing at a CAGR of 7.2% from 2021 to 2030.[58]

Inorganic carbonates are suggested as potential end products due to "being low but not lowest in thermodynamic energy content." Annemie Bogaerts and Gabriele Centi suggest "being low but not lowest in thermodynamic energy content, CO_2 should react with other compounds to form chemicals with even lower thermodynamic energy level such as inorganic carbonates."[59]

4.3.2 Fuels

The carbon in CO_2 can be used to produce fuels, including methane, methanol, gasoline and aviation fuels.[60] CO_2-based fuel is being investigated by many companies as drop-in solutions and do not present a need for new infrastructure.[61, 62, 63] Carbon monoxide produced from CO_2 can be used as a fuel by itself or combined with hydrogen and/or water to make many other liquid hydrocarbon fuels as well as chemicals including methanol (used as an automotive fuel), syngas, and so on.[64] Fuels have a large CO_2 utilization potential due to their vast market size.

Ethanol is typically produced using biological processes or as a petrochemical, through ethylene hydration, using fossil fuels. It is also often produced using corn and other crop feedstocks, but this approach is dependent on crops that otherwise could be used to grow food or waste feedstocks.[65] Several efforts are underway to construct pipelines to transport CO_2 from ethanol plants to areas with suitable geologic formations for sequestration.[66] Several companies are making headway. There are companies have developing of ethanol from CO/CO_2 as a feedstock.[67]

4.3.3 Concrete and Aggregates

Inorganic carbonate products could hypothetically be produced in large quantities include:

1. Mineral filers
2. Concrete
3. Soil stabilizers[68]

Some companies are already developing concrete and aggregates by injecting captured CO_2 into the concrete before it hardens.[69, 70, 71, 72, 73, 74] Though CO_2 can be mixed directly with traditional cements in a concrete mixer, fully CO_2-cured concrete uses non-traditional cements that are cured in CO_2 chambers as precast concrete blocks. CO_2 concrete is a key step towards CO_2 emissions reduction.

However, according to the Oil and Gas Initiative and Boston Consulting Group, economics are not yet favorable for aggregates and concrete derived from captured CO_2. For instance, construction aggregates make up the largest potential market by far in terms of CO_2 volume (estimated at ~0.5Gt CO_2 per year), but low product value makes it challenging to compete with low-cost conventional aggregates. In addition, CO_2-cured concrete is a small market in terms of overall CO_2 required (estimated at 40-70 Mtpa CO_2 per year), but the technology is nearly ready for scaling. The economics can be challenging, given high capex requirements for a low-value product.[75]

5.0 Potential Products Organizations Can Purchase under Carbon Utilization Procurement Grants

This section highlights captured CO_2 products that appear relevant to the Carbon Utilization Procurement Grants. Potential products that are at a high level of maturity and/or are available on the market are CO_2 mineralization technologies to produce value-added products for construction.

5.1.1 Carbon Dioxide in Concrete, Cement and Aggregates in Public Works Projects

Concrete is the most widely used material in the world. It is a primary structural material used to build civil infrastructure, including commercial and residential buildings, pavements, bridges, dams, marine structures, industrial plants, pipelines, and water/wastewater infrastructure. The Global Cement and Concrete Association (GCCA) reports that over 14.0 billion m^3 cubic yards of concrete was produced globally in 2020. The GCCA estimates that the global cement and concrete products market value in 2020 was approximately $440 billion.[76]

Several companies are producing limited quantities of CO_2-based concrete and concrete products such as Blue Planet Systems,[77] CarbonCure Technologies,[78] Carbon Built,[79] Carbon Upcycling,[80] Fortera Corporation,[81] and Carbicrete[82] are developing and deploying technologies for mineralizing CO_2 in concrete and aggregates.

CO_2 based concrete and aggregates include (1) carbonation of hardened concrete (2) injection of CO_2 in fresh concrete, (3) injection into reclaimed return water (4) aggregate Manufacturing, (5) recycled concrete fines, (6) concrete solidification through carbonation and (7) production of A-SCM, alternative cements, and fillers like ground limestone.[83, 84]

The types of projects that could theoretically use of concrete that utilizes CO_2: (1) highway construction, (2) school construction, and (3) projects involving the construction or renovation of state buildings.[85]

5.1.2 CO_2 Concrete and Aggregates Regulations in Construction

"Low embodied carbon concrete" rules and projects to reduce the amount of cement in concrete have cropped up around the country, including in Marin County, California; Hastings-on-Hudson, New York; and a sidewalk pilot in Portland, Oregon.

California has enacted legislation specifically for lowering the carbon intensity of concrete. Enacted in 2021, Senate Bill (SB) 596, "Greenhouse Gases: Cement Sector: Net-Zero Emissions Strategy," directs the California Air Resources Board (CARB) to develop a "comprehensive strategy for the state's cement sector to achieve net-zero emissions of greenhouse gases associated with cement used within the state as soon as possible, but not later than December 31, 2045." Cities in California are also adding a CO_2 requirement of materials, for instance, the City of Albany's Climate Action and Adaption Plan addresses embodied carbon. The city intends to also utilize its Sustainable Purchasing Policy, which would prioritize improvements for the highest emissions reduction impact purchasing decisions within each department, including vehicle and fuel purchases and low-carbon concrete.[86] Similarly, in 2020 the mayors of Los Angeles and San Francisco signed the "C40 Clean Construction Declaration," which includes embodied carbon products. The City of Los Angeles has made commitments to reducing embodied carbon for major construction by 50% before 2030.[87] San Francisco's 2021 Climate Action Plan includes requirements pertaining to use of embodied carbon products in construction, for example, the city intends to: (1) phase in policies between 2024-2026 to reduce embodied carbon by more than 10% per project by addressing at least three product categories or building assembly types; and (2) maximize replacing concrete to create more biodiverse green space on public land by 2030.[88]

Colorado House Bill 21-1303 ("Buy Clean Colorado Act") enacted in 2021 provides that – By January 1, 2024, the Office of the State Architect "shall establish by policy a maximum acceptable global warming potential for each category of eligible materials used in an eligible projects" in accordance with certain requirements. Co. Rev. Stat. § 24-92-117(3)(a) (2022). "Eligible material" as defined in the Act means "materials used in the construction of a public project, including … cement and concrete mixtures." The Act defines "Eligible project" as "a public project … for which an agency of government issues a solicitation on or after January 1, 2024 … [not including] any maintenance program for the upkeep of a public project or any road, highway, or bridge project."[89] In Oregon, HB 4139 enacted in 2022, requires the Oregon Department of Transportation to no later than December 31, 2025, establish a program that "Assesses the greenhouse gas emissions attributable to covered materials" the Department of Transportation uses in "construction and maintenance activities for the state's transportation system"; "conducts life cycle assessments of a selected set of the Department of Transportation's construction and maintenance activities;" and "devises strategies for reducing greenhouse gas emissions that include, but are not limited to, improving pavement and bridge conditions." "Covered materials" are not limited to: (1) "concrete, including ready mix concrete, shotcrete, precast concrete and concrete masonry units"; (2) "asphalt paving mixtures"; and (3) "steel." Under this program, ODOT must require contractors to submit "environmental product declarations" (EPD) before the contractor installs the covered materials (except with respect to asphalt paving mixtures), with limited exceptions.[90]

5.1.3 Market Challenges

Challenges include lack of permits and infrastructure for CO_2 transport and sequestration, market acceptance of novel and blended cements, and access to clean energy. The timelines of large industrial projects like these and future availability and acceptance of low-carbon cement are therefore subject to some unpredictability.[91] In addition, concrete production is typically low-margin, and willingness to pay a green premium is low. Therefore, "widespread deployment of CO_2-derived concrete will rely on CO_2 utilization technology players, creating easy-to-adopt solutions that are minimally disruptive to existing manufacturing processes."[92]

6.0 Chemical Industry

As noted at the outset this section reflects an additional interest of the Office of Fossil Energy and Carbon Management. Frost & Sullivan suggest that in the short-to-medium term, CCUS will find wider applications in hard-to-abate industries, such as coal-fired power plants, cement manufacturing, iron and steel, fertilizers, and chemical production through the retrofitting of existing plants. CCUS will be a key decarbonization technology for these sectors, and the demand from the hard-to-abate industries will be a major market driver.[93] As noted, one of the industries that has been hard to decarbonize is the chemical industry. This Section highlights this sector as an example of an opportunity for CCS utilization.

6.1. CO_2 Generated by the U.S. Chemical Industry

The chemical industry is based in part, on fossil energy and hydrocarbon feedstocks. This has created an industry with a significant carbon footprint that continues to grow alongside demand. According to data from the Environmental Protection Agency (EPA), the U.S. chemical industry sector was responsible for 16% of U.S. greenhouse gas emissions in 2022. The chemical industry's CO_2 footprint is over 200 million metric tons of carbon dioxide equivalent per annum. Many industrial processes emit CO_2 through fossil fuel consumption. In addition, several processes also produce CO_2 emissions through chemical reactions that do not involve combustion (Figure below).[94]

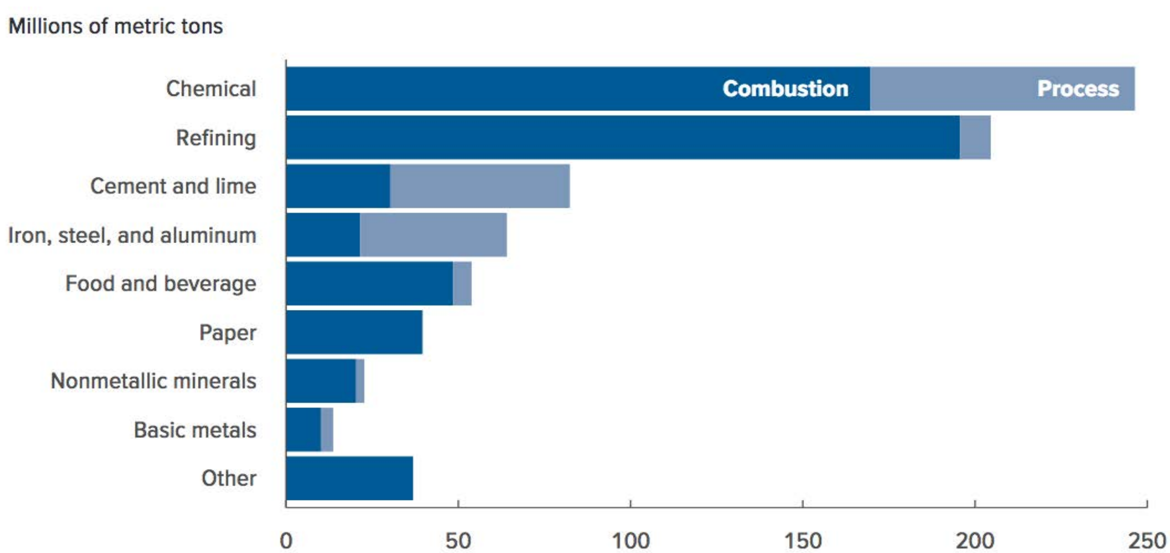

Figure 14: Combustion and Process Emissions of CO_2e from Manufacturing, by Industry, 2021

Source: Congressional Budget Office (2024)[95]

According to the EPA, the Chemicals Sector has the fourth-largest GHG emissions among sectors reporting to the Greenhouse Gas Reporting Program (GHGRP). Emissions from the chemicals sector were 179.9 million metric tons of carbon dioxide equivalent (MMT CO_2e) in 2021. The GHG emissions in this sector are emitted predominantly from facilities located in Texas and Louisiana.[96] The following Figure shows the U.S. distribution of major facility emitters by industry.

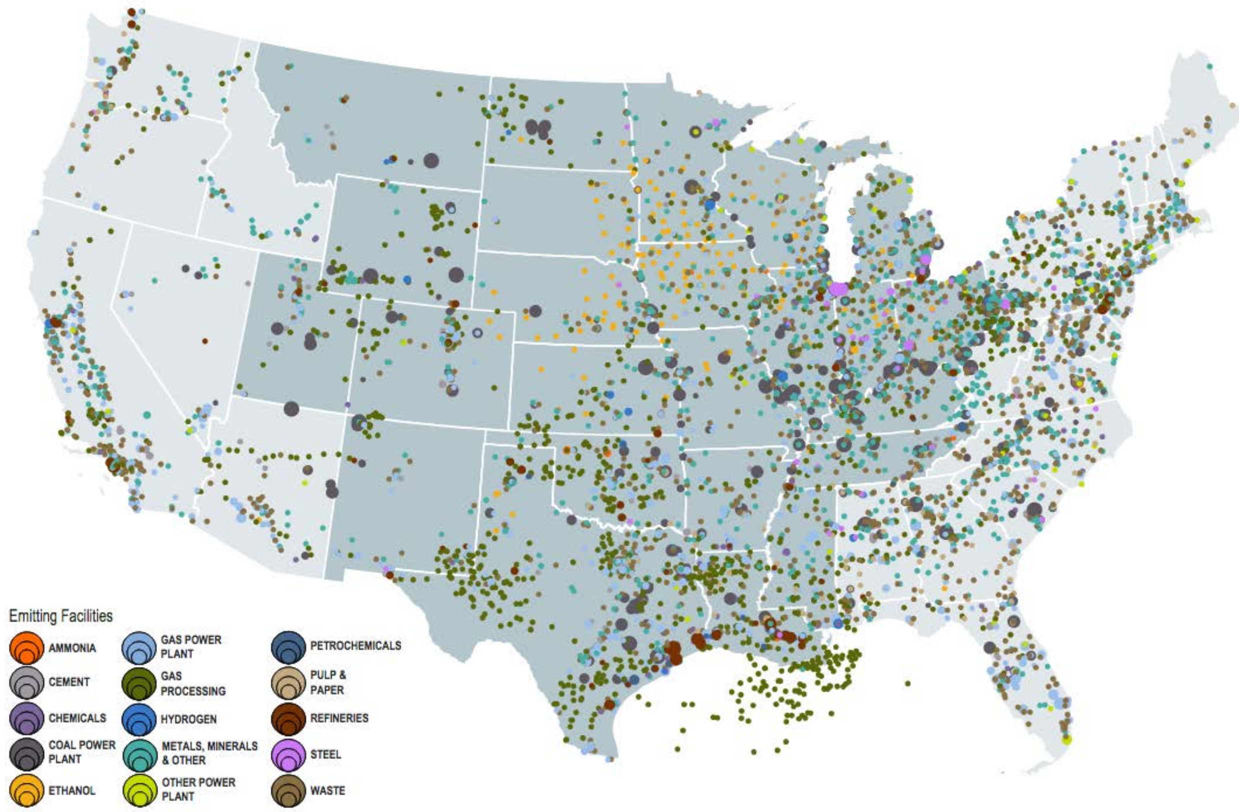

Figure 15: Major Emitter Facilities by Industry and Emissions
Source: Elizabeth Abramson et al, Great Plains Institute (2020)[97]

In 2021, 442 facilities in the Chemicals Sector submitted GHG reports to the EPA. Total reported emissions were 179.9 MMT CO_2e in 2021. Overall, the greenhouse gas emissions reported by the chemicals sector have increased from 163.1 million metric tons CO_2e in 2011 to 179.9 million metric tons CO_2e (10%) in 2021.[98] Table 4 lists Number and type of CO_2 emissions reporting facilities in 2021. The largest emission was reported by petrochemicals, hydrogen production and ammonia manufacturing.

Table 4: U.S. Chemicals Sector – Number and Type of CO_2 Emissions Reporting Facilities in 2021

Sector	Description	Number of reporting facilities in 2021	CO_2 Reported Emissions (MMT CO2e) in 2021
Adipic acid production	Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. Food-grade adipic acid is used to provide some food products with a tangy flavor.	2	1.9
Ammonia manufacturing	Ammonia is mainly used as fertilizer; directly applied as anhydrous ammonia; or further processed into urea, ammonium nitrates, ammonium phosphates, and other nitrogen compounds. Ammonia also is used to produce plastics, synthetic fibers and resins, and explosives.	29	34.4
Hydrogen production	Hydrogen is mostly used in the production of ammonia and other chemicals or in industrial applications such as hydrocracking or hydrotreating processes during petroleum refining, metals treating, and food processing.	114	41.4
Nitric acid production	Nitric acid is used in the manufacture of nitrogen-based fertilizers, adipic acid, and explosives. Nitric acid is also used for metal etching and processing of ferrous metals.	31	0.2
Petrochemical production	The petrochemical production source category consists of processes that produce acrylonitrile, carbon black, ethylene, ethylene dichloride, ethylene oxide, or methanol. • The primary use of acrylonitrile is in the production of synthetic fibers. • Carbon black is used primarily as a reinforcing agent in tires and other rubber compounds, and as a pigment. • Ethylene is used as a feedstock in the production of polyethylene and other chemicals such as ethylene oxide, ethylene dichloride, and ethylbenzene. • Nearly all ethylene dichloride is used in the production of vinyl chloride monomer, which	75	62.9

	is used in the production of polyvinyl chloride, a common plastic. • Ethylene oxide is used as a feedstock in the manufacture of glycols, glycol ethers, alcohols, and amines. • Methanol is used as a feedstock in the production of acetic acid, formaldehyde, and other chemicals.		
Phosphoric acid production	Phosphoric acid is used primarily in the manufacture of phosphate fertilizers, but it is also used in food and animal feed additives.	9	1.3
Silicon carbide production	Silicon carbide is used as an industrial abrasive and to produce ceramics. Applications of silicon carbide include semiconductors; body armor; brakes; clutches; and the manufacture of Moissanite, a diamond substitute	1	0.1
Titanium dioxide production	Titanium dioxide is used as a white pigment in paint manufacturing, paper, plastics, and other applications.	6	2.3
Other chemicals		202	18.7
Totals		442	

Source: U.S. EPA (2023)[99]

Emissions within the chemicals sector continues to increase, with the petrochemical production subsector having the largest increase by 4.2 million metric tons in 2021.[100]

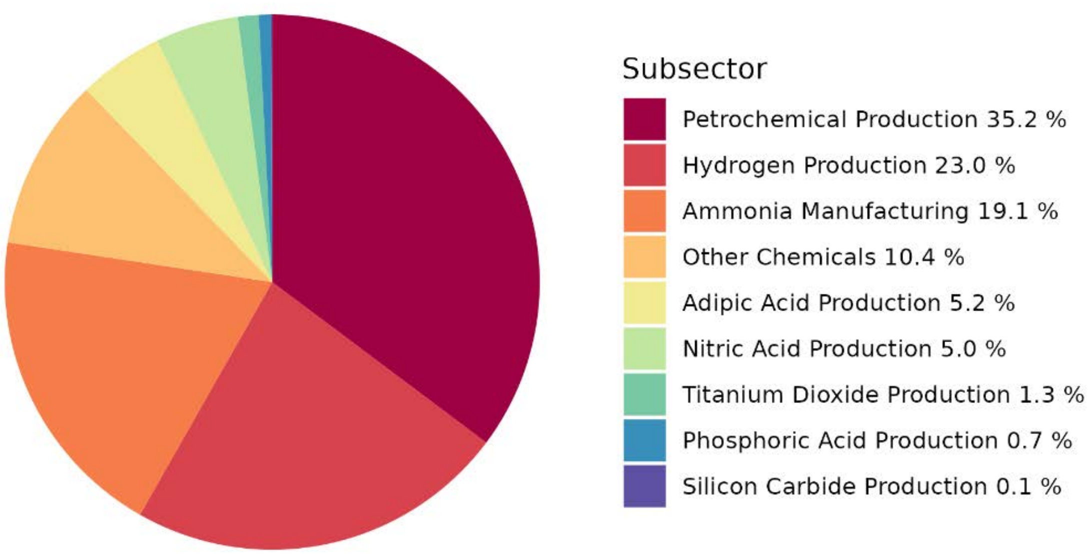

Figure 16: 2021 Total Reported Emissions from Chemicals Sector, by Subsector
Source: U.S. EPA (2023)[101]

A large percentage of emissions from the chemicals sector originate in Texas and Louisiana. In 2021, the emissions from these two states totaled 101.9 million metric tons CO_2e, which is 56.6% of the total emissions from the chemicals sector.

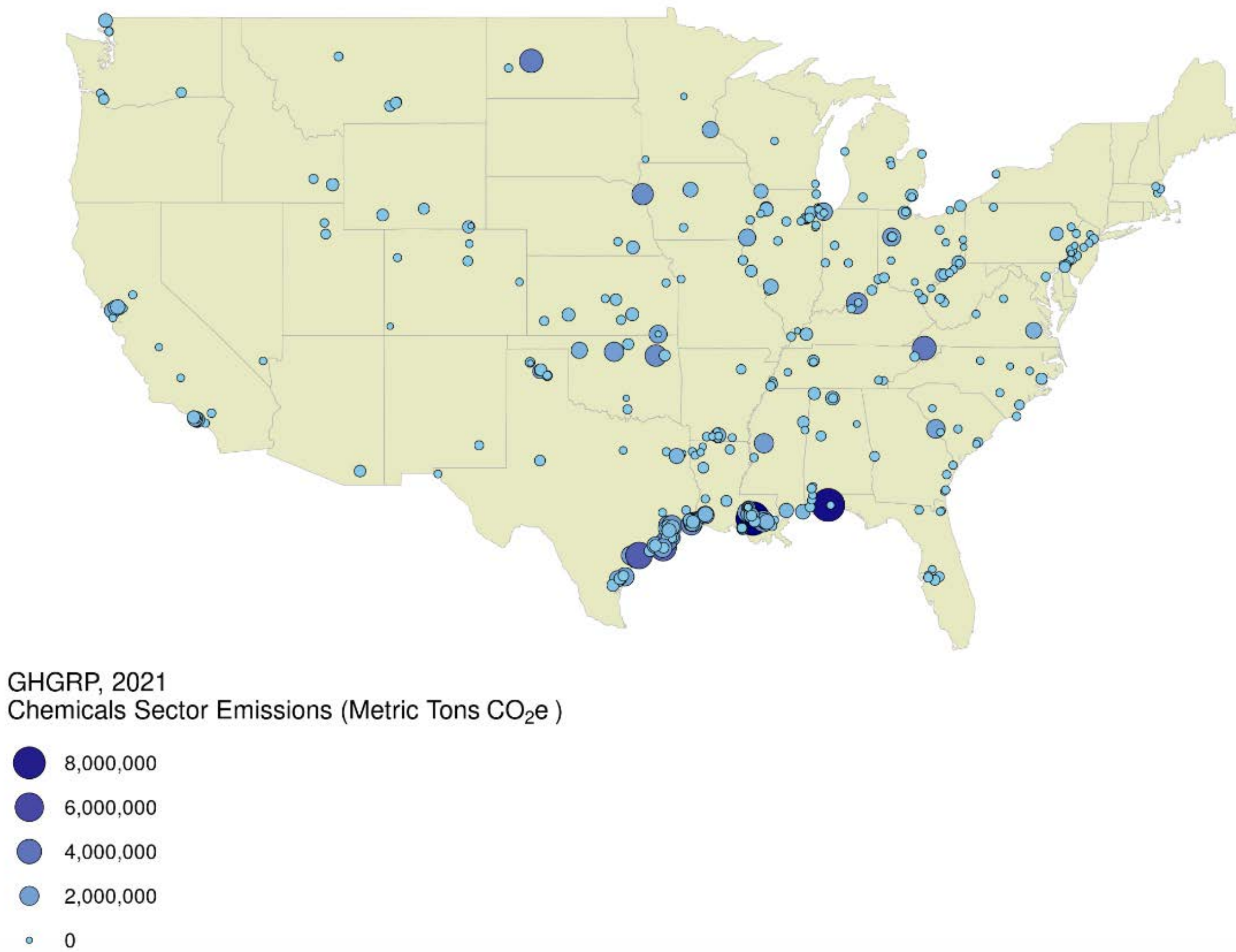

Figure 17: Location and Relative Emissions for Facilities Reporting in the Chemicals Sector (2021)
Source: U.S. EPA (2023)[102]

At present, the chemicals and refining sectors are not on track to meet these targets and will require concerted action to achieve net zero by 2050. The decarbonization pathway could evolve over a phased approach to 2050.[103] Chemicals producers and refineries could decarbonize with deployable technologies that can be adopted within the footprint of their existing asset base, including:

1. "Accelerating energy and operational efficiency measures at most facilities, requiring a ~10% efficiency improvement at >80% of chemicals & refining facilities during this phase
2. Adopting select electrification measures with a strong business case today and procuring or developing clean electricity in chemicals & refining facilities to reduce power-related emissions, accelerated with 48E incentives
3. Transitioning steam methane reformers to clean hydrogen in sectors like ammonia production and refining, accelerated with IRA incentives (~3-5 MTPA by 2030)
4. Installing CCS on high-purity streams (e.g., natural gas processing with streams of >90% CO_2 concentration), accelerated with 45Q incentives
5. Continuing to use existing technologies (e.g., bio-based feedstocks to replace petroleum in existing refineries)."[104]

According to a DOE report, these decarbonization measures "could provide a ~20–25% emissions reduction through 2030 with investments that could clear at least a 10% hurdle rate while laying the foundation for the next phase of deeper decarbonization. Together, these levers represent a ~$90–120B investment opportunity by 2030 that could be implemented largely "inside the fence" of existing plants." For success after 2040, "CCS on dilute streams could play a critical role in abating the remaining emissions gaps and would be needed to capture up to ~170 MTPA of CO_2 in the chemicals & refining sector.[105]

6.2. Chemical Industry and Decarbonization

Large CO_2 emission occur during the production of industrial materials such as iron and steel, cement, aluminum as well as refineries. The top 18 largest volume chemicals are responsible for more than 75% of emissions from all chemicals and petrochemicals produced in the United States. According to Bloomberg, industrial-gas companies, including Air Liquide, Air Products and Chemicals and Linde, emit the most in absolute terms, while agricultural-chemicals producers Yara and CF Industries are among the most intensive relative to sales.[106]

Table 5: Largest Companies Emitting CO_2 – 2021

Parent corporation or entity	2021 Emissions (CO2 equivalent metric tons)	% of CO_2 equivalent emissions from a single facility	Industrial Sectors
Koch Industries	23,053,118	18%	Chemicals, Refineries, Pulp and Paper, Minerals, Waste, Other
CF Industries	17,961,967	50%	Chemicals
Dow Inc.	16,562,065	30%	Chemicals, Power Plants, Waste, Petroleum and Natural Gas Systems, Other
Air Products & Chemicals	12,455,741	21%	Chemicals, Power Plants
Archer Daniels Midland	11,235,811	37%	Other, Chemicals, Pulp and Paper, Waste
SK Capital Partners	10,607,791	81%	Chemicals, Other, Waste
Linde	9,451,344	17%	Chemicals
LyondellBasell Industries	8,339,428	25%	Chemicals, Refineries, Other
Westlke Chemical	6,616,403	42%	Chemicals, Power Plants, Other
Nutrien Ltd.	6,387,111	29%	Chemicals

Source: University of Massachusetts Amherst Political Economy Research Institute, "Greenhouse 100 Polluters Index" (2023)[107]

Decarbonizing chemicals production, and its associated end products, remains limited. The top thirty chemical producers in the U.S. in 2023 are listed in the Table below. The C&EN ranking includes only companies that publicly disclose chemical sales. Many of the largest companies in the industry have made decarbonization commitments that have come in the form of both near-term goals (<2035) and long-term net-zero goals (2050+). Some companies such as Dow have made decarbonization commitments. For instance, Dow's total emissions were 112,028 $ktCO_2e$ in 2022, of which 25% were Scope 1, 4% were Scope 2 and 72% were Scope 3. Dow has targets for being carbon neutral for Scope 1, 2 & 3 by 2050.[108]

Table 6: U.S. Top 30 Chemical Companies – 2024

Rank	Company	Headquarters	Sector
1	Dow	Midland, Michigan	Diversified
2	ExxonMobil	Spring, Texas	Petrochemicals
3	LyondellBasell Industries	Houston, Texas	Petrochemicals
4	Mosaic	Tampa, Florida	Fertilizers
5	Air Products	Allentown, Pennsylvania	Industrial gases
6	DuPont	Wilmington, Delaware	Diversified
7	Chevron Phillips Chemical	The Woodlands, Texas	Petrochemicals
8	Celanese	Irving, Texas	Diversified
9	Albemarle	Charlotte, North Carolina	Specialties
10	Eastman Chemical	Kingsport, Tennessee	Diversified

11	Westlake Chemical	Houston, Texas	Petrochemicals
12	Corteva Agriscience	Indianapolis	Agrochemicals
13	Ecolab St.	Paul, Minnesota	Process services
14	CF Industries Holdings	Northbrook, Illinois	Fertilizers
15	Lubrizol	Wickliffe, Ohio	Specialties
16	Honeywell International	Charlotte, North Carolina	Fluorochemicals
17	Chemours	Wilmington, Delaware	Diversified
18	Huntsman	The Woodlands, Texas	Diversified
19	Olin	Clayton, Missouri	Chlorine chemistry
20	Occidental Petroleum	Houston, Texas	Petrochemicals
21	FMC Corp	Philadelphia, Pennsylvania	Agrochemicals
22	Cabot	Boston	Specialties
23	Trinseo	Wayne, Pennsylvania	Polymers
24	H.B. Fuller	St Paul, Minnesota	Specialties
25	Avient	Avon Lake, Ohio	Pigments
26	Tronox	Stamford, Connecticut	Pigments
27	NewMarket Corp.	Richmond, Virginia	Fuel additives
28	Avantor	Radnor, Pennsylvania	Laboratory chemicals
29	ChampionX	The Woodlands, Texas	Oil field chemicals
30	Ascend Performance Materials	Houston, Texas	Polymers

Source: C&EN News, (2024)[109]

According to S&P Global, more than 70% of the world's top 100 chemicals producers have committed to carbon neutrality by 2050, and more have set interim targets. For instance, BASF has committed to a 25% reduction in its absolute Scopes 1 and 2 emissions by 2025 compared to 2018. Dow Chemical Co. has committed to a 15% reduction by 2030 versus 2020, and LyondellBasell Industries has committed to a 42% reduction by 2030 compared to 2020. All three companies, as illustrative examples, are aiming for carbon neutrality in terms of Scopes 1 and 2 emissions by 2050.[110]

In a study of more than 20 decarbonization projects in industrial clusters, they refer to as “chemical parks,” in the European Union, McKinsey & Co conclude that players can reduce emissions by pursuing steam generation, utilizing residual heat, changing electricity procurement, and improving energy efficiency. McKinsey & Co define, “chemical park” as a conglomerate of chemical production plants—either owned by a single company or multiple companies—that shares infrastructure, such as utility supply and site services.[111]

Below are examples of CO_2 reduction initiatives in the chemical industry.

Ammonia Plants

It has been suggested that the chemical processes of ethylene oxide and ammonia production, natural gas processing and steam-methane reforming for hydrogen production are potential as first sources for CO_2 capture because of the high purity, i.e. over 95%.[112] In 2022, ammonia was produced by 16 companies at 35 plants in 16 States. About 60% of total U.S. ammonia production capacity was in Louisiana, Oklahoma, and Texas because of their large reserves of natural gas, the dominant domestic feedstock for ammonia.[113] CF industries Holdings, Inc.; Nutrien Ltd.; Koch Nitrogen Co., LLC; and Dyno Nobel, Inc., in descending order of production capacity, accounted for 72% of total U.S. ammonia production capacity in 2018. The largest U.S. producer of anhydrous ammonia by quantity is CF Industries, with 5 production facilities in Louisiana, Oklahoma, Mississippi, and Iowa.[114]

Ammonia producers are making efforts in CCS. For example, in Louisiana, Exxon entered an agreement to store up to 2 million metric tons per year of CO_2 captured from CF Industries' ammonia plant in Donaldsonville, starting in 2025. CF Industries to capture up to 2 million metric tons of CO_2 from operations.[115] CF Industries is investing $200 million to build a CO_2 dehydration and compression unit at its Donaldsonville, Louisiana, facility to enable captured CO_2 to be transported and stored. ExxonMobil will then transport and permanently store the captured CO_2 in secure geologic storage it owns in Vermilion Parish. EnLink's transportation network will be used to deliver CO_2 to permanent geologic storage.[116]

Ethylene

By the end of 2022, the U.S. had 34 ethylene facilities in the U.S.[117] Manufacturers include Dow, Exxon Mobil Corporation, Shell Global, Chevron Phillips Chemical, LyondellBasell Industries Holdings B.V, BASF SE, Westlake Corporation, NOVA Chemicals and many others.[118]

Ethylene is mainly produced from Naphtha (i.e. 43%) and ethane (i.e. 35%). On a global scale the ethylene production accounts for almost 13% of the global petrochemical industry's CO_2 emissions. The issue is the manufacturing method: steam cracking is an energy intensive process which generates 1.2 tons of CO_2 emissions per ton of ethylene produced.[119] Conventional cracking generates roughly 1–1.8 metric tons (Mt) of CO_2 for every metric ton of ethylene produced.[120] With the market for ethylene projected to grow to 340 Mt by 2050 and a commitment to achieve net-zero carbon emissions in the same time frame, the industry is facing challenges of CO_2.[121]

Ethylene is used in the manufacture of polyethylene (PE), polyethylene terephthalate (PET)/polyester, polyvinyl chloride, polystyrene and ethylene oxide (EO)/ethylene glycol, as well as fibers and other organic chemicals. PE accounts for 60% of global ethylene demand. Commercial production of ethylene is carried out by steam cracking hydrocarbon feedstocks.[122]

6.3. Profile of the U.S. Chemical Industry

The International Trade Administration of the Department of Commerce identifies the chemical industry as one of the largest manufacturing industries in the United States, with more than 13,000 companies producing more than 70,000 products.[123] The U.S. Chemical sector distributes those products to more than 750,000 end users. Production involves two common processes—steam cracking and steam methane reformation—totaling a large concentration of emissions.[124]

The U.S. Chemical Sector is made up of four distinct components: agricultural chemicals, basic chemicals, specialty chemicals, and consumer products. Each component supports a specific and integral part of America's chemical needs.

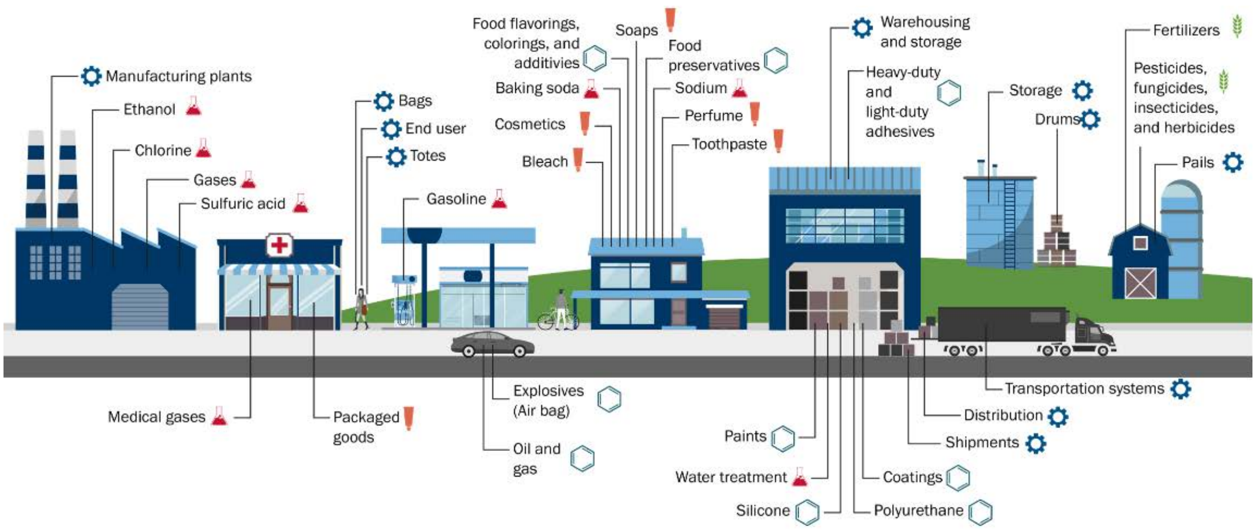

Figure 18: Examples of Where Chemical Products are Used Across Sectors

Source: Department of Homeland Security, Cybersecurity and Infrastructure Security Agency (2023)[125]

There are about 11,128 chemical manufacturing facilities in the U.S. segmented into:[126]

1. "**Agricultural chemical industry**: The agricultural chemical industry supplies farmers and home gardeners with fertilizers, herbicides, pesticides, and other agricultural chemicals. The segment also includes companies involved in the formulation and preparation of agricultural and household pest control chemicals, as well as companies responsible for manufacturing and storage. In 2022, there were 991 establishments in this subsector.
2. **Consumer products** include packaged products often referred to as "household products." This includes everything from soaps and detergents to oral hygiene and hair and skin care products to personal care products (e.g., cosmetics, deodorants). There were 2,356 establishments in this sector.
3. **Basic chemicals** segment produces both inorganic and organic chemicals. Organic chemicals are used in the production of other chemicals and to make products such as dyes, plastics, and petrochemical products. Inorganic chemicals usually are used to make solid and liquid chemicals and industrial gases; sodium, sulfuric acid, and chlorine are some of the most common. Inorganic chemicals also serve as catalysts in the manufacture of chemicals (used to speed up or aid a reaction). There are 2,446 establishments in this subsector. Subsegments include:

    a. Petrochemical – 459 refineries in 2022
    b. Chlorine
    c. Sulfuric acid
    d. Industrial gases

4. **Specialty chemicals** are individual molecules or mixtures of molecules (i.e., formulations) that are manufactured on the basis of a unique performance or function. Many other sectors rely on specialty chemicals for their products, including automotive, aerospace, agriculture, and cosmetics and food, among others. In 2017, there were 2,420 establishments in this subsector."[127]

The chemicals sector comprises thousands of companies of various sizes throughout multiple value chains. However, some segments are more concentrated than others. For example,

1. "Domestic production of key bulk chemicals (e.g., ethylene, propylene, and BTX) is concentrated in five primary producers that comprise ~50% of the U.S. market across ~40 facilities.
2. Inorganic and specialty chemicals production is highly concentrated. Inorganic chlor-alkali production has five domestic producers, accounting for ~85% of production capacity
3. 75% of specialty chemical ammonia is produced by five primary producers."[128]

U.S. chemical manufacturing facilities are concentrated in five states, including California, Texas, Ohio, Illinois, and Pennsylvania.

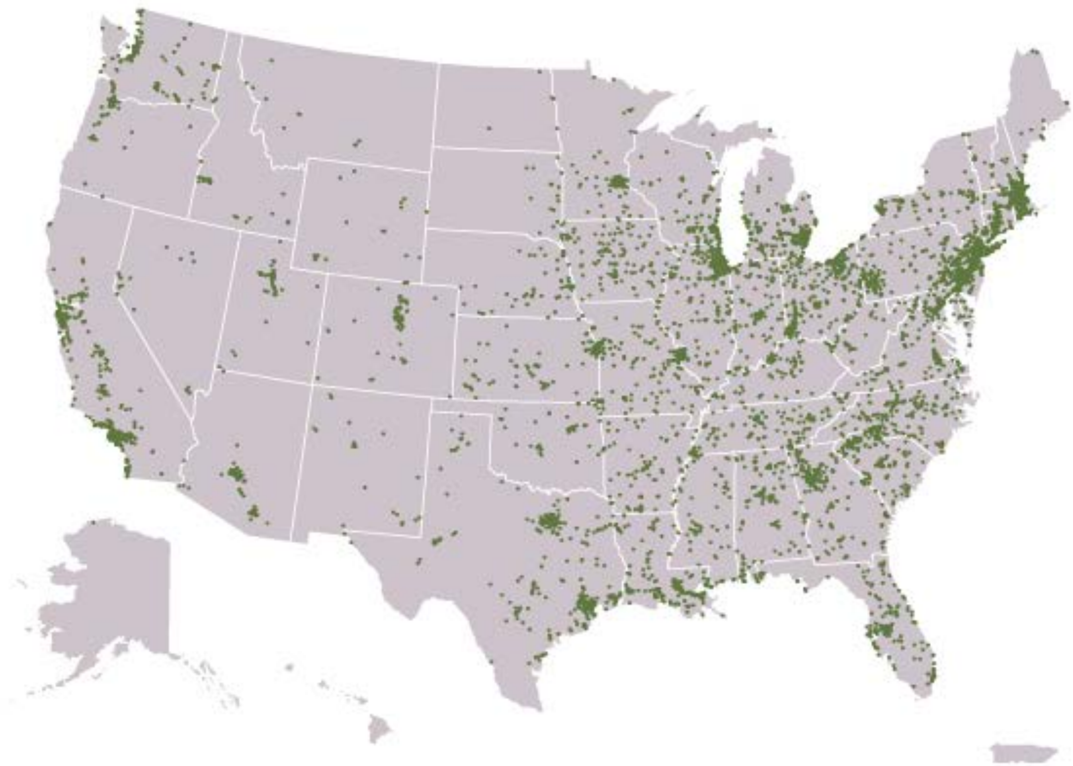

Figure 19: Location of Chemical Manufacturing Facilities
Source: U.S. Environmental Protection Agency (2016)[129]

A large percentage of chemical industries are located in regions with renewable energy resources like solar as shown in the following Figure.

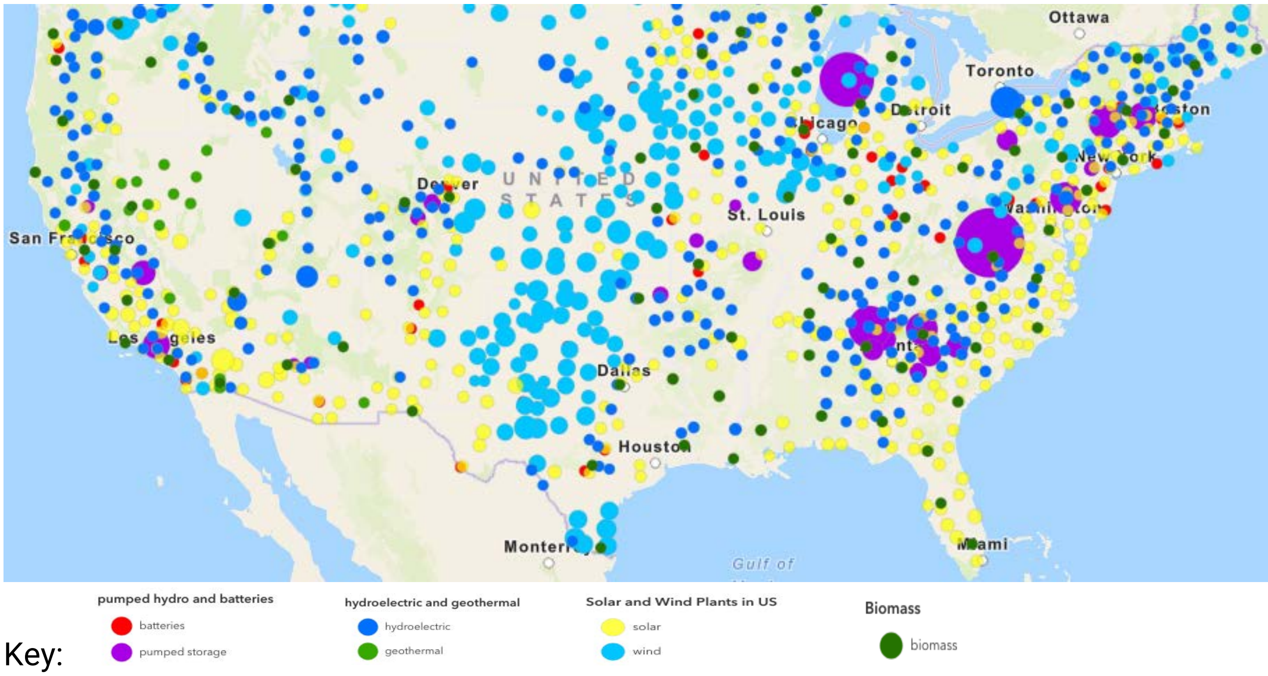

Figure 20: Renewable Energy in the U.S. (2024)
Source: University of Minnesota (2023)[130]

6.4. Examples of Products in the Chemical Industry

Using various processes, CO_2 can be converted into various chemicals. The balance of this section provides examples of potential high value products from CO_2 utilization.

6.4.1 C2+ Compounds

C2+ compounds are important targets for CO_2 utilization because they constitute fuels, commodity chemicals, and chemical feedstocks. Key C2 compound targets are ethylene, ethanol, oxalate, and oxalic acid (for example, shown in the following Figure).

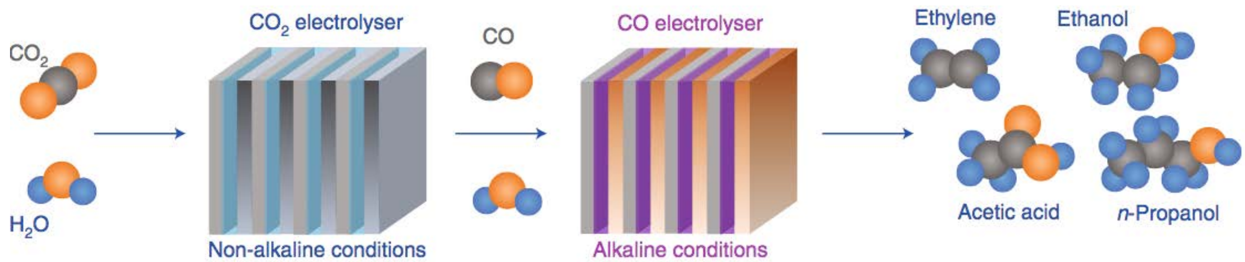

Figure 21: Schematic of a Two-Step Electrolysis Process for CO_2 Conversion to Multi-Carbon Products Using Only CO_2 and H_2O as Reactants

Source: Matthew Journy, et al (2019)[131]

In their analysis of electrochemical conversion of CO_2 to value-added chemical products, Matthew Journey and colleagues show the economic feasibility and improved environmental impact of a high-volume commercial process generating acetic acid and ethylene compared to the current state of the art. Acetic acid is a bulk and basic chemical, and its production capacity was in 2022, market volume of acetic acid worldwide amounted ~ 17.48 million metric tons. It is forecast that the market volume of this organic compound will grow to around 23.6 million metric tons worldwide in the year 2030.[132] Ethanol and higher alcohols, as well as liquid (C5+) hydrocarbons, are not only basic chemicals but also engine fuels and fuel additives.[133]

Other C2+ compounds that could be synthesized from CO_2 include alcohols, carboxylic acids, fuels, pigments, and proteins.[134] The global carboxylic acid market size was valued at $17.1 billion in 2022 and is projected to reach $30.8 billion by 2031, registering a CAGR of 6.8% during the forecast period (2023-2031). Key market drivers include the demand for natural preservatives and additives for sour taste in food and beverages drives the growth of carboxylic acid. Additionally, consumer preference for green and bio-based products presents a significant opportunity for the carboxylic acid market.[135]

6.4.1 CO_2-based Proteins

CO_2-based protein production by microbes is another CO_2 utilization pathway that has been proposed.[136] The proteins have applications in human and animal feed.[137] There is a large U.S. market for animal feed, expected to grow to $1.95 billion in 2024, and is expected to reach $2.44 billion by 2029,growing at a CAGR of 4.68% during the forecast period (2024-2029).[138]

Several companies are developing CO_2-based proteins.[139] For example, Novozyme and partners are investigating the production of proteins through fermentation, using biological and electrochemical processes, the consortium partners will process CO_2 and turn it into acetate, which is vinegar – a substance already present in the metabolism of the microorganisms used for fermentation. The acetate can then produce proteins that can be used directly in human food. By creating alternatives to animal proteins, the foundations believe they can reduce the need for meat and dairy production, which puts a significant strain on natural resources, by using land for the animals and growing crops to feed them. The process eliminates the use of sugar, which is an additional benefit.[140]

6.4.2 Carbonate Solvents

Carbonate solvents are an important component of the electrolyte inside lithium-ion batteries, which help to enhance battery performance and longevity, enabling the advancement and adoption of electric vehicle technology. There is an interest in manufacturing carbonate solvent from CO_2. For example, in early 2024, Dow announced intentions to invest in ethylene derivatives including the production of carbonate solvents, critical components to the supply chain of lithium-ion batteries. The company plans to capture CO_2 from the ethylene oxide manufacturing process and will utilize it to produce carbonate solvents needed for the electrification of vehicles.[141]

6.4.3 Niche Products: Diamonds, Perfumes, Liquor and Others

The chemical industry has been subject to fundamental shifts including increased consumer demand for lower-carbon products and increased consumer awareness of recycling and the use of recycled materials and greater demand for resource-efficient production. Currently, there are limited CO_2 to CO product lines, including:[142]

- Textiles - e.g., plastic-based clothing textiles
- Chemicals
- Consumer packaging - e.g., packaging for shampoo and skincare products) - These are products customers have been willing to pay a premium for initiatives focused on decarbonization

Consumer-facing products made with CO_2 might not have a large CO_2 utilization potential by volume but, are high margin and target consumers with an interest in green products such as CO_2-derived products. Examples of such products on the market of in development include:

- Liquor, perfumes and hand sanitizers, volumes are low with high margins[143]
- Limited edition sunglasses made from bioplastic, made from carbon sequestered in farm and forest waste[144]
- Synthetic textiles[145]
- Diamonds[146]

Increasingly, consumers are willing to pay for products that demonstrate carbon negative chemistry, thereby, increasing demand and incentivizing firms to produce more to preserve their market share, maintain their reputation, or increase profits. For example, a 2023 joint study by McKinsey & Co. and NielsenIQ, "consumers care about sustainability—and back it up with their wallet," found that between 2018 to 2022, sales of products with environmental, social, and governance claims grew by roughly 28% compared to 20% for products that made no social or sustainability claims.[147] In addition, one study found that green chemistry-marketed products significantly outperform their conventional counter-parts in consumer markets. The study also suggested investor and consumer pressures have forced manufacturers to develop and invest in sustainable and green chemistry products.[148] The value of global green chemicals was an estimated $121.5 billion in 2022 and is projected to reach $319.45 billion in 2032, growing at a CAGR of 10.20% during the forecast period from 2023 to 2032. The market is driven by the growing awareness of environmental concerns, regulations promoting sustainability, and increasing consumer demand for eco-friendly products.[149]

6.4.4 Polymers and Polymer Precursors

CO_2 can be used in the synthesis of a range of intermediates for use in chemical and pharmaceuticals production. Conversion methods require the use of catalysts. There are five key end products of polymers: polycarbonates, polyols/polyurethanes, polyolefins, polyhydroxyalkanoates and Polyethylene terephthalate. Each has differing market size and penetration.[150] One of the most promising technologies is the use of CO_2 to make various polymers, such as polycarbonates. Polymers and polymer precursors are high-demand commodities. Several CO_2-based polycarbonates are commercially available, containing up to 50 percent CO_2 by weight. For instance, Covestro AG in partnership with RWTH Aachen University developed a catalyst for transforming CO_2 into polyols, a building blocks for polyurethanes such as foams and binders for mattress foam, sports floor binders, and car interiors.[151] CO_2-based polyurethane is another product under development. Polyurethanes are widely used in various fields such as automotive, furniture, mattresses, construction, and industrial applications including high-performance foams, coatings, adhesives, sealants, elastomers, and more.[152]

Boston Consulting Group suggest that producing polymers using captured CO_2 has the potential to develop into several small to medium-sized markets. There are five key end products of polymers: polycarbonates, polyols/polyurethanes, polyolefins, polyhydroxyalkanoates and Polyethylene terephthalate. Each has differing market size and penetration.[153]

The global market for polymers is expected to grow from a value of ~$ 716 billion in 2022 and is expected to reach approximately $1,207.11 billion by the end of 2032, growing at a compound annual growth rate (CAGR) of 5.4% from 2023 to 2032. The major market driver is one of its uses in many industries, including the medical, aerospace, packaging, automotive, construction, and electrical appliances industries. Other polymer uses include in fibers, rubbers, and fabrics, and for some plastic applications, such as materials in vehicles and appliances.[154]

7.0 Summary and Conclusion

The primary purpose of this report was to see what information is available to size the current and future market for CO_2-derived products that could potentially be purchased by states, local government and public utilities – i.e., those entities which might apply for a Carbon Utilization Procurement Grant. In addition, this report explores other questions of interest to the Office of Fossil Energy and Carbon Management (FECM) regarding opportunities for inorganic carbonate products (CO_3^{2-}), chemicals and fuels derived from CO as well as the market for CO_2 derived products in the chemical industry. The market for captured CO_2 is still nascent. However, most activity appears to be taking place in the concrete industry. There appear to be many applications in the concrete industry that are of potential interest to states, municipalities and utilities that are considering participation in the Carbon Utilization Procurement Grant.

Endnotes

1 U.S. Department of Energy, "Funding Notice: Bipartisan Infrastructure Law: Carbon Utilization Procurement Grants," April 29, 2024

2 U.S. Department of Energy, "UPGrants Eligible Entities," Accessed October 4, 2024

3 Robert Osei-Kyei, et al, "Critical review of the drivers and barriers for adopting net zero carbon procurement for construction projects," December 2024

4 Congressional Budget Office, "Carbon Capture and Storage in the United States," December 13, 2023

5 Congressional Budget Office, "Carbon Capture and Storage in the United States," December 13, 2023

6 Frost & Sullivan, "Technology Growth Opportunities in the Synthesis of Chemicals from Carbon Dioxide (CO2)," April 2024

7 Frost & Sullivan, "Global Oil and Gas Industry Outlook and Growth Opportunities, 2024," June 2024

8 Frost & Sullivan, "Global Oil and Gas Industry Outlook and Growth Opportunities, 2024," June 2024

9 Congressional Budget Office, "Carbon Capture and Storage in the United States," December 13, 2023

10 Congressional Budget Office, "Carbon Capture and Storage in the United States," December 13, 2023

11 Congressional Budget Office, "Carbon Capture and Storage in the United States," December 13, 2023

12 Frost & Sullivan, "Global Oil and Gas Industry Outlook and Growth Opportunities, 2024," June 2024

13 PWC, "Proposed regulations provide rules on Section 45V credit eligibility, greenhouse gas emissions rate," February 2024

14 U.S. Congress, Pub. L. No. 117-169, § 13104, 136 Stat. 1818, 1924-29; Congressional Research Service, "The Section 45Q Tax Credit for Carbon Sequestration," August 25, 2023

15 Congressional Budget Office, "Carbon Capture and Storage in the United States," December 13, 2023

16 See for example, John Bistline, Neil Mehrotra, and Catherine Wolfram, "Economic Implications of the Climate Provisions of the Inflation Reduction Act," Brookings Papers on Economic Activity (March 2023); Goldman Sachs, "Carbonomics: The Third American Energy Revolution" (March 22, 2023); Credit Suisse, "U.S. Inflation Reduction Act—A Tipping Point in Climate Action," (September 28, 2022); BNEF is forecasting the 45Q credit could

total over US$100 billion between 2023 and the early 2030s, in "US is Set to Expand Global Lead in Capturing Carbon," (July 15, 2024)

17 Elizabeth Abramson, Dane McFarlane, and Jeff Brown, "Transport Infrastructure for Carbon Capture and Storage," 2020

18 MarketsandMarkets, "Industrial Gases Market by Type (Oxygen, Nitrogen, Hydrogen, Carbon Dioxide, Acetylene, Inert Gases), End-use Industry (Chemicals, Electronics, Food & Beverages, Healthcare, Manufacturing, Metallurgy, and Refining), and Region - Global Forecast to 2028," February 2028

19 Frost & Sullivan, "Technology Growth Opportunities in the Synthesis of Chemicals from Carbon Dioxide (CO2)," April 2024

20 Craig Bettenhausen, "We are mining CO_2 in America," *Chemical & Engineering News*, April 30, 2023

21 Frost & Sullivan, "Global market overview of the industrial gases," September 2024

22 MarketsandMarkets, "Industrial Gases Market by Type (Oxygen, Nitrogen, Hydrogen, Carbon Dioxide, Acetylene, Inert Gases), End-use Industry (Chemicals, Electronics, Food & Beverages, Healthcare, Manufacturing, Metallurgy, and Refining), and Region - Global Forecast to 2028," February 2028

23 Frost & Sullivan, "Technology Growth Opportunities in the Synthesis of Chemicals from Carbon Dioxide (CO2)," April 2024

24 Henriette Naims, "Economics of carbon dioxide capture and utilization—a supply and demand perspective," May 2016

25 MarketsandMarkets, "Carbon Capture, Utilization, and Storage Market by Service (Capture, Transportation, Utilization, Storage), Technology (Chemical Looping, Solvents & Sorbent, Membranes), End-Use Industry, and Region - Global Forecast to 2030," February 2024

26 U.S. Government Accountability Office, "Opportunities Exist to Improve the Department of Energy's Management of Risks to Carbon Capture Projects," May 2024

27 Goldman Sachs, "Carbonomics: The Third American Energy Revolution," March 22, 2023

28 Congressional Research Office, "Carbon Capture and Sequestration (CCS) in the United States," October 2022

29 Frost & Sullivan, "Innovations in Carbon Capture Utilization (CCU) Strategies: Sustainable Approaches and Value Creation," July 2024

30 National Academies of Sciences, Engineering, and Medicine, "Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities," 2024

31 National Academies of Sciences, Engineering, and Medicine, "Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities," 2024

32 National Academies of Sciences, Engineering, and Medicine, "Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities," 2023

33 National Academies of Sciences, Engineering, and Medicine, "Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities," 2023
34 National Academies of Sciences, Engineering, and Medicine, "Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities," 2024
35 National Academies of Sciences, Engineering, and Medicine, "Carbon Dioxide Utilization Markets and Infrastructure: Status and Opportunities," 2024
36 Oil and Gas Initiative and Boston Consulting Group, "Carbon capture and utilization as a decarbonization lever," White paper, April 2024
37 Oil and Gas Initiative and Boston Consulting Group, "Carbon capture and utilization as a decarbonization lever," White paper, April 2024
38 Frost & Sullivan, "Technology Growth Opportunities in the Synthesis of Chemicals from Carbon Dioxide (CO2)," April 2024
39 Market Reseach Future, "US Carbon Monoxide Market Research Report Information By Application (Metal Fabrication, Chemicals, Ore Processing & Extraction, Pharma & Biotechnology, and Electronics)–Market Forecast Till 2032," July 2024
40 Wilbur S, Williams M, Williams R, et al., "Toxicological Profile for Carbon Monoxide," Agency for Toxic Substances and Disease Registry, June 2012
41 MarketsandMarkets, "Industrial Gases Companies - Air Liquide (France) and Linde plc (England) are Leading Players in the Industrial Gases Market," February 2024
42 Akash Kaithal, et al, "Carbon monoxide and hydrogen (syngas) as a C1-building block for selective catalytic methylation," 2021
43 S&P Global, "Carbon monoxide production from syngas via cryogenic partial condensation process," 2016
44 Fortune Business Insights, "Carbon Monoxide Market Size, Share & Industry Analysis, By Application (Metal Fabrication, Chemicals, Ore Processing and Extraction, Pharma & Biotechnology, and Electronics) and Regional Forecast, 2024-2032," July 8, 2024
45 Fortune Business Insights, "Carbon Monoxide Market Size, Share & Industry Analysis, By Application (Metal Fabrication, Chemicals, Ore Processing and Extraction, Pharma & Biotechnology, and Electronics) and Regional Forecast, 2024-2032," July 8, 2024
46 Fortune Business Insights, "Carbon Monoxide Market Size, Share & Industry Analysis, By Application (Metal Fabrication, Chemicals, Ore Processing and Extraction, Pharma & Biotechnology, and Electronics) and Regional Forecast, 2024-2032," July 8, 2024
47 Fortune Business Insights, "Carbon Monoxide Market Size, Share & Industry Analysis, By Application (Metal Fabrication, Chemicals, Ore Processing and Extraction, Pharma & Biotechnology, and Electronics) and Regional Forecast, 2024-2032," July 8, 2024

48 Fortune Business Insights, "Carbon Monoxide Market Size, Share & Industry Analysis, By Application (Metal Fabrication, Chemicals, Ore Processing and Extraction, Pharma & Biotechnology, and Electronics) and Regional Forecast, 2024-2032," July 8, 2024
49 Allied Market Research, "Carbon Monoxide Market Size, Share, Competitive Landscape and Trend Analysis Report, by Purity, by Application : Global Opportunity Analysis and Industry Forecast, 2023-2032," January 2024
50 Frost & Sullivan, "Technology Growth Opportunities in the Synthesis of Chemicals from Carbon Dioxide (CO2)," April 2024
51 Nancy W. Stauffer, "Turning carbon dioxide into valuable products: Assistant Professor Ariel Furst and her colleagues are looking to DNA to help guide the process," September 7, 2022, MIT Energy Initiative
52 Frost & Sullivan, "Technology Growth Opportunities in the Synthesis of Chemicals from Carbon Dioxide (CO2)," April 2024
53 Maressa Brennan, Hannah Murdoch, et al, "Pathway to Commercial Liftoff – Decarbonizing Chemicals & Refining," September 2023
54 By Danielle Riedl, "5 Things to Know About Carbon Mineralization," June 22, 2023
55 Jia Li, Mingzhi Luo, Kun Wang, Gaomiao Li, Guoquan Zhang, "Review of carbon dioxide mineralization of magnesium-containing materials," August 2023
56 Cambridge Carbon Capture Ltd, "Direct Air CO2 Capture & Mineralization," January 21, 2021
57 Future Market Research, "Magnesium Carbonate Mineral Market Outlook," June 2021
58 Allied Market Research, "Carbonate Market Size, Share, Competitive Landscape and Trend Analysis Report, by Type, Application and End Use : Global Opportunity Analysis and Industry Forecast, 2021-2030," December 2021
59 Annemie Bogaerts and Gabriele Centi, "Plasma Technology for CO2 Conversion: A Personal Perspective on Prospects and Gaps," 2020
60 International Energy Agency, "Putting CO2 to Use," September 2019
61 Occidental, "1PointFive fast facts," September 2023
62 1PointFive, "1PointFive and Amazon Announce 10-year Carbon Removal Credit Purchase Agreement," September 12, 2023
63 Twelve, "The element of change is in the air," no date
64 Massachusetts Institute of Technology, "Turning carbon dioxide into fuel and useful chemicals," *ScienceDaily*, November 27,2017
65 Scott Irwin, "CO2 Production by the U.S. Ethanol Industry and the Potential Value of Sequestration," February 19, 2024
66 Kevin Baskins, "Summit's controversial bid to build a carbon capture pipeline wins Iowa board's approval," *Des Moines Register*, June 26, 2024

67 LanzaTech, "LanzaTech produces Ethylene from CO2, changing the way we make products today," October 11, 2022
68 Frost & Sullivan, "Technology Growth Opportunities in the Synthesis of Chemicals from Carbon Dioxide (CO2)," April 2024
69 CarbonCure, "CarbonCure Celebrates Milestone of 50 Million Cubic Yards of Lower Carbon Concrete," March 6, 2024
70 Sulzer Chemtech, "Sulzer and Blue Planet deepen collaboration to accelerate decarbonization of concrete and the construction sector," November 30, 2022
71 Les Gioja, "FEED Study of Carbon Capture Inc DAC and CarbonCure Utilization Technologies Using United States Steel's Gary Works Plant Waste Heat," August 15-19, 2022
72 Shaun Andah, "DAC Concrete for the US," February 20, 2023
73 Carboncure, "CarbonCure Secures $80M USD In New Equity Round Led By Blue Earth Capital," July 11, 2023
74 Solidia, "Solidia Technologies™ Pivots to Commercialization with Headquarter Move to San Antonio," October 19, 2022
75 Oil and Gas Initiative and Boston Consulting Group, "Carbon capture and utilization as a decarbonization lever," White paper, April 2024
76 Global Cement and Concrete Association, "Cement and concrete around the world," Accessed October 29, 2024
77 Blue Planet Systems, "Permanent Carbon Capture," Accessed October 28, 2024
78 Carbon Cure Technologies, "Concrete that Matters," Accessed October 28, 2024
79 Carbon Built, "Ultra-low Carbon Concrete," Accessed October 28, 2024
80 Carbon Upcyling, "Carbon Upcycling delivers first 200 tons of CO2 to BURNCO for Low-Carbon Concrete Development," April 29, 2024
81 Isabella O'malley, "Making cement is very damaging for the climate. One solution is opening in California," April 11, 2024
82 Carbicrete, "CarbiCrete Technology," Accessed October 28, 2024
83 Eve Pope, "Building a Net-Negative Future: CO2-Derived Concrete," February 21, 2024
84 Volker Sick, et al, "CO2 Utilization and Market Size Projection for CO2-treated Construction Materials," May 2022
85 University of Wyoming School of Energy Resources, "Prefeasibility Study on the Use of Carbon Dioxide in Concrete Public Works Projects in Wyoming," December 1, 2022
86 City of Albany, "City of Albany Climate Action and Adaptation Plan," December 2019
87 City of Los Angeles, "Council adopts motion to regulate embodied carbon in the City of Los Angeles," April 10, 2024
88 City of San Fransisco, "2021 Climate Action Plan," 2021

89 Colorado House Bill 21-1303, Buy Clean Colorado Act" 2021
90 State of Oregon, HB 4139, 2022
91 Willy Carlsen, Ankita Gangotra and Kevin Kennedy, "Cutting-edge projects aim to decarbonize US cement emissions," July 17, 2024
92 Eve Pope, "Building a Net-Negative Future: CO2-Derived Concrete," February 21, 2024
93 Frost & Sullivan, "Innovations in Carbon Capture Utilization (CCU) Strategies: Sustainable Approaches and Value Creation," July 2024
94 U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022," April 2024
95 Congressional Budget Office, "Emissions of Greenhouse Gases in the Manufacturing Sector," February 2024
96 U.S. EPA, "2011-2021 Greenhouse Gas Reporting Program Sector Profile: Chemicals Sector (Non-Fluorinated)," March 2023
97 Elizabeth Abramson, Dane McFarlane, and Jeff Brown, "Transport Infrastructure for Carbon Capture and Storage," 2020
98 U.S. EPA, "2011-2021 Greenhouse Gas Reporting Program Sector Profile: Chemicals Sector (Non-Fluorinated)," March 2023
99 U.S. EPA, "2011-2021 Greenhouse Gas Reporting Program Sector Profile: Chemicals Sector (Non-Fluorinated)," March 2023
100 U.S. EPA, "2011-2021 Greenhouse Gas Reporting Program Sector Profile: Chemicals Sector (Non-Fluorinated)," March 2023
101 U.S. EPA, "2011-2021 Greenhouse Gas Reporting Program Sector Profile: Chemicals Sector (Non-Fluorinated)," March 2023
102 U.S. EPA, "2011-2021 Greenhouse Gas Reporting Program Sector Profile: Chemicals Sector (Non-Fluorinated)," March 2023
103 The Royal Society, "Catalyzing change: Defossilizing the chemical industry," May 2024
104 Maressa Brennan, Hannah Murdoch, et al, "Pathway to Commercial Liftoff – Decarbonizing Chemicals & Refining," September 2023
105 Maressa Brennan, Hannah Murdoch, et al, "Pathway to Commercial Liftoff – Decarbonizing Chemicals & Refining," September 2023
106 Bloomberg, "Many global chemicals companies trail on carbon-transition goals," January 27, 2021
107 University of Massachusetts at Amherst, "Greenhouse 100 Polluters Index (2023 Report, based on 2021 Data)," Accessed July 30, 2024
108 Climate Action 100+, "Dow (DOW) Climate Transition Analysis," October 2023
109 C&EN News, "U.S. Top 50 Chemical Companies of 2024," 2024

110 S&P Global, "Decarbonizing Chemicals Part One: Sector wide Challenges Will Intensify Beyond 2030," September 5, 2023

111 Wenke Bengtsson, et al, McKinsey & Co., "Decarbonizing the chemical industry," April 12, 2023

112 Henriette Naims, "Economics of carbon dioxide capture and utilization—a supply and demand perspective," May 2016

113 U.S. Geological Survey, "Nitrogen (Fixed) Ammonia: Mineral Commodity Summaries," January 2023

114 U.S. Geological Survey, "2018 Minerals Yearbook: Nitrogen [Advance Release]," October 2018

115 Exxon, "Enabling low-carbon ammonia: our landmark agreement with CF Industries," September 11, 2023

116 Exxon, "Landmark emissions-reduction project in Louisiana announced; CF Industries, ExxonMobil, EnLink Midstream to collaborate," October 12, 2022

117 Courtney Bernhardt, "Plastics industry boom brings flood of new ethylene "cracker" plants, despite frequent environmental violations," September 22, 2020

118 Market Research Future, "Ethylene Market Research Report Information By Feedstock (Naphtha, Ethane, Propane, Butane, Others) By Application (Polyethylene [HDPE, LDPE, LLDPE], Ethylene Oxide, Ethylbenzene, Ethylene Dichloride, Vinyl Acetate, Others), By End Use Industry (Packaging, Automotive, Building & Construction, Agrochemical, Textile, Chemicals, Rubber & Plastics, Soaps & Detergents, Others) and By Region (North America, Europe, Asia-Pacific, Latin America, Middle East & Africa)-Global Forecast to 2032," March 2024

119 Wood Mackenzie, "Ethylene: global carbon contributor," April 9, 2024

120 Subodh Sarin et al, "Reduced Carbon Intensity Ethylene Production," IHS Markit, December 2021

121 Wood Mackenzie, "Ethylene: global carbon contributor," April 9, 2024

122 Michael Sims, "Chemical profile: US ethylene," October 29, 2020

123 U.S. International Trade Administration, "Chemical Industry," Accessed July 31, 2024

124 Department of Homeland Security, "Chemical Sector Profile," March 2022

125 Department of Homeland Security, CISA, "Chemical Sector Profile," March 2023

126 Department of Homeland Security, CISA, "Chemical Sector Profile," March 2023

127 U.S. International Trade Administration, "Chemical Industry," Accessed July 31, 2024

128 Department of Homeland Security, "Chemical Sector Profile," March 2023

129 U.S. EPA, "Location of U.S. Facilities," 2016

130 University of Minnesota, "Renewable energy in the U.S.," Accessed November 15, 2024

131 Matthew Jouny, et al, "Carbon monoxide electroreduction as an emerging platform for carbon utilization," December 2019
132 Statista, "Market volume of acetic acid worldwide from 2015 to 2022, with a forecast for 2023 to 2030," June 2023
133 Steven Ramsey, et al, U.S. Department of Agriculture, "Global Demand for Fuel Ethanol Through 2030," February 2023
134 Chenggang Wan, Guichun Yang, and Yue Weng, "The science of green carbon: Convert CO2 into higher carboxylic acids," January 2022
135 Straits Research, "Carboxylic Acid Market Size, Share & Trends Analysis Report By Product (Acetic Acid, Ascorbic Acid, Azelaic Acid, Formic Acid, Valeric Acid, Citric Acid, Stearic Acid, Caproic Acid, Benzoic Acid, Others), By End-Use (Food and Beverages, Aromas, Animal Feed - 2032," 2024
136 Oil and Gas Initiative and Boston Consulting Group, "Carbon capture and utilization as a decarbonization lever," White paper, April 2024
137 Novozyme, "Transforming CO2 into nutritious food proteins," Accessed August 7, 2024
138 Mordor Intelligence, "United States Animal Protein Market Size & Share Analysis - Growth Trends & Forecasts up to 2029," 2023
139 Wayne Labs, "How NovoNutrients upcycles CO2 into alternative proteins for human and animal food," March 4, 2022
140 Food Ingredients First, "Future food: Transforming carbon dioxide into protein without using land, water or fertilizer," June 14, 2023
141 Dow, "Dow announces intent to invest in new world-scale carbonate solvents facility in the U.S.," March 25, 2024
142 Wenke Bengtsson, et al, McKinsey & Co., "Decarbonizing the chemical industry," April 12, 2023
143 Simon Mainwaring, "How Air Company Is Transforming Manufacturing By Making Products Out Of Thin Air," *Forbes*, May 2, 2022
144 H&M, "Converting greenhouse gases into new materials," May 5, 2021
145 H&M, "Converting greenhouse gases into new materials," May 5, 2021
146 Juliet Isselbacher, "Sequestering Carbon Dioxide in Diamonds," June 21, 2021
147 McKinsey & Co., "Consumers care about sustainability—and back it up with their wallet," February 6, 2023
148 Jay Golden, et al, "Green Chemistry," October 2021
149 Precedence Market Research, "Green Chemicals Market (By Type: Bio-alcohols, Bio-Polymers, Bio-organic acids, Bio-ketones, Others; By Application: Industrial & Chemical, Food & Beverages, Pharmaceuticals, Packaging, Construction, Automotive, Other) - Global Industry Analysis, Size," November 2023
150 Oil and Gas Initiative and Boston Consulting Group, "Carbon capture and utilization as a decarbonization lever," White paper, April 2024
151 Petra Schäfer, "CO_2 technology competes as one of top three inventions," May 4, 2021
152 Mary Bailey, "Sanyo Chemical and Econic Technologies to collaborate on CO2-based polyols production," April 17, 2024

153 Oil and Gas Initiative and Boston Consulting Group, "Carbon capture and utilization as a decarbonization lever," White paper, April 2024

154 Precedence Market Research, "Polymers Market (By Product Type: Thermoplastics, Thermosets, Elastomers; By Material: Polyethylene, Polypropylene, Polyvinyl Chloride, Polyethylene Terephthalate, Polystyrene, Polyurethane; By Application: Packaging, Building and Construction, Automotive," August 2023