CARBON SOLUTIONS

Finding New Opportunities for Carbon Capture with *CO_2NCORD*

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1. Introduction

1.1 Need for carbon capture and storage

Mitigating climate change requires a monumental shift in anthropogenic carbon dioxide (CO_2) emissions. The largest source of global CO_2 emissions is from fossil fuel combustion for power generation and industrial processes (International Energy Agency, 2023a). Commonly referred to as the energy transition, the required changes for decarbonization are primarily related to how energy is generated and used. Several studies have examined pathways to reach net zero carbon emissions by 2050 to keep global warming below 1.5°C. One such study by the International Energy Agency (IEA) projected the technologies required to reach net-zero emissions globally by 2050 (International Energy Agency, 2023b). The IEA study estimated that low-emission sources of electricity, such as wind and solar, will be responsible for 34% of reductions, hydrogen use for 4% of reductions, and carbon capture, utilization, and storage (CCUS) for 8%. The 8% global reduction due to CCUS requires sufficient infrastructure to capture 3,736 million tonnes of CO_2 every year (International Energy Agency, 2023c). Princeton's Net-Zero America study projected energy technology needs for the United States and estimated that between 700 and 1,700 million tonnes of CO_2 would need to be annually captured and either used or sequestered (Larson, et al., 2021); a range between 20% to 50% of the estimated capture necessary in IEA's global study.

1.2 Screening CCS opportunities

Carbon capture and storage (CCS) requires separating CO_2 from a facility's emissions or production streams, purifying and compressing it, transporting it to a storage site, and injecting the CO_2 into the subsurface for long-term storage. Each part of the carbon value chain (capture, transport, and storage) requires careful planning, detailed engineering, and capital-intensive investments. Before making investments, it is necessary to screen potential options and opportunities. An advantage of screening is that it enables co-locating capture technology with nearby storage sites and other facilities that plan to capture CO_2, presenting an opportunity for decreased costs.

1.3 Goal of this study

The purpose of this study is to screen carbon capture opportunities in the United States. The analysis is intended to identify opportunities and project costs using publicly available data. It is not intended to replace a Front-End Engineering Design (FEED) study that would result in a more comprehensive, facility-specific cost estimate based on detailed operations data.

2. Results

2.1 Estimating capture opportunities

In 2022, the EPA Greenhouse Gas Reporting Program (GHGRP) included 6,491 point-source emitters in the United States (U.S. Environmental Protection, 2023a). However, not all CO_2 emissions are prime candidates for CCS, nor are all emission sources included in GHGRP. For this study, we applied CARBON SOLUTIONS' CO_2 National Capture Opportunities and Readiness Database (*CO_2NCORD*) to identify capture opportunities, remove uncapturable streams, and identify additional capturable emissions. Figure 1 shows the capturable CO_2 at point source emitters nationwide, color-coded by industry.

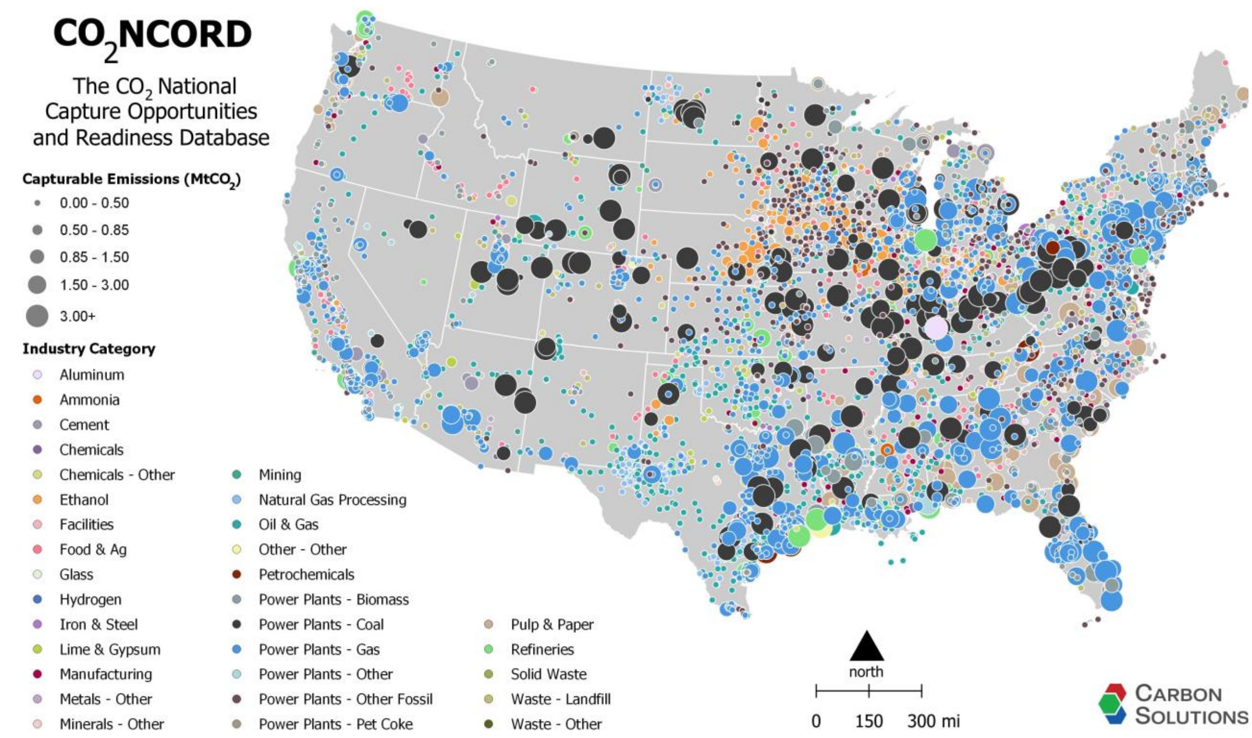


Figure 1: CO_2 capture opportunities in the contiguous United States identified with CO_2NCORD, color-coded by industry. Circle size represents the magnitude of annual emissions. Category descriptions can be found in Section 4.4 within the Appendix.

The greatest portion of capturable CO_2 emissions across the contiguous U.S. is from coal-fired power production, at 835 million metric tonnes. The next largest is from natural gas power plants, at 624 million tonnes. Despite coal power production generating significantly more CO_2, in 2023 only 16% of the total U.S. power production was generated from coal, while 43% was generated from natural gas (U.S. Energy Information Association, 2024b). Coal has a CO_2 emission factor about 1.8 times higher than natural gas, meaning coal combustion produces almost double the amount of CO_2 to produce the same amount of power as from gas (U.S. Environmental Protection Agency, 2024b).

Among non-power sources, petroleum refineries generate the largest portion of capturable CO_2 emissions, at about 160 million tonnes. Most of these emissions are from the fluid catalytic cracking (FCC) unit, wherein the heavy hydrocarbon portion of petroleum is “cracked” to allow for the formation of common fuels like gasoline and diesel (Adeanenche, Aliyu, Atta, & El-Yakubu, 2023). Indeed, the FCC accounts for 25-35% of emissions at a refinery (Guelc, Meredith, & Snape, 2023) and is the primary source of “capturable” emissions identified by *CO_2NCORD.* The next largest portion of capturable, non-power emissions in the U.S. comes from pulp and paper production, at 140 million tonnes. About 75% of these emissions are biogenic in source. Biogenic emissions include emissions generated during the natural carbon cycle, as well as those generated from the combustion of biological material (U.S. Environmental Protection Agency, 2017). If captured, biogenic CO_2 may contribute to net-negative CO_2 emissions.

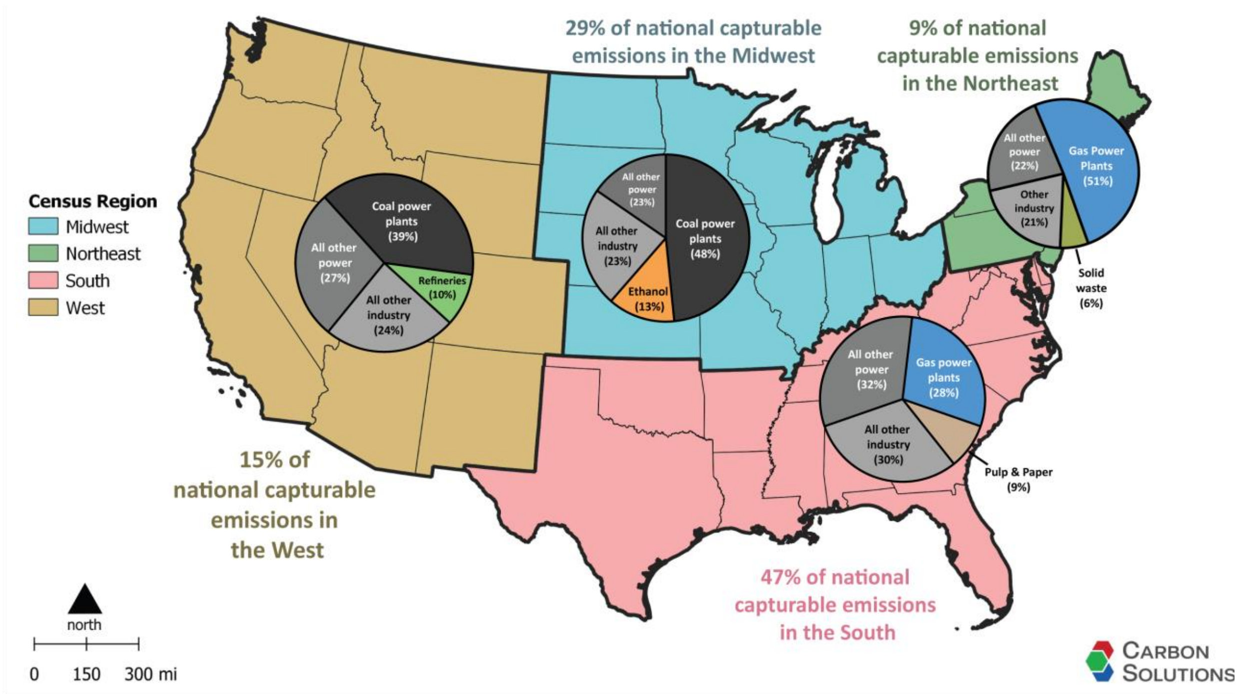


Figure 2: Percentage of annual capturable emissions in major U.S. regions, and a breakdown of the associated power and industry sector emissions. The largest power and industry emitter in each region is shown.

As shown in Figure 2, capturable CO_2 emissions vary by region. The U.S. Census Bureau divides the U.S. into four major regions: Northeast, South, Midwest, and West (U.S. Census Bureau, 2021). Of these regions, the South represents 47% of total capturable U.S. emissions, followed by the Midwest at 29%. Regionally, coal still dominates capturable emissions in two of the four regions, representing the greatest portion in the Midwest and West, at 48% and 39%, respectively. However, natural gas power production emissions represent the largest percentage of capturable emissions in the Northeast, at 51%. Emissions are split evenly between coal and natural gas in the South, at 27% and 28%, respectively. Within the non-power sectors, ethanol production produces the largest portion of capturable emissions in the Midwest at 13%, refineries are the predominant sector in the West at 10%, pulp and paper in the South at 9%, and solid waste combustion in the Northeast at 6%.

2.2 Overview of costs

Once capturable emissions are determined for each facility, *CO_2NCORD* estimates the cost per tonne of CO_2 captured per "stream" of CO_2 at a facility. A capturable stream at a facility is CO_2 from a source or sources that can reasonably be combined and routed through the same capture equipment. Cost models initially developed by the National Energy Technology Laboratory (NETL) were adapted for *CO_2NCORD* and generalized for a broader range of industries. They determine the recommended equipment type and size based on a stream's estimated composition and total CO_2 flow (NETL, 2022; NETL, 2023a; NETL, 2023b). The cost models simulate retrofitting an existing plant with amine-based carbon capture and preparing captured CO_2 to pipeline quality.

Cost models used in *CO_2NCORD* estimate unique capture costs based on various inputs, including typical plant capacity utilization, state-wide water scarcity, and state energy prices. Costs are scaled based on the maximum CO_2 flow a system may expect, which can be estimated with a capacity utilization factor, determined independently for each stream and facility type. Capture systems require cooling, which can be completed by a dry or wet system and have different associated costs. The U.S. Water Risk Atlas is used to determine what type of cooling a facility should use (Kuzma, et al., 2023). State-wide natural gas and electricity prices from 2022 (U.S. Energy Information Administration, 2024a; U.S. Energy Information Administration, 2023a) are used to calculate energy costs. Costs are annualized using a capital charge factor of 0.096, based on a 20-year plant life (NETL, 2023a). Costs are capped at $500/tonne, as this is the current estimated cost of capturing CO_2 directly from the air via direct air capture (DAC) technology (Bisotti, Hoff, Mathisen, & Hovland, 2024). Sources are likely to reach this price if they are too small for the cost model to generate an appropriate estimate, in which case an alternative equipment configuration, sizing, and type would be necessary to explore. All costs are presented in 2022 USD and inflated using the U.S. gross national product (GNP) (U.S. Bureau of Economic Analysis, 2023). The cost per tonne of CO_2 captured, visualized across the U.S., is given in Figure 3. As can be seen, capture cost is generally lower for sources with higher quantities of emissions.

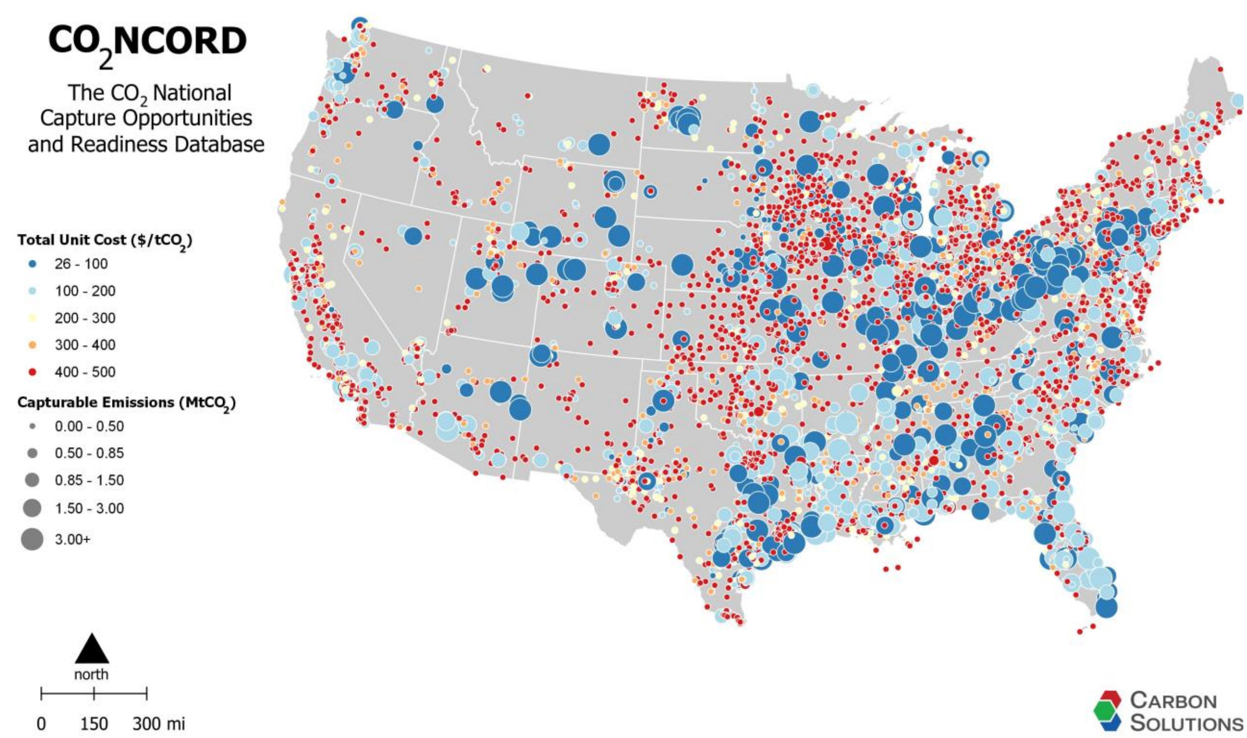


Figure 3. Cost of capturing CO_2, visualized across the U.S. Color indicates the relative cost of capture; circle size indicates the quantity of capturable emissions produced annually.

Supply curves of the capturable CO_2 across all sectors in the contiguous United States, across the U.S. power sector, and across all non-power industrial sectors are presented in Figure 4. Supply curves sort the capture cost from each facility, lowest to highest, to identify the least cost option for meeting a capture target. The cost of capture for most U.S. emissions is below $170/tonne for both power and industrial facilities. This accounts for about 2,100 million tonnes of CO_2, or 85% of the total capturable emissions in the U.S., with 1,400 million tonnes from power generation and 700 million tonnes from industrial emissions. Above $170/tonne, the capture cost begins to increase exponentially for every additional quantity of CO_2 captured.

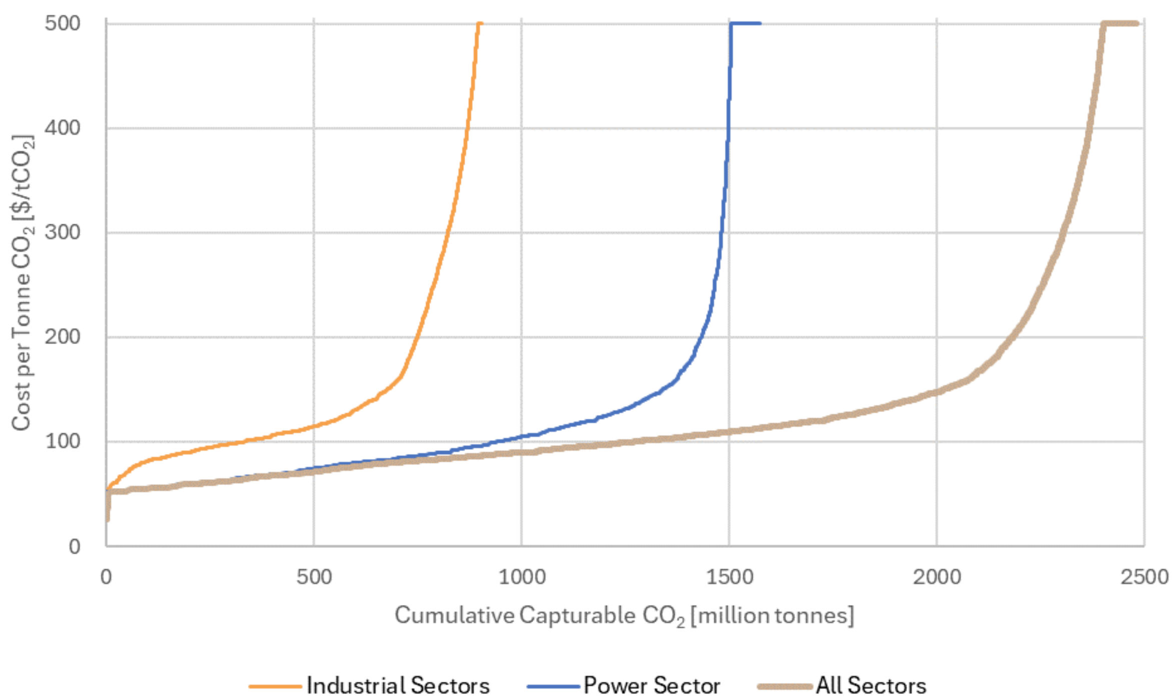


Figure 4. Supply curves of annual capturable CO_2 across the U.S. versus cost per tonne CO_2 captured, separated into all industrial non-power sector CO_2, power sector CO_2, and CO_2 from all sectors. X-axis shows cumulative capturable CO_2 in million tonnes. Y-axis shows cost per tonne CO_2 captured in 2022 USD.

2.3 Sector-specific costs

Costs vary by sector, depending on the capturable quantity of CO_2, typical capacity factor, facility locations, and chosen cost model parameters. Figure 5 presents supply curves for the United States' CO_2 from only power generation, illustrating how the cost of capture varies across the nation's different power sources.

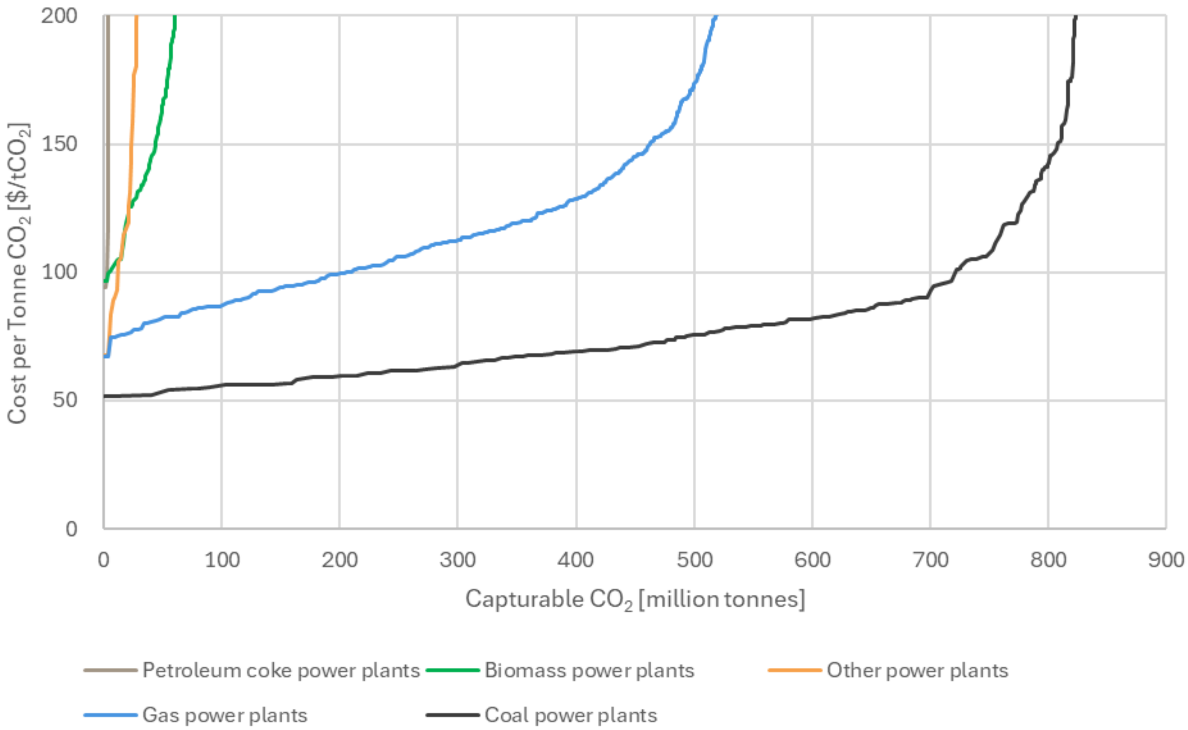


Figure 5. Supply curve of U.S. power production sources. X-axis shows annual cumulative capturable CO_2 in million tonnes. Y-axis shows cost per tonne CO_2 captured in 2022 USD. Listed fuel represents the predominant fuel reported to be burned at each facility. "Other" power plants includes other fossil and non-fossil fuel sources, such as fuel gas and emissions from renewable facilities.

Figure 5 shows that the cost of capture for coal power plants is the lowest for 22% of all capturable power emissions and remains the lowest cost overall. The relatively high concentration of CO_2 in coal production off-gas streams reduces the cost of capture for these sources, as does the high quantity of emissions per capturable stream. Indeed, the cost of capture reduces substantially when a single capture system handles high amounts of CO_2; as coal power production produces some of the most CO_2 per facility, the relative cost of capture is lower. On average, coal power plants produce 3,600,000 tonnes of capturable CO_2 per facility, whereas gas power plants produce an order of magnitude less, at 380,000 tonnes. CO_2 emitted from petroleum coke power plants, biomass power plants, and other fuel-type plants is significantly smaller per facility, at an average of 92,000 tonnes per year. This leads to a higher cost per unit of CO_2 captured. Gas power plants represent the second largest quantity of CO_2 capturable below $150/tonne, at about 460 million tonnes. Many natural gas power plants are operated as peaker plants, meaning they are only operated during times of high electricity demand. Thus, some of these facilities have a higher cost of capture from not operating throughout the year.

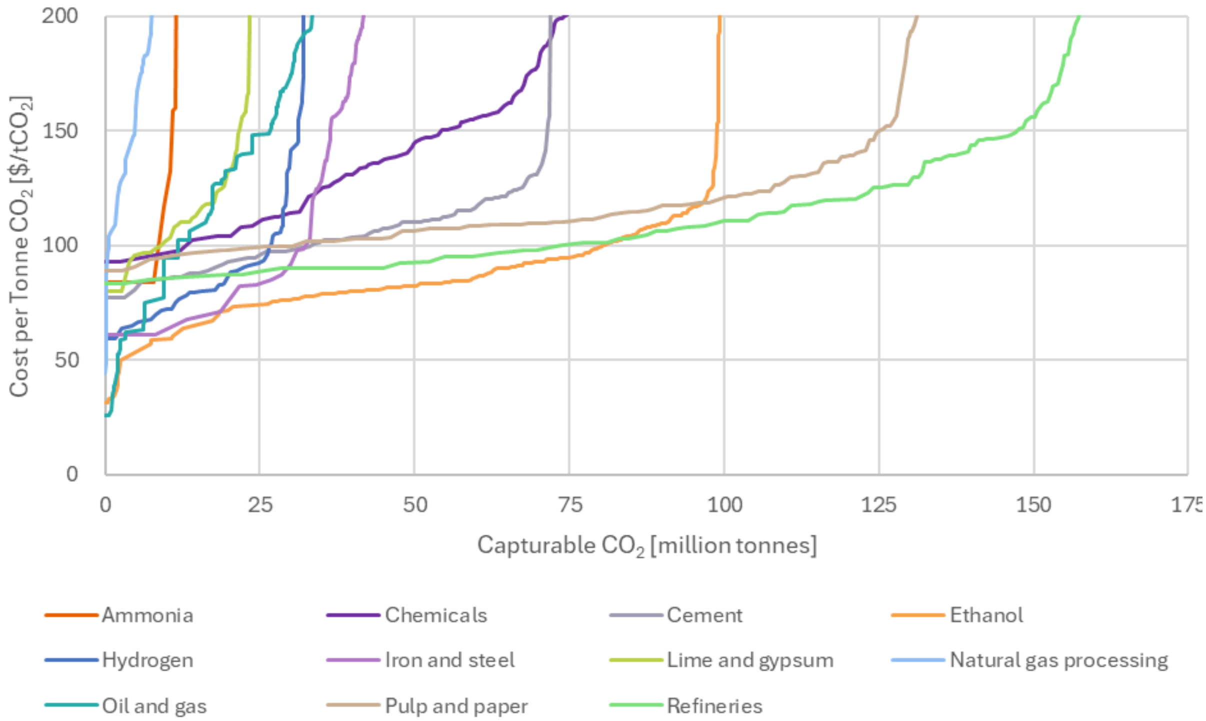


Figure 6. Supply curves of selected U.S. industrial sectors. X-axis shows annual cumulative capturable CO_2 in million tonnes. Y-axis shows cost per tonne CO_2 captured in 2022 USD. "Chemicals" includes CO_2NCORD categories chemicals, chemicals – other, and petrochemical production.

As shown in Figure 6, the ethanol industry is one of the least expensive industries for carbon capture. Ethanol production yields biogenic CO_2 through fermentation, releasing a nearly pure CO_2 stream. Thus, only compression equipment is required to bring the CO_2 to pipeline quality conditions, meaning the initial capital investment is lower. This also means that, even if a facility has a relatively small amount of capturable CO_2, the cost of capture can be low. Refineries have the most capturable CO_2, with a majority below $150/tonne and 45% below $100/tonne. Pulp and paper production represents the second largest quantity of capturable CO_2 but has on average a higher cost, with only 22% of emissions below $100/tonne. Iron and steel facilities have around 67% of capturable emissions below $100/tonne, and the cement industry has around 47%. The cement and chemical industries have similar quantities of capturable CO_2 but exhibit very different curves. The primary variation between industry curves is determined by the amount of CO_2 per stream (i.e. the amount of CO_2 actually captured by a single capture system), the average capacity factor estimated for a plant (which determines the size of capture system required), and the baseline cost for equipment, which on average increases for lower concentrations of CO_2 in a stream.

2.4 45Q tax credit

A primary use for *CO_2NCORD* is screening for low-cost facilities. Per the 2022 amendment of the U.S. Inflation Reduction Act, the U.S. 45Q tax credit offers $85 per tonne of captured and geologically sequestered CO_2 (Jones & Marples, 2023). Figure 7 shows all capturable sources across the U.S. estimated to be capturable below $85/tonne. The cost of transport and storage is not considered.

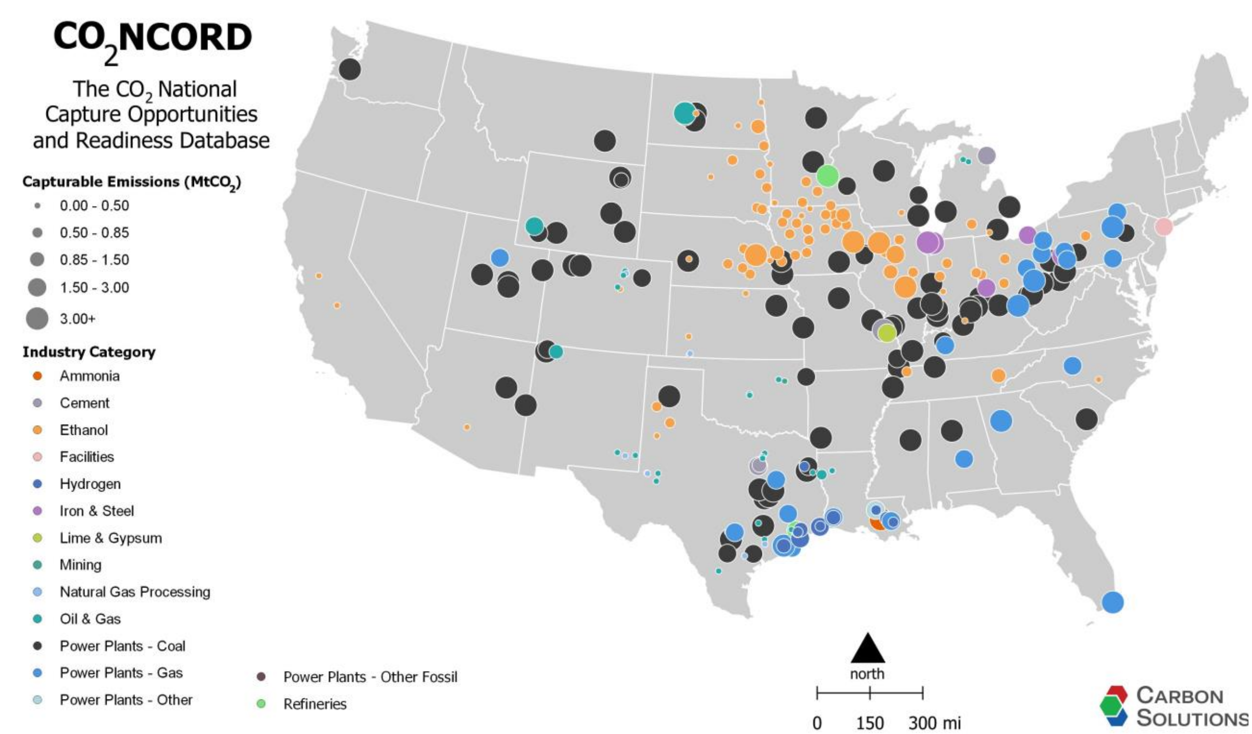


Figure 7. Facilities across the U.S. with CO_2 capturable at below $85 per tonne. Circle size indicates the quantity of capturable emissions generated annually, in million tonnes. Circle color indicates the industry type.

As shown in Figure 7, a variety of sources are capturable below the 45Q tax credit amount. There are 94 coal power plants shown, and together they represent 74% of the low-cost capturable CO_2. Ethanol plants also have a low cost of capture, despite producing comparatively small amounts of CO_2 per facility. At only 7% of the total 45Q capturable emissions, 77 ethanol facilities have CO_2 which can be captured for less than $85 per tonne. Two types of plants are left when investigating these low-cost options – facilities with high quantities of capturable CO_2 which drives down the cost per tonne captured, and facilities that always have a low cost of capture because of the relative purity of their CO_2 stream. If a stream of CO_2 requires a limited amount of equipment to purify, the initial capital investment is substantially lower. Ethanol, oil and gas production, and natural gas processing facilities all produce high-purity CO_2 which can be captured below $85 per tonne. The remaining low-cost sources all produce high quantities of caputurable CO_2.

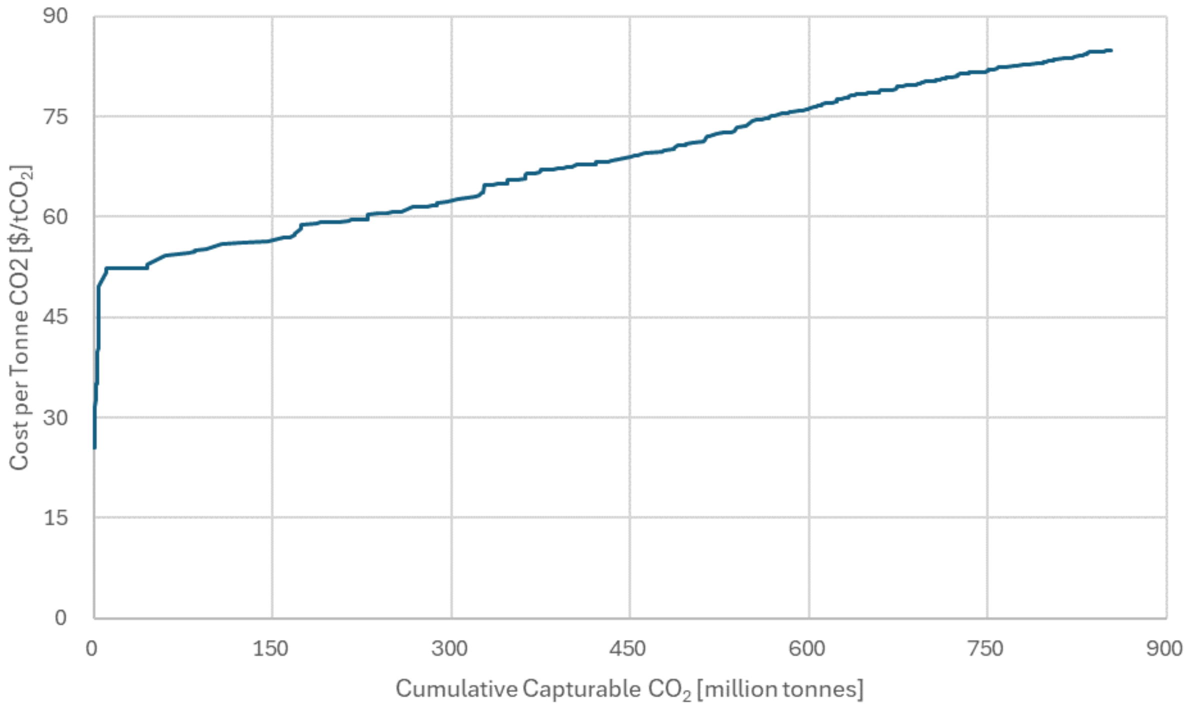


Figure 8. Supply curve of capturable CO_2 across the U.S. for all sources below $85 per tonne. X-axis shows annual cumulative capturable CO_2 in million tonnes. Y-axis shows cost per tonne CO_2 captured in 2022 USD.

Figure 8 shows that a majority of sources capturable below $85 per tonne range between $52 and $84/tonne. About 850 million tonnes of CO_2 can be captured in the U.S. below the 45Q limit. However, it is important to consider that the cost of transport and storage will increase CCS costs. Below $85, there's a nearly linear relationship between capturable CO_2 and cost per tonne. The cost of capture increases by about $1/tonne per additional 25 million tonnes of CO_2 captured.

2.5 Regional CO_2 supply and costs

CO_2 supply and costs vary both by region as well as the predominant industries within a region. Figure 9 gives supply curves for capturable CO_2 in all four census regions within the United States. As can be seen, the South has the greatest portion of capturable CO_2. A large majority of this CO_2 is from Texas, at 33% of the South's and 15% of the entire nation's capturable emissions. The Midwest has the next largest portion of capturable CO_2 with a majority from Indiana, at 15% of the region's and 4% of the nation's capturable emissions. Below 500 million tonnes CO_2 captured, the Midwest has a marginally lower cost of capture than the South. However, as noted above, a smaller proportion of capturable emissions is available in the Midwest compared to the South.

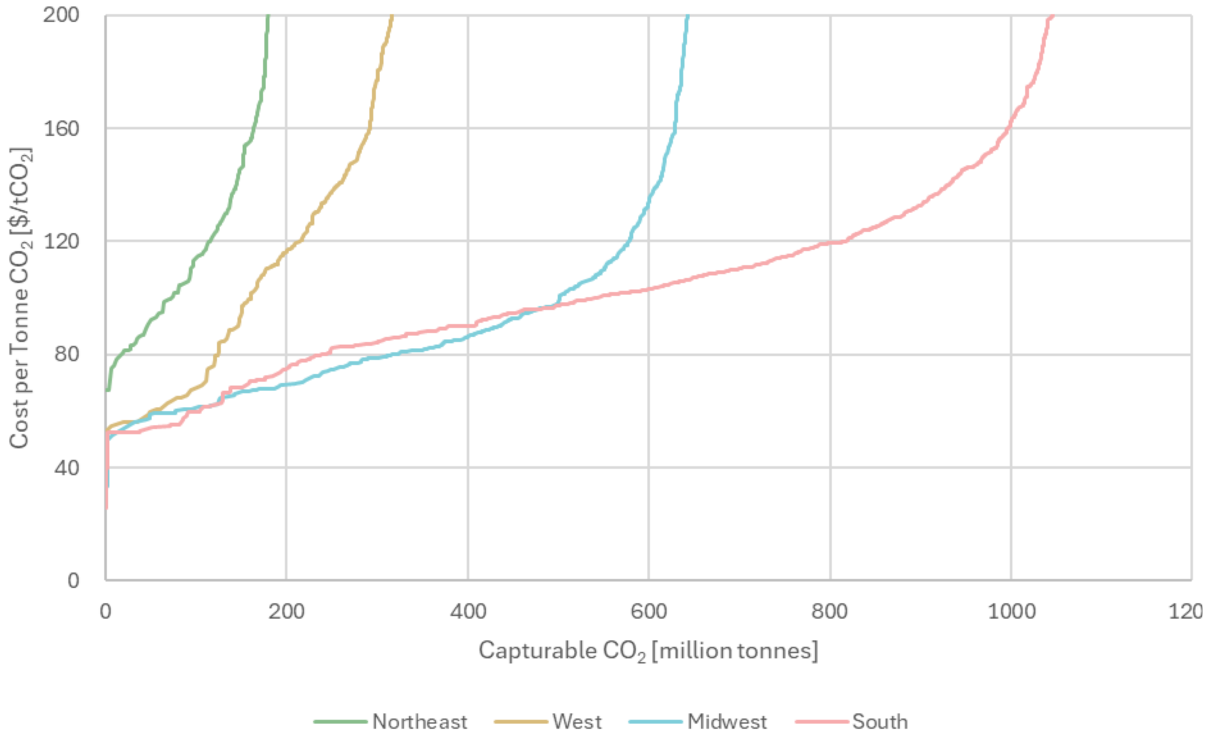


Figure 9. Supply curves of capturable CO_2 from industrial sectors across the U.S., by region. A maximum of $200 per tonne CO_2 is shown. X-axis shows annual cumulative capturable CO_2 in million tonnes. Y-axis shows cost per tonne CO_2 captured in 2022 USD.

Figure 10 shows the breakdown of CO_2 that is capturable below $200/tonne from all non-power industrial sectors in each census region of the U.S. Depending on the region, the largest sector of low-cost CO_2 varies. In the Midwest, ethanol is a large majority at 43%. In fact, 83% of all ethanol facilities are located in the Midwest. In the Northeast, solid waste combustion accounts for a majority of low-cost, industrial capturable emissions, at 31%. Industrial emissions from the Northeast only account for 8% of all industrial sources below $200 per tonne, meaning the capturable tonnage from Northeast solid waste combustion is comparatively small, at 12 million tonnes total. In the West, refineries represent the largest portion of below $200 per tonne capturable emissions, at 34%. In total, they account for 34 million tonnes of CO_2. Pulp and paper are the largest source of low-cost capturable emissions in the South, at 30% of the South's industrial emissions. About 80% of these pulp and paper emissions are biogenic from the combustion of natural sources, like wood and paper byproducts.

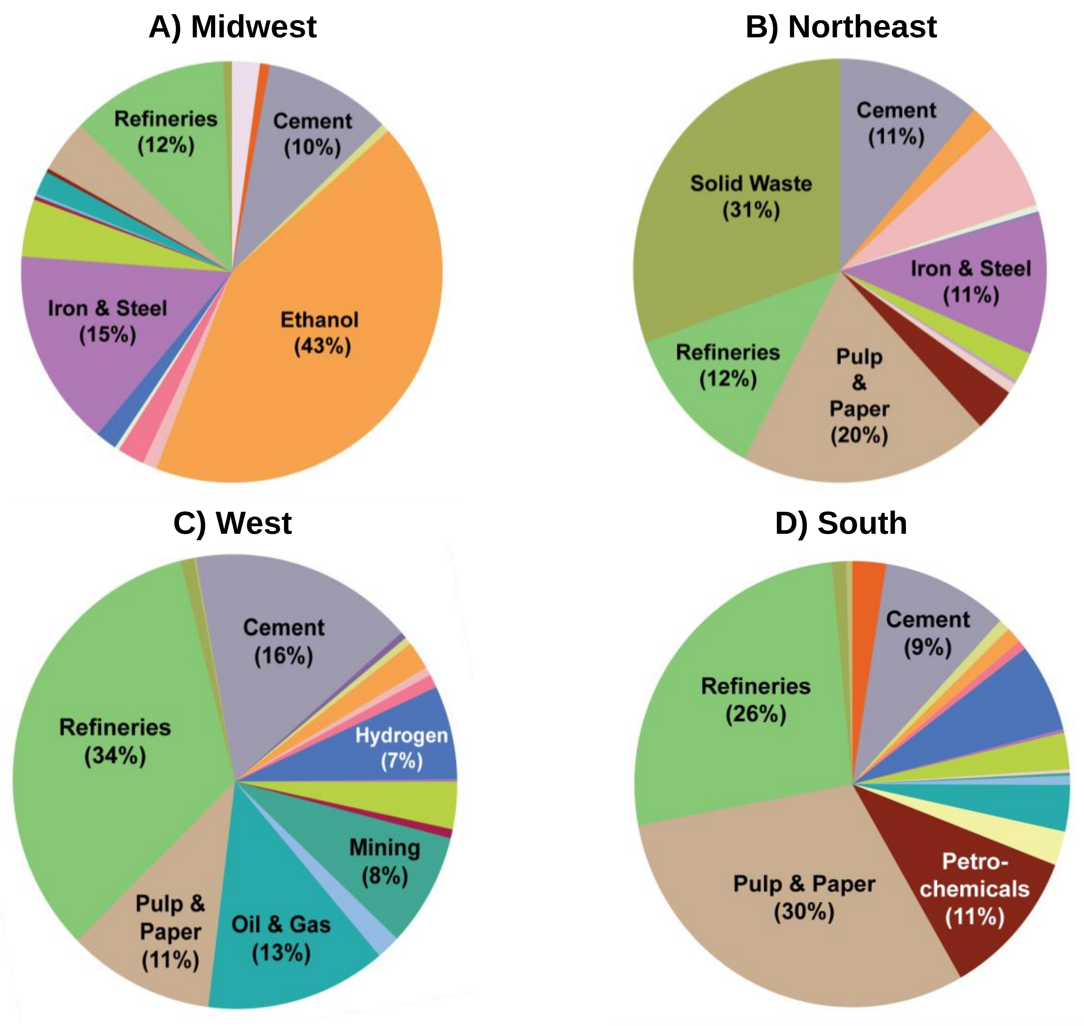


Figure 10. Composition of U.S. industrial emissions capturable below $200 per tonne, broken out by U.S. census regions (A) Midwest, (B) Northeast, (C) West, and (D) South.

The cost of capture varies between both facility and industry. Between facilities in the same industry, the variation illustrated in this analysis is determined exclusively by the capturable quantity of CO_2, but other factors are likely to affect capture cost. For example, in the cement industry, the cost of capture may vary for the same capturable quantity of CO_2, depending on the fuel type combusted, if the cement is produced in a wet or dry process, the quantity of air intake at the facility, the presence of co-pollutants, the current existence of pollutant control equipment, and retrofit difficulty. Additionally, an alternative form of capture may be more effective for a specific facility than amine-based capture, such as cryogenic capture, membrane capture, or an adsorption-based capture process. However, the results from *CO_2NCORD* allow for initial national screening for facilities particularly suited for early adoption of CCS.

3. Conclusions

In this study, we analyzed power and industrial facilities to identify new opportunities for carbon capture. This analysis was performed by applying CARBON SOLUTIONS' *CO_2NCORD* software. The software estimated the capturable tonnage of CO_2 at facilities across the United States and calculated the cost of capture at each facility. The key findings of this study are:

- 2,482 million tonnes of CO_2 capture opportunities were identified from 7,591 facilities in the United States. The opportunity varies by region with:
    - 1.175 billion tonnes of CO_2 from 2998 facilities identified in the South,
    - 712 million tonnes of CO_2 from 2183 facilities identified in the Midwest,
    - 375 million tonnes of CO_2 from 1383 facilities identified in the West, and
    - 220 million tonnes of CO_2 from 1027 facilities identified in the Northeast

U.S. Capture opportunities		
Region [-]	Capturable CO_2 (Million tonnes / year)	Facilities (#)
Midwest	712	2,183
Northeast	220	1,027
South	1175	2,998
West	375	1,383
Total	2,482	7,591

- The price and availability of CO_2 capture also varies by facility and industry:
    - 854 million tonnes of CO_2 projected to cost less than $85/tonne,
    - 1,267 million tonnes below $100/tonne, and
    - 2,128 less than $175/tonne.

- The availability of CO_2 projected to cost less than the 45Q $85/tonne tax credit varies by region:
    - 388 million tonnes of CO_2 from 124 facilities in the Midwest,
    - 302 million tonnes of CO_2 from 104 facilities in the South,
    - 131 million tonnes of CO_2 from 34 facilities in the West, and
    - 32.5 million tonnes of CO_2 from 13 facilities in the Northeast.

U.S. Capture opportunities less than 45Q $85/tonne tax credit		
Region [-]	Capturable CO_2 [Million tonnes / year]	Facilities [#]
Midwest	388	124
Northeast	33	13
South	302	104
West	131	34
Total	854	275

- Opportunities will need more a detailed evaluation considering site-specific data and including capture options other than amine-based technology.

CARBON SOLUTIONS is continuing to develop *CO_2NCORD* and are actively applying it in commercial projects and government grants.

4. Appendix

4.1 About the *CO_2NCORD* Software

The CO_2 National Capture Opportunities and Readiness Database (*CO_2NCORD*) is being further developed by CARBON SOLUTIONS with the goal of screening the location, cost, and quantity of CO_2 emissions that could be captured for carbon capture and sequestration (CCS) across the United States. Shown in Figure 11, *CO_2NCORD* utilizes a five-step workflow. It begins with publicly available CO_2 data. Next, the data is analyzed to determine combinations of emissions in each facility that could be captured (capture streams). Each capture stream is categorized and then a cost is assigned based on the type of stream and amount of CO_2 to be captured. Next, facilities are categorized into recognizable industries. Finally, the results can be filtered based on user preferences.

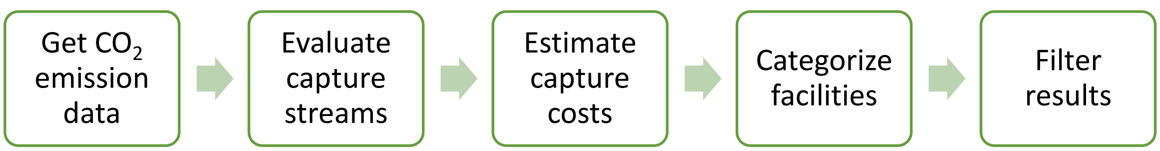


Figure 11. CO_2NCORD workflow.

4.2 Emission data

CO_2NCORD ingests and fuses together CO_2 emission data from a variety of sources. *CO_2NCORD* starts with EPA's Greenhouse Gas Reporting Program (GHGRP), which includes industrial and power facilities (U.S. Environmental Protection, 2023a). *CO_2NCORD* accesses GHGRP via the Envirofacts API to utilize unit-level emission and fuel type information (U.S. Environmental Protection Agency, 2023b). Next, *CO_2NCORD* ingests EPA's Emissions and Generation Resource Integrated Database (eGRID) which includes the majority of power plants in the United States. Ethanol fermentation emissions are not required to be reported to either GHGRP or eGRID, therefore *CO_2NCORD* separately includes ethanol production data from both the U.S. EIA (U.S. Energy Information Administration, 2023b) and Renewable Fuels Association (Renewable Fuels Association, 2023) which is translated into projected CO_2 biogenic emissions using a method by Xu et al. (Xu, 2010).

4.3 Projecting costs

CO_2NCORD has two approaches for projecting capture costs: 1) with literature-based estimates and 2) with cost models. The literature-based approach is detailed in a 2024 CCUS Conference presentation (Bennett, et al., 2024). This study used the cost model approach, detailed below.

CO_2NCORD uses the available CO_2 for capture to estimate capture costs. A facility may have multiple CO_2 exit streams or may report multiple streams when all emissions are actually released from a single emission point. For example, cement facilities typically report emissions generated in their kiln as two different streams: emissions from fuel burned in the kiln and emissions from the decomposition of raw material in the kiln. In this case, both emissions should be grouped, as they are generated and emitted from the same location. As such, *CO_2NCORD* aggregates and disaggregates streams based on the type of equipment generating a stream, facility type, and fuel type to estimate the quantity of CO_2 that is most likely to be captured by a single capture system. It should be noted that the distance between streams is not known, and some streams aggregated may, in fact, be too far away to be reasonably captured by the same equipment.

Once capturable CO_2 streams are identified, they are then evaluated to determine capture cost. Capture models built by the National Energy Technology Laboratory (NETL) have been updated and generalized to fit a variety of industries (NETL, 2022; NETL, 2023a; NETL, 2023b). Initially, the models were designed to accommodate natural gas combined cycle power plants, pulverized coal power plants, cement production, hydrogen production, natural gas processing, ammonia production, and ethanol production. Based on equipment configuration, stream purity, and plant similarities, the seven models were generalized for each industry deemed capturable in the United States. *CO_2NCORD* chooses a model for each stream based on industry and stream type. Then it estimates a maximum CO_2 emission amount, using average capacity factors for each industry. Capacity factors are either taken directly from eGRID or estimated using 2022 data from the United States Geological Survey (USGS), from industry associations, and from techno-economic models of average production (American Iron and Steel Institute, 2023; Baron, Perpinan, Bailera, & Pena, 2023; Bolen, 2024; Hatfield, 2024; Merrill, 2024; U.S. Environmental Protection Agency, 2024a). When data is unavailable, capacity factors are chosen from a similar industry's value. Using the maximum CO_2 emission amount, equipment prices from a baseline case are scaled using an exponential relationship (NETL, 2019), and a wet vs. dry cooling scheme is chosen based on the availability of water per state (Kuzma, et al., 2023). A retrofit factor, depending on the industry, is applied to all equipment costs to account for costs encountered when retrofitting an existing facility.

The total plant cost is the sum of all equipment costs, and the total operating cost is determined using a ratio of the baseline total plant cost and total operating cost to the calculated total plant cost. Then, energy requirements are estimated using a ratio of the baseline energy requirements and total plant cost to the calculated total plant cost and scaled by the plant's estimated capacity factor. Energy costs are calculated using state-specific natural gas and electricity costs from the EIA (U.S. Energy Information Administration, 2023a; U.S. Energy Information Administration, 2024a). Operating costs are estimated using a similar ratio of baseline operating costs (both variable and fixed) and baseline total plant cost to the calculated total plant cost, and the variable operating costs are scaled by the plant's capacity factor. All costs are then scaled to the appropriate cost year (2022 USD for this study) using the gross national product (GNP) inflator (U.S. Bureau of Economic Analysis, 2023).

The final capital and operating costs are annualized based on a user-chosen capital charge factor or combination of financing period and discount rate and then divided by the capturable quantity of CO_2. For the case of this study, a capacity factor of 0.096 is used (NETL, 2023a). These calculations result in a cost per tonne CO_2 for each identified capturable stream. If a stream is identified to have a higher cost than a user-chosen "cap", the stream cost is set to the cap cost.

For the purpose of this study, a cap of $500 per tonne captured is used, based on the current cost of direct air capture (Bisotti, Hoff, Mathisen, & Hovland, 2024). Facility-wide capture costs aggregate all stream costs using a weighted average, weighted by captured CO_2 quantity.

4.4 Categorizing facilities

Once capturable emissions and costs are estimated for each stream, facilities are categorized based on their stream types, NAICS codes, fuels combusted, and EPA sector types. A brief description of the categories is as follows:

***CO_2NCORD* Categories**	**Category Description**
Aluminum	Aluminum production
Ammonia	Ammonia and nitrogenous fertilizer manufacturing
Cement	Cement and concrete manufacturing
Chemicals	Basic commodity organic and inorganic chemical manufacturing
Chemicals - Other	All other chemical production
Ethanol	Ethanol and biofuel production
Facilities	Military, university, public service, residential, research buildings, and other non-industrial facilities
Food & Ag	Food production and agriculture processing
Glass	Glass and glassware production
Hydrogen	Hydrogen production
Iron & Steel	Iron, steel, and ferroalloy production and product manufacturing
Lime & Gypsum	Lime and gypsum manufacturing
Manufacturing	All other manufacturing processes
Metals - Other	Manufacturing of all other metals not included in Iron & Steel
Minerals - Other	Other mineral processing
Mining	Solid material mining
Natural Gas Processing	Natural gas processing and production
Oil & Gas	Oil and gas extraction, distribution, and manufacturing
Other - Other	Transportation, construction, and all other non-categorized facilities
Petrochemicals	Petrochemical manufacturing
Power Plants - Biomass	Biomass-electrical generators
Power Plants - Coal	Coal-fired electrical generators
Power Plants - Gas	Natural gas-fired electrical generators
Power Plants - Other	Electrical generators using other non-fossil fuels
Power Plants - Other Fossil	Other fossil fuel-fired electrical generators
Power Plants - Pet Coke	Petroleum coke-fired electrical generators
Pulp & Paper	Pulp and paper manufacturing and product production
Refineries	Petroleum refining
Solid Waste	Solid waste combustion and incineration
Waste - Landfill	Other solid waste disposal
Waste - Other	Other waste facilities

4.5 User interface

The data outputs and emissions data from *CO_2NCORD* are available and explorable through a graphical user interface (GUI) that allows the user to filter data based on various criteria and then download that data to use in other research and applications. The GUI is written using the Dash package in the Julia programming language. The GUI has been deployed on a cloud-based hosting platform where it is available as a secure web-application accessible through username and password authentication. The application allows the user to filter based on the capture cost and the capturable CO_2 of a given facility as well as the industry that has been assigned to each facility. The user can also filter by geography based on either state, a latitude-longitude coordinate and radius, or through a custom shapefile that the user uploads.

The GUI also presents different visualizations for analyzing and interpreting the data accessible to the user by toggling the different tabs that appear in the application. The primary visualization is the map, which shows the emissions sources geographically. The size of each emission source is dependent on the tonnage of capturable CO_2 emissions and the source color is dependent on the industry (shown in Figure 12). The user can also add various data layers to the map, including existing and proposed CO_2 pipelines, existing Class VI injection wells, and areas of federally-designated disadvantaged communities (White House Council on Environmental Quality, 2022), among others. The user is also able to pan and zoom throughout the map to explore the data independently. Other visualizations include the 'Histogram' table which shows the average unit capture cost (\$/tonne CO_2) for each industry in ascending order plotted against the total annual capturable tonnage of CO_2 (tonne/yr) for each industry to demonstrate the supply curve of CO_2 for the filtered dataset. The 'Scatter Plot' tab shows the same latitude and longitude parameters but for each individual capture point, rather than by industry. Lastly, the facility and industry tables show tabular data for each individual facility and aggregated by industry respectively.

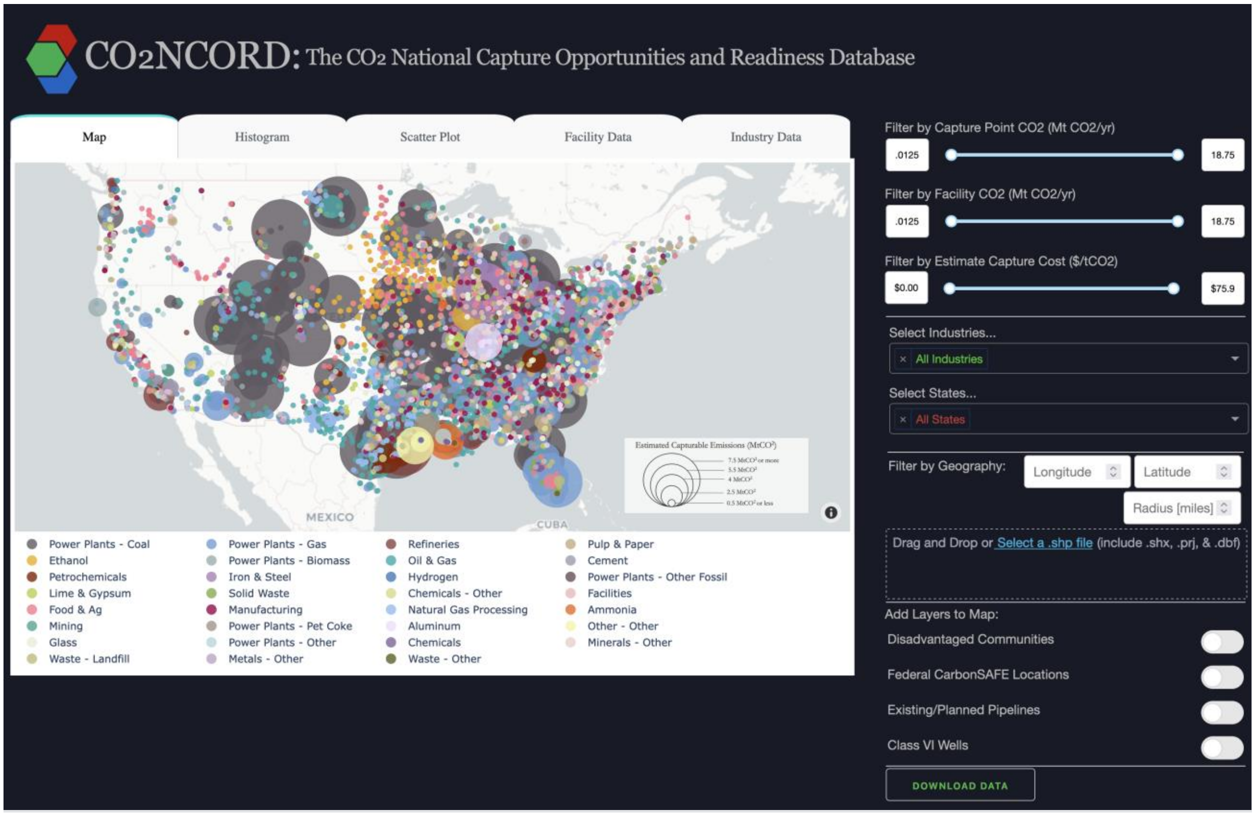


Figure 12. CO_2NCORD Graphical User Interface: The CO_2NCORD map view with multiple filter options.

5. References

Adeanenche, D., Aliyu, A., Atta, A., & El-Yakubu, B. (2023). Residue fluid catalytic cracking: A review on the mitigation strategies of metal poisoning of RFCC catalyst using metal passivators/traps . *Fuel*.

American Iron and Steel Institute. (2023, December 30). *This Week's Raw Steel Production.* Retrieved from American Iron and Steel Institute: https://www.steel.org/industry-data/

Baron, C., Perpinan, J., Bailera, M., & Pena, B. (2023). Techno-economic assessment of glassmaking decarbonization through integration of calcium looping carbon capture and power-to-gas technologies. *Sustainable Production and Consumption*, 121-133.

Bennett, J., Sale, K., Rodriguez, D., Talsma, C., Gilhooley, C., Lubeck, V., . . . Middleton, R. (2024). Identifying Opportunities and Cost for CO2 Capture at Power and Industrial Facilities in the United States. *Carbon Capture, Utilization, and Storage conference (CCUS)*, (p. 4014460). Houston, TX. doi:10.15530/ccus-2024-4014460

Bisotti, F., Hoff, K. A., Mathisen, A., & Hovland, J. (2024). Direct Air capture (DAC) deployment: A review of the industrial deployment. *Chemical Engineering Science*.

Bolen, W. P. (2024, January). *Soda Ash.* Retrieved from U.S. Geological Survey: https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-soda-ash.pdf

Guelc, F., Meredith, W., & Snape, C. E. (2023). CO2 capture from fluid catalytic crackers via chemical looping combustion: Regeneration of coked catalysts with oxygen carriers . *Journal of the Energy Institute*.

Hatfield, A. K. (2024, January). *Cement.* Retrieved from U.S. Geological Survey: https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-cement.pdf

International Energy Agency. (2023a, March). *CO2 Emissions in 2022.* Retrieved from International Energy Agency: https://www.iea.org/reports/co2-emissions-in-2022

International Energy Agency. (2023b, September). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 deg C Goal in Reach*. Retrieved from https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

International Energy Agency. (2023c, September). *CCUS: Net Zero Emissions Guide*. Retrieved from https://www.iea.org/reports/ccus

Jones, A. C., & Marples, D. J. (2023, August 25). *The Section 45Q Tax Credit for Carbon Sequestration.* Retrieved from Congressional Research Service: https://sgp.fas.org/crs/misc/IF11455.pdf

Kuzma, S., Bierkens, M., Lakshman, S., Luo, T., Saccoccia, L., Sutanudjaja, E. H., & Van Beek, R. (2023). *Aqueduct 4.0: Updated decision-relevant global water risk indicators.* Retrieved from World Resources Institute: doi.org/10.46830/writn.23.00061

Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., . . . Swan, A. (2021). *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report Summary.* Princeton, NJ: Princeton University.

Merrill, A. M. (2024, January). *Aluminum.* Retrieved from U.S. Geological Survey: https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-aluminum.pdf

NETL. (2019, April). *Quality Guidelines for Energy System Studies - Capital Cost Scaling Methodology: Revision 3 Reports and Prior.* Retrieved from National Energy Technology Laboratory: https://netl.doe.gov/projects/files/QGESSCapitalCostScalingMethodologyRevision3ReportsandPrior_040119.pdf

NETL. (2022, December 21). *Industrial CO2 Capture Retrofit Database (IND CCRD).* Retrieved from National Energy Technology Laboratory: https://www.netl.doe.gov/energy-analysis/details?id=a9f14d58-52d3-4a06-85cc-33d5cba5c895

NETL. (2023a, March 30). *Pulverized Coal CO2 Capture Retrofit Database.* Retrieved from OSTI.GOV: https://www.osti.gov/biblio/1968297

NETL. (2023b, March 16). *OSTI.GOV.* Retrieved from Natural Gas Combined Cycle Carbon Capture Retrofit Database: https://www.osti.gov/biblio/1962372

Renewable Fuels Association. (2023, September 18). *Biorefinery Locations Table*. Retrieved from https://ethanolrfa.org/resources/ethanol-biorefinery-locations

U.S. Bureau of Economic Analysis. (2023, December 11). *Price Indexes for Gross Domestic Product, Gross National Product, and Net National Product.* Retrieved from Bureau of Economic Analysis: https://apps.bea.gov/iTable/?reqid=19&step=2&isuri=1&categories=survey#eyJhcHBpZCI6MTksInN0ZXBzIjpbMSwyLDMsM10sImRhdGEiOltbImNhdGVnb3JpZXMiLCJTdXJ2ZXkiXSxbIk5JUEFfVGFibGVfTGlzdCIsIjQyIl0sWyJGaXJzdF9ZZWFyIiwiMTk5MCJdLFsiTGFzdF9ZZWFyIiwiMjAyMiJdLFsiU2NhbGUi

U.S. Census Bureau. (2021, October 8). *Geographic Levels.* Retrieved from United States Census Bureau: https://www.census.gov/programs-surveys/economic-census/guidance-geographies/levels.html#par_textimage_34

U.S. Energy Information Administration. (2023a). *Annual Electric Power Industry Report.* Retrieved from U.S. Energy Information Administration: https://www.eia.gov/electricity/annual/html/epa_02_10.html

U.S. Energy Information Administration. (2023b). *U.S. Fuel Ethanol Plant Production Capacity*. Retrieved from https://www.eia.gov/petroleum/ethanolcapacity/

U.S. Energy Information Administration. (2024a, February 29). *Natural Gas Prices.* Retrieved from U.S. Energy Information Administration: https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PIN_DMcf_a.htm

U.S. Energy Information Association. (2024b, February 29). *What is U.S. electricity generation by energy source?* Retrieved from U.S. Energy Information Association: https://www.eia.gov/tools/faqs/faq.php?id=427&t=3#:~:text=About%2060%25%20of%20this%20electricity,was%20from%20renewable%20energy%20sources.

U.S. Environmental Protection. (2023a). *Greenhouse Gas Reporting Program (GHGRP)*. Retrieved from www.epa.gov/ghgreporting

U.S. Environmental Protection Agency. (2017, January 19). *Carbon Dioxide Emissions Associated with Bioenergy and Other Biogenic Sources.* Retrieved from United States Environmental Protection Agency: https://19january2017snapshot.epa.gov/climatechange/carbon-dioxide-emissions-associated-bioenergy-and-other-biogenic-sources_.html

U.S. Environmental Protection Agency. (2023b). *Envirofacts*. Retrieved from https://enviro.epa.gov/

U.S. Environmental Protection Agency. (2024a). *eGRID with 2022 Data*. Retrieved from https://www.epa.gov/egrid/download-data

U.S. Environmental Protection Agency. (2024b, February 13). *Emission Factors for Greenhouse Gas Inventories.* Retrieved from U.S. Environmetnal Protection Agency: https://www.epa.gov/system/files/documents/2024-02/ghg-emission-factors-hub-2024.pdf

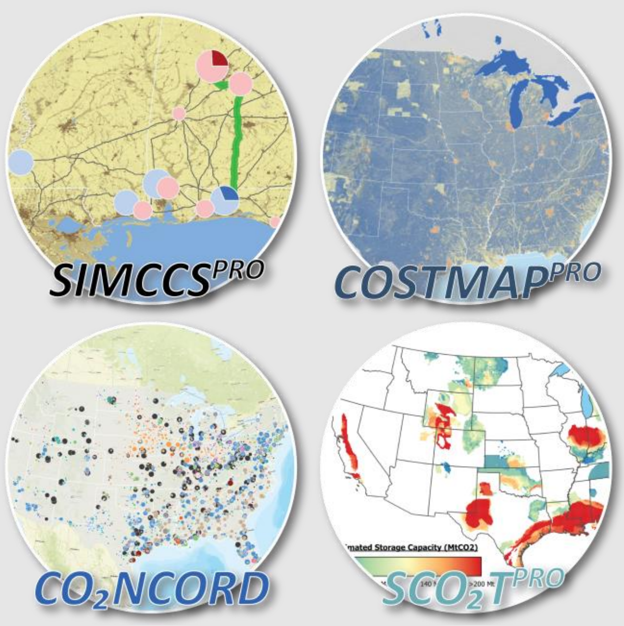
White House Council on Environmental Quality. (2022). *Climate and Economic Justice Screening Tool*. Retrieved March 8, 2024, from https://screeningtool.geoplatform.gov

Xu, Y. I. (2010). Adding value to carbon dioxide from ethanol fermentations. *Bioresource Technology, 101*(10), 3311-3319. Retrieved from https://doi.org/10.1016/j.biortech.2010.01.006

6. About Carbon Solutions

CARBON SOLUTIONS (carbonsolutionsllc.com) is a mission-driven, fast-growing small business focused on low-carbon energy **Research & Development** and **Software & Services**. Energy applications include CO_2 capture and storage (CCS), direct air capture (DAC), energy storage, geothermal energy, wind energy, the hydrogen economy, and energy equity. CARBON SOLUTIONS was launched in 2021 and currently has around 30 employees with more than 50 projects to date. In addition, CARBON SOLUTIONS has around 25 expert energy consultants that cover the entire CCS value chain.

The company currently leads and participates in around a dozen DOE-funded R&D projects in a diverse range of areas, including CO_2 capture-transport-storage, energy storage, wind energy, geothermal energy, and next-generation carbon-negative power fueled by coal waste and biomass (carbonsolutionsllc.com/rd-projects). The company has developed unique award-winning, industry-leading *SimCCS^PRO^* to understand, analyze, and support decisions for CO_2 capture, transport, and storage, including when, where, and how much CO_2 to capture and store, when and how to route CO_2 pipelines, and to assess economics across the entire CCS value chain.



***SimCCS^PRO^* is the world's leading software to optimally understand how and when to optimize CO_2 capture, transport, and storage investments. SimCCS has won two prestigious R&D 100 Awards and is the most-used and most-cited CCS infrastructure software.**

***CO_2NCORD* is a dynamic software and database that characterizes thousands of CO_2 capture opportunities across the United States. The software uniquely fuses and analyzes CO_2 emissions data from multiple data sources and develops unique approaches to calculate capturable CO_2 and advanced capture economics.**

***CostMAP^PRO^* is the most advanced CO_2 pipeline routing and cost tool, combining multiple geographies—such as population, land cover, lane ownership environmental challenges, social impacts, topography, existing rights of way, etc.—to produce custom-weighted pipeline routes and potential networks.**

***SCO_2T^{PRO}* is a dynamic CO_2 sequestration screening tool for identifying potential CO_2 storage sites based on dynamic CO_2 injection and dynamic plume evolution coupled with advanced economics.**