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Appendix F. Appendix to Chapter 7.3: CO_2 Emissions from Stationary Sources

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Disclaimer

Availability

This report and supporting documentation, data, and analysis tools are available online:

- Report landing page: https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources
- Data portal: https://bioenergykdf.ornl.gov/bt23-data-portal

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Appendix F. Appendix to Chapter 7.3: CO_2 Emissions from Stationary Sources

Appendix F.1: Supplemental Methods

This analysis used a variety of datasets and resources to generate the results shown throughout. This methodology is subject to various key assumptions and caveats, all of which should be used to understand and evaluate the applicability of the results to use in downstream analysis, as well as outline future areas of work to improve this analysis. Several key assumptions in this work are summarized and briefly discussed in Table F-1.

Table F-1. Key Assumptions Used in This Analysis

Assumption	Discussion
CO_2 utilization siting	As noted throughout, this work assumed that CO_2 utilization technologies would be collocated with the stationary source of CO_2 being utilized to avoid transportation costs of CO_2. While this assumption likely depicts near-term deployment of small-scale CO_2 utilization, future large-scale systems might employ different siting strategies depending on available infrastructure and markets for CO_2-based products. For example, if a CO_2 pipeline is constructed that connects various stationary sources, a utilization pathway could be centralized near offtakers for CO_2-based products. This future is highly uncertain and will depend on how stationary sources change over time and the buildout of CO_2 transportation and storage infrastructure. Depicting future CO_2 networks is beyond the scope of this work but is a topic that future work could address.
Cost to price approximations	This work assumed that near-term prices for purified CO_2 emissions are equal to the cost of installing and operating equipment required to capture and purify those emissions from existing point sources. In other words, the cost of capturing CO_2 is equal to the near-term market price. In reality, a market price is set in part by the cost of a feedstock but is also influenced by demands for the material, policy incentives, and other factors. It is important to note that CO_2 is not currently managed as a commodity and is rather viewed as a waste. Similar to other solid and organic waste materials, if demand for these wastes increases, their prices are likely to respond to demand increases and shift. Conventional economics suggests that increases in demand drives corresponding increases in prices, although this is highly uncertain and likely to vary over time and from source to source. Detailed consideration of price/demand response and modeling market prices was beyond the scope of this national-level work but should be considered in future analyses. Note that the costs of capture do not include any applicable tax incentives.

Total CO_2 Resource Data Methods

This work used data generated by the U.S. Environmental Protection Agency's (EPA's) Greenhouse Gas Reporting Program (GHGRP) as a starting basis for nationwide CO_2 from stationary sources in 2022 (EPA 2022). Data reported in the 2022 data summary spreadsheet provided by the EPA include information on biogenic vs. non-biogenic CO_2 emissions by facility for direct emitters (EPA 2022). Other emissions are also included in the EPA dataset covering natural gas gathering, boosting, and transmission infrastructure. These sources were not included in this resource assessment due to a lack of reliable capture and storage data, and because they only represent a small (less than 5%) portion of total emissions.

CO_2 Supply Curve Data Sources and Methods

The National Energy Technology Laboratory (NETL) has produced three carbon capture retrofit databases (CCRDs) (NETL 2023a, 2023b, 2023c). The CCRDs provide high-level estimates of the incremental costs for retrofitting individual point sources with CO_2 capture and/or compression systems. The point sources are select units from the power generation and industrial sources sectors in the United States that are either in operating or standby status. The power generation sources are subdivided into pulverized coal, which includes coal-fired and atmospheric fluidized bed units, and natural gas combined cycle, which includes natural-gas-fired, combined-cycle and combined-cycle, single-shaft units. Industrial sources include ammonia, cement, ethanol, hydrogen, and natural gas processing industries. The technologies used for CO_2 capture in the CCRDs, as described by NETL (Schmitt et al. 2022; Hughes and Zoelle 2023), are based primarily on Shell's Cansolv CO_2 capture system for low purity process streams (with the exception of refinery hydrogen production) and CO_2 compression and dehydration for nearly pure process streams.

Data for the industrial sector are publicly available and were sourced from the EPA. Data for the power sector came from a licensed product, Hitachi Energy Velocity Suite. All runs were based on 2021 as the reference year. The values for the industrial sources included in the CO_2 supply curve were developed by the U.S. Department of Energy Office of Fossil Energy and Carbon Management using the current publicly available NETL Industrial CCRD (Revision 62, release date Dec. 19, 2023). Because the NETL Industrial CCRD is not configured to produce separate cost estimates for the low-purity streams at ethanol and ammonia facilities, where capture from both high- and low-purity streams is an option, several modifications to the CCRD were necessary to generate the supply curve developed for this study. Note that the results produced by the CCRDs are based on scaling of cost and performance data drawn from techno-economic analyses of industry-specific processes and should not be considered reflective of a direct vendor quote for any system modeled in the CCRDs. Additional detail on the applicability of the data and the accuracy of the results is provided in the NETL documents "User Guide for the Public Power Generation CO_2 Capture Retrofit Database Models" and "User Guide for the Public Industrial CO_2 Capture Retrofit Database Models" (embedded in the downloadable CCRD tools). Further detail on the methodology utilized to calculate the costs of retrofitting pulverized coal (Buchheit et al. 2023) and natural gas combined-cycle (Schmitt et al. 2023) plants are provided by NETL in comprehensive reports. Note that the industrial CCRD does not currently include the petroleum refining or iron and steel sectors. For those sectors, the cost estimates were leveraged from the recent *Pathways to Commercial Liftoff: Carbon Management* report and adjusted to represent 2021 dollars (Fahs et al. 2023).

Table F-2. Key Outputs and Information about Each of the Sectors Considered in This Assessment. In Addition to Facility Counts, Amounts, and Costs of Capture, the Table Also Describes the Streams That Are Accounted for in Each Sector, the Applicable GHGRP Subpart, and the Source for Estimating the Cost of Capture (Figure 7.28).

Sector	Facility Count (All)	Facility Count at <$250/U.S. Ton	CO_2 Captured, Million U.S. Tons per Year (All Facilities)	CO_2 Captured, Million U.S. Tons per Year (Facilities with Cost of Capture <$250/U.S. Ton)	Cost of Capture Weighted Average ($/U.S. Ton)	Capture Rate	Streams Accounted for	EPA GHGRP Subparts	Cost of Capture Source
Pulverized coal power	502	475	1,050	1,042	$72.3	95%	Flue gas	D	NETL pulverized coal CCRD
Natural gas combined-cycle power	695	569	684	672	$97.3	95%	Flue gas	D	NETL natural gas combined-cycle CCRD
Stationary combustion	4,993	1,856	663	540	$178.5	90%	Flue gas – not otherwise accounted for in ammonia, ethanol, and iron and steel	C	NETL industrial CCRD; see detailed discussion
Ammonia – high purity [b]	29	29	7	7	$25.1	100%	High-purity vent (stripper offgas)	G	NETL industrial CCRD
Ammonia – low purity	29	27	19	19	$79.4	90%	Low-purity combustion emissions	C	NETL industrial CCRD
Ethanol – high purity [b]	192	192	40	40	$29.3	100%	High-purity vent (fermentation)	Estimated	NETL industrial CCRD
Ethanol – low purity	192	180	40	40	$110.3	90%	Low-purity combustion emissions	C	NETL industrial CCRD
Iron and steel	121	121	77	77	$74.8	90%	Blast furnace flue gas	C and Q	Fahs et al. (2023)
Refinery fluid	85	85	48	48	$76.7	90%	Fluid catalytic cracking regenerator overhead gas;	Y	Fahs et al. (2023)

Sector	Facility Count (All)	Facility Count at <$250/U.S. Ton	CO_2 Captured, Million U.S. Tons per Year (All Facilities)	CO_2 Captured, Million U.S. Tons per Year (Facilities with Cost of Capture <$250/U.S. Ton)	Cost of Capture Weighted Average ($/U.S. Ton)	Capture Rate	Streams Accounted for	EPA GHGRP Subparts	Cost of Capture Source
catalytic cracker							process heat/furnaces included under stationary combustion		
Natural gas processing	307	292	18	18	$32.4	100%	Includes only vent stream from the acid gas removal units	W	NETL industrial CCRD
Hydrogen	87	87	41	41	$54.9	99%	Raw syngas stream from steam methane reformer upstream of pressure swing adsorption unit	P	NETL industrial CCRD
Cement	90	90	87	87	$70.1	90%	Kiln offgas (includes combustion and process CO_2 in a single stream)	H	NETL industrial CCRD
Total	7,322	4,003	2,773	2,630					

[a] Captured amount for all but high-purity sources include 90% capture from external boiler to supply energy to the capture system.

[b] Excludes facilities that already capture CO_2 as identified in the EPA GHGRP.

High-Purity CO_2 from Ethanol and Ammonia: Data Sources and Methods

Two of the sectors included in this assessment include both high- and low-purity streams of exhaust gas from which CO_2 could be captured—ammonia and ethanol. High-purity streams are of interest because they do not require the separate processes needed for low-purity streams. Generally, high-purity streams only require moisture removal and compression. Additionally, these streams are less likely to contain contaminants that may be present in other streams, requiring less additional purification for applications with strict purity requirements. As a result, high-purity streams are less costly to capture and are thus highlighted in detail within this section.

In ammonia production, the high-purity point-source stream comes from a process that separates CO_2 from syngas resulting from the reforming process. These emissions are reported to the EPA GHGRP in Subpart G, whereas the combustion-related emissions from ammonia production are reported to Subpart C. Many of the existing ammonia facilities already capture some fraction of the high-purity emissions (24 of 32 facilities that report to GHGRP). Using data from industry reporting (fertilizer institute) and the EPA, it is estimated that 77% of this high-purity CO_2 is already captured.

The high-purity stream in the ethanol sector comes from the fermentation process. Similar to the high-purity ammonia, this stream only requires cooling and compression, making it less costly to capture. Since this CO_2 originates from corn, it is biogenic. The GHGRP does not require the reporting of these emissions, so they must be estimated using stoichiometry based on the amount of ethanol produced (EIA 2023) according to the EPA's approach (EPA 2010).

Estimating Cost of Capture for Stationary Combustion

Subpart C of the GHGRP governs reporting of stationary combustion and includes processes such as boilers, simple and combined-cycle combustion turbines, engines, incinerators, and process heaters (Code of Federal Regulations 2016). The reporting rule allows sites with multiple point sources to aggregate reporting based on the amount of fuel combusted at the site. To avoid double counting, combustion emissions associated with facilities reported separately in the cost curve were removed from the list of facilities evaluated. The costs of capturing streams depend on many site-dependent factors including the number and spatial orientation of different point sources. Therefore, using GHGRP data alone does not allow for a robust estimation for the cost of capture for stationary combustion sources. To avoid underestimating the cost of capture for facilities reporting in this category, the number of emissions points was estimated for each reporting site using data on point-source emissions reported to the EPA's National Emissions Inventory (NEI) (EPA 2017).

The NEI tracks emissions from a variety of processes, not just fuel combustion, meaning that simply using the number of emission points would likely overstate the point sources that release CO_2. Therefore, carbon monoxide was selected as a proxy combustion co-pollutant and selected to further filter the point sources in the NEI. To leverage the point-source data from NEI, it was necessary to map facilities from the GHGRP. Note that GHGRP and NEI each have unique facility IDs associated with the corresponding program. EPA's Standardized Emission and Waste Inventories (StEWI) tool was used to create the crosswalk (Ingwerson et al. 2021). Even after leveraging that tool, about half of the GHGRP facilities with reporting to Subpart C were without corresponding matches to NEI data. For those facilities, matches were made on the basis of two identifying attributes—the ZIP code and North American Industry Classification System code of the reporting facility, which are reported to both inventories. Using the matches to the NEI data, the number of point sources for each GHGRP facility reporting to Subpart C was estimated using the point-source inventory data from 2017. Any GHGRP facilities that were not matched to an NEI ID were assumed to only have one point source.

To calculate the costs of capture, NETL's industrial CCRD tool was leveraged based on using the same cost assumptions for capture of combustion emissions from the ethanol sector. For each facility, the costs were calculated for capture system sized by weighting the emissions of CO_2 according to the weighted emissions of CO across all the combustion point sources matched from the NEI point-source inventory for each facility. For example, if a single point source represented 50% of the CO emissions for a facility, it was assumed to also contribute 50% of the CO_2 emissions for the facility. Note that this is a conservative estimation approach and additional work is necessary to evaluate whether some point sources could be combined within a facility, potentially resulting in a lower cost of capture.

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