Department of Energy
Washington, DC 20585

Material Requirements for Carbon Capture and Storage Retrofits on Existing Coal-Fueled Electric Generating Units

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Summary

The Department of Energy (DOE) has developed this analysis of commodity material requirements for retrofitting existing U.S. coal-fueled electric generating units (EGUs) with carbon capture and storage (CCS) and compared those requirements to historical global and U.S. production rates. Natural gas-fired electricity generation with CCS is an important part of the U.S. strategy to achieve a 100 percent clean electricity sector by 2035 and net zero emission economy-wide by 2050 but is not in scope for this analysis. [1]

The analysis considered the following commodities: monoethanolamine (MEA) solvent for carbon capture, triethylene glycol (TEG) for carbon dioxide (CO_2) drying, and steel and cement for construction.

Key findings from this analysis:

- The analysis determined that for a scenario in which 73 gigawatts (GW) of coal-fueled EGUs are retrofitted with CCS, the maximum annual commodity requirements to construct and operate the CCS systems are likely to be much less than their respective global production rates.
- The maximum requirements are expected to be at least one order of magnitude lower than global annual production for all the commodities except MEA, which is ~24% of global annual production. However, this represents a stress test scenario. DOE is working to commercialize other capture methods, including membrane-based and cryogenic carbon capture, that would diversify the portfolio of capture technologies and further reduce MEA dependencies.
- For steel and cement, the maximum annual requirements are also expected to be at least one order of magnitude lower than U.S. annual production rates.
- Given a large pool of potential suppliers, and absent a significant surge in global demand, no bottlenecks are anticipated for select specialized equipment (i.e., absorbers, strippers, heat exchangers, and compressors) under the 73 GW deployment scenario.

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[1] See, e.g., U.S. Department of State and the Executive Office of the President, “The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050,” November 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/us-long-term-strategy.pdf.

Coal-Fueled EGU Capacity Assumed to Retrofit with Carbon Capture

The decision of whether to retrofit a fossil EGU with CCS, use other methods to reduce emissions, retire it, or reduce operations will be unique to each generating unit, and depends on factors such as the unit age, operating and fuel costs of each unit, the relative costs of other fuels and electricity generation technologies, state and federal incentives for CCS, access to CO_2 transportation and storage infrastructure, and other factors.

The Environmental Protection Agency (EPA) National Electric Energy Data Systems (NEEDS) database includes 73 GW of coal EGUs with currently no firm commitment to retire or convert to natural gas by 2040.[2] However, the set of coal EGUs likely to retrofit with CCS could be smaller when accounting for each unit's capacity and age. Capture costs on a dollar-per-ton basis tend to be higher for smaller capacity coal EGUs.[3] Additionally, coal retirements in recent years have tended to come from older units: the capacity-weighted average age of coal EGUs scheduled to retire in 2024 is almost 54 years.[4]

Table 1 describes the two scenarios considered by this analysis. In Scenario 1, 73 GW (pre-retrofit capacity) of existing coal EGUs are retrofitted with CCS. In Scenario 2, 42 GW (pre-retrofit capacity) of coal EGUs are retrofitted with CCS. For each scenario, it is assumed that installations of all CCS retrofits are initiated and completed within the five-year period 2028 to 2032, with each installation taking three years to construct. Furthermore, it is assumed that the CCS capacity is deployed in three equal tranches, with the tranches starting construction at the beginning of 2028, 2029, and 2030 and the tranches beginning operations in 2031, 2032, and 2033. Finally, it is assumed that all coal EGUs operate at a 70% capacity factor after they have been retrofitted with CCS.

Table 1: Scenarios for Retrofitting Existing Coal EGUs with CCS

	Scenario 1: 73 GW	**Scenario 2: 42 GW**
Characteristics of Plants that are Retrofitted with CCS	• existing coal EGU with no firm commitment to retire or convert to natural gas by 2040 • any generation capacity • any age	• existing coal EGU with no firm commitment to retire or convert to natural gas by 2040 • generation capacity greater than 50 MW • less than 60 years old (as of 2024)
Total Pre-Retrofit Generation Capacity of Retrofitted Coal EGUs	73 GW	42 GW

[2] The NEEDS data base tracks electricity generation unit information including basic geographic, operating, air emissions, and other data including announced retirement dates. https://www.epa.gov/power-sector-modeling/national-electric-energy-data-system-needs

[3] In the National Energy Technology Laboratory carbon capture retrofit database, no coal-fueled EGUs 50 MW or smaller, when assumed to operate at 70% capacity factor (pre- and post-retrofit), have carbon capture costs less than $85/t CO_2 (expressed in 2018 dollars). If expressed in current year dollars, this MW threshold would be higher. The incentive provided by the 45Q tax credit is currently $85/t CO_2 and will not be adjusted for inflation until 2026.

[4] https://www.eia.gov/todayinenergy/detail.php?id=61425

Total Full-Load Carbon Capture Capacity of Retrofitted Coal EGUs	571 Metric Tons Per Annum (Mtpa) CO_2 (at 100% capacity factor)	327 Mtpa CO_2 (at 100% capacity factor)

Commodity Material Requirements for Retrofitting Existing Coal-Fueled EGUs with CCS

A 2022 DOE study[5], "Carbon Capture, Transport, and Storage - Supply Chain Deep Dive Assessment" (hereafter referred to as the DOE CCS supply chain study), estimated certain subsets of commodity material requirements for a scenario in which the U.S. deploys by 2050 sufficient CCS capacity to capture and store 2,000 Mtpa. The study assumed that the CCS deployments all used carbon capture systems that required MEA solvents[6] and CO_2 dryers that required TEG[7]. The study estimated required quantities of MEA and TEG for carbon capture, steel for carbon transport and storage (only) [8], and cement for carbon storage (only).

The assumption that all carbon capture systems use MEA solvents is used as a stress test on the MEA supply chain; however, many other carbon capture technologies are being developed that provide alternatives to MEA and could further reduce supply chain risk. For example, DOE is partnering with the Wyoming Integrated Test Center to pilot membrane-based carbon capture on the equivalent of 10 megawatts (MW) of flue gas supplied by the Basin Electric Dry Fork coal power plant.[9] The DOE Office of Clean Energy Demonstrations (OCED) is working with the Southern States Energy Board to conduct a front-end engineering design (FEED) study to evaluate cryogenic-based carbon capture.[10] As these and other carbon capture technologies mature, they are expected to reduce reliance on first-generation MEA-based systems.

The following analysis was based on the findings of the DOE CCS supply chain study, with two exceptions:

- *Steel and cement requirements for the carbon capture plant*: Since the DOE CCS supply chain study did not include estimates of steel and cement quantities required for the capture system, another source was referenced to fill that gap. A 2022 study entitled, "Front-End Engineering Design (FEED) Study for a Carbon Capture Plant Retrofit to a Natural Gas-Fired Gas Turbine Combined Cycle Power Plant" (hereafter referred to as the Bechtel FEED study) was prepared by Bechtel National, Inc. for

[5] Carbon Capture, Transport, & Storage: Supply Chain Deep Dive Assessment

[6] The study selected MEA for its case study because it is currently the most advanced in its technical readiness level and is already in common commercial use. Future CCS deployments could potentially use different solvents, or capture technologies that do not use solvents (e.g., membranes, sorbents, and cryogenic separation), which would reduce dependencies on the MEA supply chain.

[7] The study notes that, "There are several technologies to dry the CO_2; however, it is anticipated that triethylene glycol (TEG) will be used for most carbon capture in the United States in 2050 due to its effectiveness and widespread use in the natural gas industry."

[8] The study notes that, "The most significant amount of steel will be needed for the transportation pipeline… A smaller amount of steel will be used for injection and monitor wells… This analysis will not examine the steel needed for other parts in detail; however, they are not insignificant. The capture, drying, and liquification processes will require steel in the form of absorption towers, contactors, drums, boilers, heat exchangers, and other smaller parts."

[9] https://www.netl.doe.gov/projects/project-information.aspx?p=FE0031587

[10] https://www.energy.gov/sites/default/files/2024-01/OCED_CCFEEDs_AwardeeFactSheet_SSEB_1.5.24.pdf

DOE. The Bechtel FEED study was for the potential installation of a post-combustion capture and compression unit at Panda's Sherman natural gas–combined cycle (NGCC) power plant in Sherman, Texas. The capture plant in the Bechtel FEED study was based on conventional technology comprising a non-proprietary aqueous MEA solvent with regeneration steam extracted from the host plant. The following analysis was based on that study's estimates of steel and cement requirements for an MEA-based carbon capture system.

- *MEA requirements for the carbon capture plant*: To estimate MEA quantities, the DOE CCS supply chain study referenced a 2010 DOE study, "Cost and Performance Baseline for Fossil Energy Plants Revision 2." Since the Bechtel FEED study is based on more recent data than the 2010 DOE study, the following analysis was based on that study's estimates of MEA requirements for an MEA-based carbon capture system[11].

It is noted that the Bechtel FEED study was for a natural gas combined cycle EGU rather than a coal-fueled EGU. It is also noted that carbon capture steel and cement requirements estimated by the Bechtel FEED study were dependent on the specific capture system configuration and site conditions at the project site in Sherman, Texas. Steel and cement requirements depend on how the carbon capture system is integrated with the base plant and what balance-of-plant systems are required (e.g., auxiliary energy systems, water treatment systems, cooling systems, substations). Accordingly, since the following analysis uses the Bechtel FEED study, with its specific carbon capture system design and site conditions, as a basis to estimate cement and steel requirements for various CCS retrofits of coal-fueled EGUs located in different locations, it is acknowledged that the results are only rough order of magnitude estimates.

Listed in Table 2 are the commodity material requirements estimated by the referenced studies to construct and operate CCS capacity. For construction, the MEA and TEG quantities represent the amounts needed for first fills of the associated equipment. For operations, the MEA and TEG quantities represent the amounts needed to replenish during operations.

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[11] The Bechtel FEED study used an adsorption bed for CO_2 drying rather than TEG, so this analysis relied on the DOE CCS supply chain study for estimating TEG quantities.

Table 2: Commodity Material Requirements for Construction and Operation of Coal EGU CCS Retrofits (assuming MEA-based capture)

	CONSTRUCTION tonnes per Mtpa-CO_2 CCS capacity			OPERATION tonnes per Mt CO_2 captured
	CO_2 Capture System	CO_2 Transport & Storage*	Total	CO_2 Capture System
Steel	1200	16,500	17,700	NA
Cement	2600	551	3,151	NA
MEA	450	NA	450	1,100
TEG	13	NA	13	20

*Cement quantities for transport are not included.
Source for steel, cement and MEA for capture system construction and operation: 2021 Bechtel National, Inc. study, "Front-End Engineering Design (FEED) Study for a Carbon Capture Plant Retrofit to a Natural Gas-Fired Gas Turbine Combined Cycle Power Plant"[12]
Source for all other data: 2022 DOE study, "Carbon Capture, Transport & Storage: Supply Chain Deep Dive Assessment"[13]

Based on the commodity requirements in Table 2, the quantities of steel and cement (Table 3) and MEA and TEG (Table 4) were calculated (prorated) for each of the CCS retrofit scenarios.

Table 3: Steel and Cement Requirements for Coal EGU CCS Retrofits (assuming MEA-based capture)

Year	Capacity Deployed, Mtpa-CO_2 (end of 3-year construction period)	Quantity Required for Construction*, kt	
		Steel	Cement
Scenario 1: 73 GW			
2028		3,371	600
2029		3,371	600
2030		3,371	600
2031	190		
2032	190		
2033	190		
Scenario 2: 42 GW			
2028		1,930	344
2029		1,930	344
2030		1,930	344
2031	109		
2032	109		
2033	109		

*Assumes that steel and cement are required in first year of construction.

[12] https://www.osti.gov/servlets/purl/1836563
[13] accessed at https://www.energy.gov/sites/default/files/2022-02/Carbon%20Capture%20Supply%20Chain%20Report%20-%20Final%202.25.25.pdf

In Table 4, the annual quantities of MEA and TEG required for operation increase from 2031 to 2032 because in 2031 only the first tranche would be operating, while in 2032 both the first and second tranches would be operating.

Table 4: MEA and TEG Requirements for Coal EGU CCS Retrofits (assuming MEA-based capture)

Year	Capacity Deployed, Mtpa-CO_2 (end of 3-year construction period)	Quantity Required for Construction*, kt		Quantity Required for Operation**, kt		Total Annual Requirement, kt	
		MEA	TEG	MEA	TEG	MEA	TEG
Scenario 1: 73 GW							
2028							
2029							
2030		86	2.5			86	2.5
2031	190	86	2.5	147	2.7	232	5.1
2032	190	86	2.5	293	5.3	379	7.8
2033	190			440	8.0	440	8.0
Scenario 2: 42 GW							
2028							
2029							
2030		49	1.4			49	1.4
2031	109	49	1.4	84	1.5	133	2.9
2032	109	49	1.4	168	3.1	217	4.5
2033	109			252	4.6	252	4.6

*Assumes that MEA and TEG (for first fills) are required in the final (third) year of construction.
**Assumes capture system is operated at 70% capacity factor.

Table 5 lists U.S. and global annual production rates for steel, cement, MEA, and TEG.

Table 5: Maximum Annual Commodity Material Requirements Compared to Historical Annual Production

	Steel, kt	Cement, kt	MEA, kt	TEG, kt
Scenario 1 Annual Maximums	3,371	600	440	8.0
Scenario 2 Annual Maximums	1,930	344	252	4.6
U.S. Annual Production	87,000 in 2019	87,000 in 2019	not reported	not reported
Global Annual Production	1,870,000 in 2019	4,100,000 in 2019	1,840 in 2020	500 in 2019
Source of U.S. and global annual production: 2022 DOE study, "Carbon Capture, Transport & Storage: Supply Chain Deep Dive Assessment"[14]				

As shown in Table 5, the maximum annual commodity requirements for Scenario 1 (73 GW of CCS retrofits) are 3,371 kilotonnes (kt) for steel, 600 kt for cement, 440 kt for MEA and 8.0 kt for TEG. Each of these maximum annual requirements is much less than the global production rate for the respective commodity. In fact, the maximum annual Scenario 1 requirements are at least one order of magnitude lower than global annual production for all of the commodities except MEA, which is 24% of global annual production. For steel and cement, the maximum annual Scenario 1 requirements are also at least one order of magnitude lower than U.S. annual production rates.

As stated previously, the estimates for steel and cement are uncertain because CCS retrofit projects will have varying site conditions and feature carbon capture system configurations that require different balance-of-plant systems. However, given that steel and cement needs are still an order or more of magnitude less than domestic and global production, even if requirements were tripled, they would comprise only 12% and 2% of their annual U.S. production rates, respectively.

The maximum annual commodity requirements for Scenario 2 (42 GW of CCS retrofits) are 1,930 kt for steel, 344 kt for cement, 252 kt for MEA and 4.6 kt for TEG. Each of these maximum annual requirements is much less than the global production rate for the respective commodity. In fact, the maximum annual Scenario 2 requirements are at least one order of magnitude lower than global annual production for all of the commodities except MEA, which is 14% of global annual production. For steel and cement, the maximum annual Scenario 2 requirements are also at least one order of magnitude lower than U.S. annual production rates.

Specialized Equipment Requirements for Retrofitting Existing Coal-Fueled EGUs with CCS

In February 2022, S&P Global issued a report entitled "CCUS supply chain review" that assessed the demand for certain equipment categories (absorbers, strippers, heat exchangers, and compressors) that could be generated by the slate of global CCUS projects that were actively being developed for potential

[14] https://www.energy.gov/sites/default/files/2022-02/Carbon%20Capture%20Supply%20Chain%20Report%20-%20Final%202.25.25.pdf

deployment between 2022 and 2031. Some of the proposed projects were fully integrated across all three components of the CCUS value chain: capture, transport and storage. Others only featured one or two of these components. In sum, they amounted to infrastructure that would capture and/or transport and/or store ~550 Mtpa of CO_2. This is similar in magnitude to the 571 Mtpa of CCS retrofits in Scenario 1 of this analysis, and larger than the amount in Scenario 2.

S&P Global's assessment of this potential deployment (assuming that no projects would be delayed or canceled) indicated that equipment supply bottlenecks would not be expected because of the large pool of potential suppliers. For post-combustion carbon capture, S&P Global identified nine potential suppliers of absorbers and strippers. In addition, five companies were identified as having potential to be major suppliers of heat exchangers for CCUS projects and fifteen companies were identified as potential suppliers of CO_2 compressors for various parts of the CCUS value chain.

Recognizing that just over two thirds of S&P Global's projected CCS deployments are based on projects at early stages of development (planned or announced), it is reasonable to expect that not all of the potential deployments will be realized. Moreover, it is expected that a portion of S&P Global's projected CCS deployment includes a number of the facilities included in Scenarios 1 and 2. Given that DOE expects installation of CCS on coal units would occur in the 2028 – 2033 timeframe, it is anticipated that sufficient production capacity will exist (including idled capacity once demand is satisfied for the nearer-term projections considered in the S&P Global assessment) to meet U.S. demand for specialized equipment even under the higher CCS retrofit projections in Scenario 1.