The Economics of Carbon Capture, Utilization & Storage

By Dr. Jeff Kleck

As the energy landscape transitions toward sustainability, mitigating emissions from existing fossil fuel infrastructure remains a challenge. Carbon Capture, Utilization, and Storage (CCUS) technologies offer a potential solution, enabling reductions in carbon dioxide (CO_2) emissions while maintaining extant fossil-based energy systems. By capturing CO_2 at the source and either storing it permanently or repurposing it for industrial applications, CCUS can serve as a bridge between current energy demands and net-zero goals.

This paper examines the mechanisms of carbon capture, the current state of emissions, the economic feasibility of retrofitting existing fossil fuel facilities, and emerging technologies with the potential to drive further emissions reductions. Additionally, it explores the impact of CCUS on grid stability, energy market dynamics, and broader decarbonization strategies. As we work toward lower emission targets, understanding the role of CCUS in both near-term emissions reductions and long-term energy planning is critical for shaping a sustainable and resilient energy future.

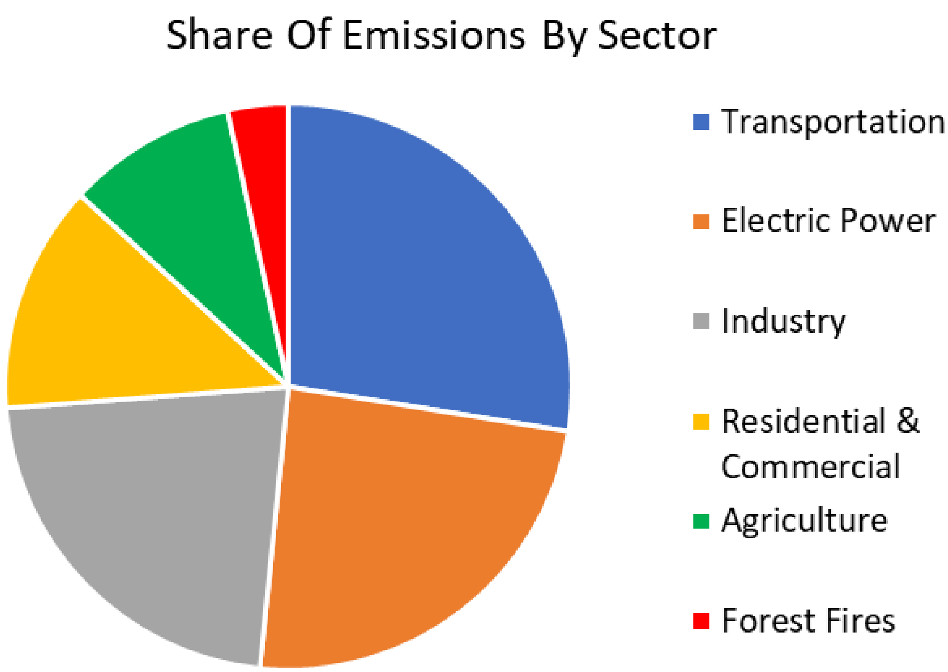
Understanding Carbon Capture - Mechanisms and Applications:

Carbon capture involves intercepting CO_2 emissions at their source, thus preventing them from entering the atmosphere. The three primary methods for carbon capture include:

- Pre-combustion capture: Carbon Dioxide (CO_2) is removed from fuels before combustion, typically through gasification.
- Post-combustion capture: The most widely used approach, capturing CO_2 from flue gases after fossil fuels are burned.
- Oxy-fuel combustion: Fossil fuels are burned in a pure oxygen environment, producing a flue gas mainly consisting of CO_2 and water vapor, simplifying the capture process.

Captured CO_2 can be transported to geological storage sites or utilized in industrial applications, such as enhanced oil recovery (EOR) or in the production of carbon-based materials.

Understanding Emissions:
Across all sectors (not including forest fires), the U.S. emits 6,343 MMT (million metric tons) of CO_2 equivalents emitted (EE)[1], with 4,676 MMT (73.7% of the CO_2 EE) from fossil fuel combustion. When talking about the efficacy of CCUS systems, it is important to keep these total numbers in mind. To aid further in this, here are the percentage of total national CO_2 EE by sector (forest fire data is from 2021, all other data is from 2022):

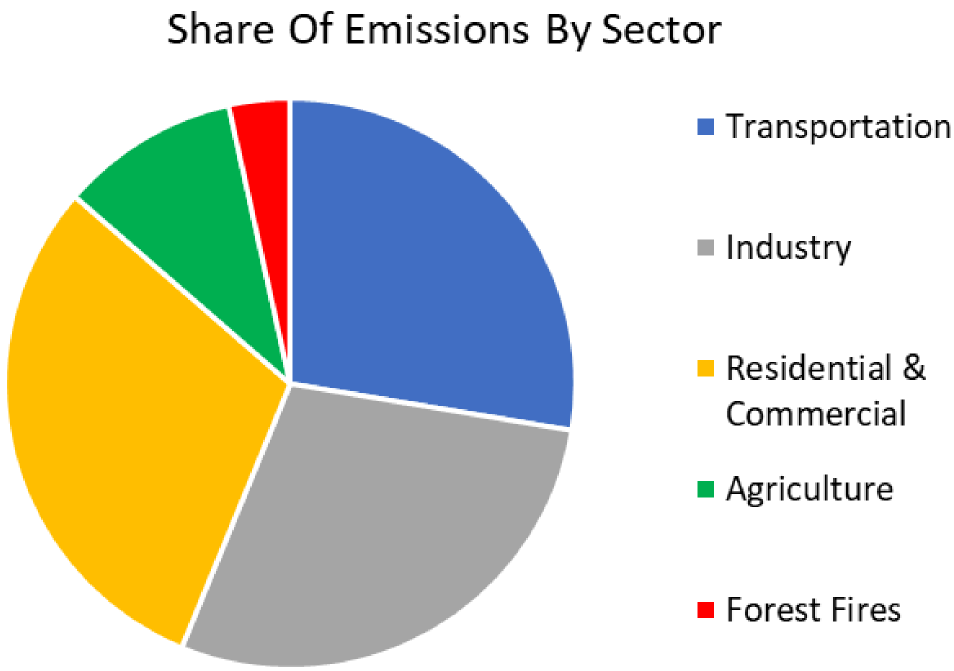


Sector	CO_2 EE (%)	CO_2 EE (MMT)	CO_2 EE (kg)
Transportation	27.4	1802.5	1.80×10^{12}
Electric Power	24.0	1577.5	1.58×10^{12}
Industry	22.1	1452.5	1.45×10^{12}
Residential & Commercial	13.0	855.0	8.55×10^{11}
Agriculture	9.6	634.0	6.34×10^{11}
Forest Fires	3.5	227.0	2.27×10^{11}

Values for U.S. Territories make up the less than 1% difference to 100%.

[1] CO_2 equivalents emitted (EE) is a unit of measurement used to compare the emissions from various greenhouse gases by converting amounts of other gases to the equivalent amount of carbon dioxide.

Electric power is generated for the use of the individual sectors of the economy, so it is helpful to attribute the CO_2 equivalents emitted (EE) production from electric power generation to the relevant sector this power is being utilized in. The redistributed table presents such end-user results (forest fire data is from 2021, all other data is from 2022):



Sector	CO_2 EE (%)	CO_2 EE (MMT)	CO_2 EE (kg)
Transportation	27.5	1807.8	1.81×10^{12}
Industry	28.5	1872.9	1.87×10^{12}
Residential & Commercial	30.1	1976.1	1.98×10^{12}
Agriculture	10.1	663.6	6.03×10^{11}
Forest Fires	3.5	227.0	2.27×10^{11}

Values for U.S. Territories make up the less than 1% difference to 100%. Forest Emissions and Sinks: Forest Fires emitted 227 MMT of CO_2 equivalents from 7.1 million affected acres (29000 square kilometers) in 2021, while U.S. Forests sequestered 794 MMT of CO_2 equivalents the same year

References and Data Sources:
EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks, 2022; EPA National Emissions and Removal, 2022; U.S. Forest Carbon Data: In Brief, 2023

Carbon Capture for Energy Production:

As previously mentioned, 73.7% of U.S. emissions come from fossil fuel combustion. Electricity generation contributes 24.0% of total emissions (indirect fossil fuel combustion as noted below), while the remaining 49.7% of total emissions from fossil fuel combustion comes from other sectors burning fossil fuels on-site for energy (direct fossil fuel combustion as noted below). While utility-scale fuel combustion has proper economies of scale for CCUS, many other processes, such as personal vehicle fuel combustion, do not. Because so much of our emissions come from large-scale plants, understanding their economic implications is essential.

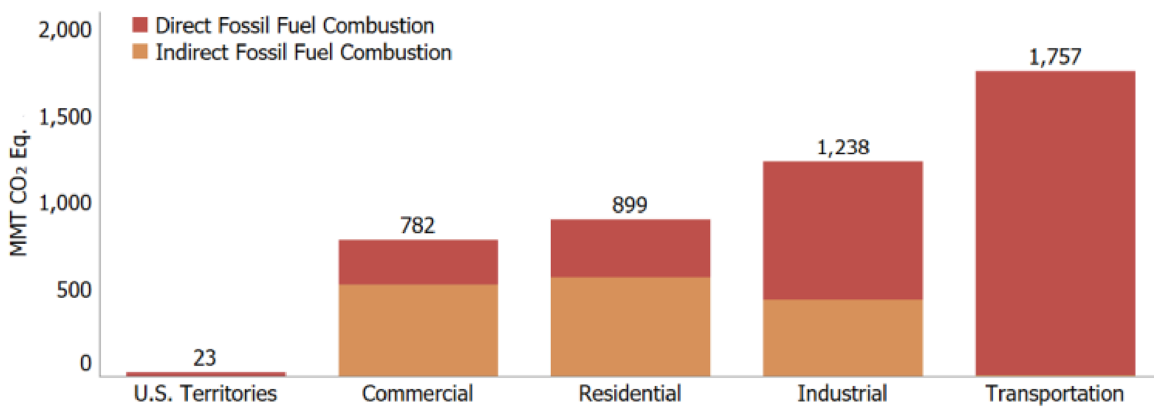


Image courtesy of EPA

Utility-Scale Carbon Capture and Cost Analysis:

The implementation of Carbon Capture, Utilization, and Storage (CCUS) has a measurable impact on the cost structure of utility-scale power generation. The table below outlines the key cost metrics in United States Dollars (USD) for coal, natural gas, and nuclear facilities focusing on Levelized Cost of Energy (LCOE), which is a metric that shows the average lifetime cost per kWh for a facility.

Fuel Type	**Base LCOE (USD per kWh)**	**Base LCOE + observed capacity factors + heat rates (USD per kWh)**
Coal	0.069	0.112
Natural Gas	0.040	0.048
Nuclear	0.068	0.067

Fuel Type	**Base LCOE (USD per kWh)**	**Base LCOE + 33% increase in fuel price (USD per kWh)**
Coal	0.069	0.075
Natural Gas	0.040	0.049
Nuclear	0.068	0.071

Fuel Type	**Base LCOE (USD per kWh)**	**Base LCOE + CCU systems (USD per kWh)**	**Cost of CO_2 Captured (USD per Ton)**
Coal	0.069	0.098 - 0.120	37 - 42
Natural Gas	0.040	0.054 - 0.057	42 - 52
Nuclear	0.068	0.068	N/A

Analysis of Costs

- LCOE Calculations: LCOE calculations represent the costs of building a new facility based on data from existing plants. Carbon capture rate is assumed to be 90%. Heat rates are a measure of how much thermal energy is required to produce 1 kWh of electricity. Observed values are the average values of the respective fleet of facilities for 2023. All cost data is from 2023 EIA data.
- Coal Facilities: Base LCOE assumes $3,700 per kWh overnight cost, $35 per kW-year fixed O&M, $4 per MWh variable O&M, 9,000 MMBtu/kWh heat rate, $2.2 pr MMBtu of coal, 85% capacity factor, 30 year plant lifespan, 7% discount rate. CCU systems add $1,700–2,000 per kWh to overnight costs.The average observed capacity factor for coal plants was 42.4% and the average observed heat rate was 10,550 Btu/kWh in 2023.
- Natural Gas Facilities: base LCOE assumes a natural gas combined cycle (NGCC) system, $1,000 per kWh overnight cost, $10 per kW-year fixed O&M, $3 per MWh variable O&M, 6,300 MMBtu/kWh heat rate, $4.00 per MMBtu of natural gas, 85% capacity factor, 30 year plant lifespan, 7% discount rate. CCU systems add $600–900 per kWh to overnight costs. The average observed capacity factor for NGCC plants was 59.6% and the average observed heat rate was 7,150 Btu/kWh in 2023.
- Nuclear Facilities: these calculations are for a multi-reactor, non SMR facility. Base LCOE assumes $4,900 per kWh overnight cost, $110 per kW-year fixed O&M, $2 per MWh variable O&M, $.007 per kWh of fuel, 90% capacity factor, 40 year lifespan, 7%

discount rate. The average observed capacity factor for nuclear plants was 93% in 2023. Nuclear facilities do not need CCU systems because they do not emit carbon.

References and Data Sources:

EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks, 2022; EPA National Emissions and Removal, 2022; The Energy & Environmental Research Center's Economic Case for CCUS: Reducing Capture Costs and Increasing Demand for Commodity CO_2, 2022; EIA Annual Energy Outlook, 2023; EIA Electric Power Monthly, 2023

Carbon Capture for Industrial Processes:
The production of CO_2 via industrial processes which are not attributable to fossil fuel combustion yielded approximately 168.9 MMT CO_2 in 2022. This translates to approximately 8.5% of the total CO_2 EE generated for the Industrial sector and 2.6% of the total CO_2 EE generated from all sectors. A detailed breakdown of these non fossil fuel combustion contributions follow:

Industrial Process	**CO_2 EE (%)**	**CO_2 EE (MMT)**	**CO_2 EE (kg)**
Iron, Steel, Coke	24.1	40.7	3.70×10^{10}
Cement	24.8	41.9	3.80×10^{10}
Petrochemical	17.1	28.8	2.62×10^{10}
Other	34.0	57.5	5.22×10^{10}

Iron, Steel, metallurgical Coke, cement, and petrochemical (non combustion) production. “Other” consists of ammonia production at 12.6 MMT, lime production at 12.2 MMT, and various other processes.

Fuel Type	**Cost of CO_2 Captured (USD per Ton)**
Steel	40 - 100
Cement	60 - 120

While most industrial emissions are a result of fossil fuel combustion, the economies of scale of on site production can make direct fuel combustion CCUS challenging. One mitigation option is to place Small Modular Reactors (SMRs) or Micro Modular Reactors (MMRs) on site to supply the heat/electricity needed for processes. Another option is to have these facilities directly acquire electricity from utility companies which have proper economies of scale for fossil fuel power plant CCU systems or create their electricity with non-emitting sources like nuclear, solar or wind.

References and Data Sources:
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 – Industrial Processes and Product Use; Levelised cost of CO_2 capture by sector and initial CO_2 concentration, 2019 – Charts – Data & Statistics - IEA

Carbon Capture for Transportation:
Because of space and weight constraints, point-source CCU systems are currently unfeasible for most vehicles. As a result, the leading option to decarbonize this sector would be decoupling from fossil fuels. The most promising options to accomplish this are replacing existing engines with electric and hydrogen models in personal vehicles and hydrogen and nuclear models in airplanes and ships. The associated costs, as well as the reductions in carbon emissions, would vary greatly by application.

Efficacy of Direct Air Capture:
Unlike more conventional capture methods targeting point sources of carbon emissions, direct air capture (DAC) removes CO_2 directly from the atmosphere. Because it is not targeting a point source, DAC is several multiples of the costs of the point source CCUS systems mentioned prior.

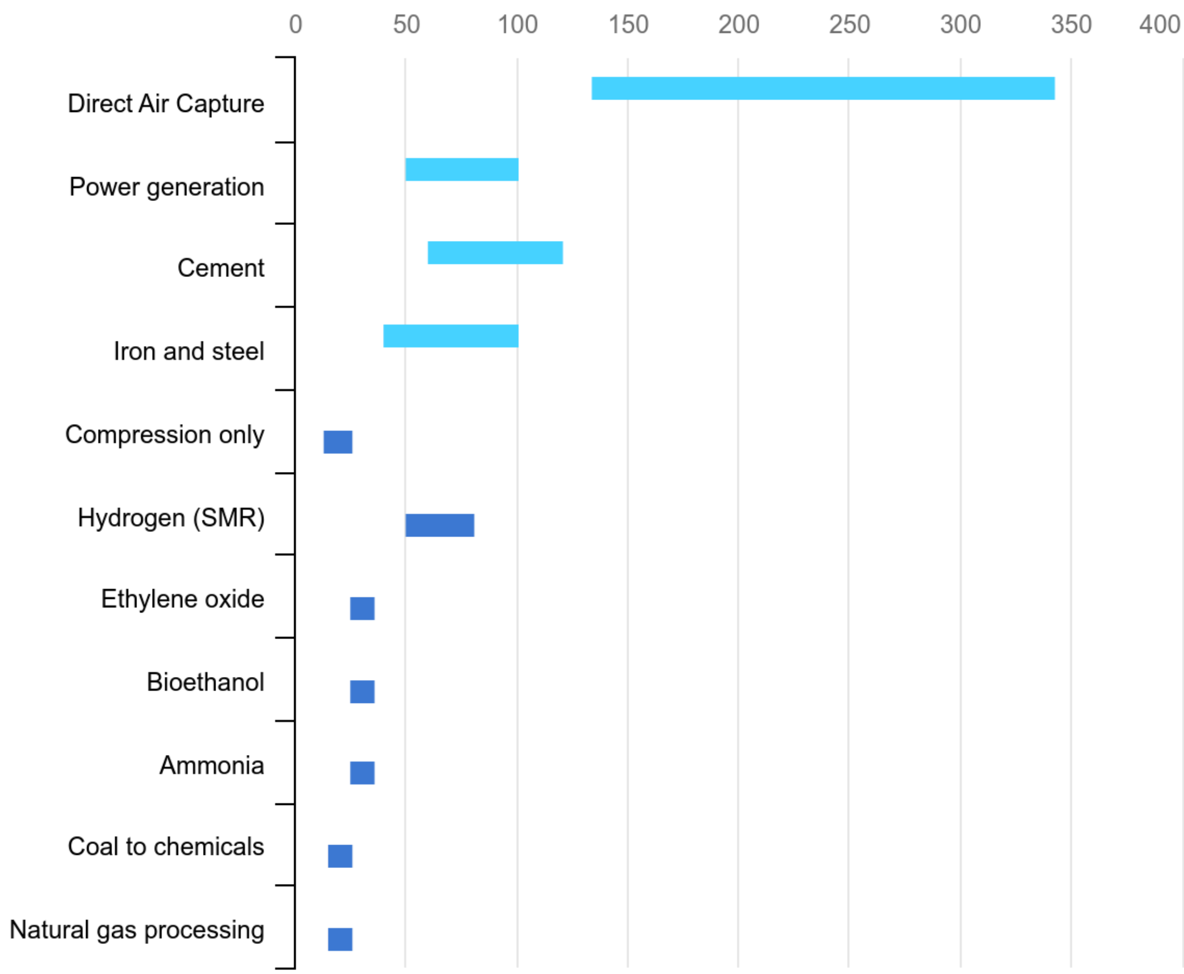


Image courtesy of IEA. Light blue represents less economically viable and dark blue represents more economically viable processes.

References and Data Sources:
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 – Industrial Processes and Product Use; Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019

Conclusion:
The U.S. will need to greatly increase grid capacity in the coming years to meet anticipated demand. This raises a fundamental question: which technologies add that capacity most cost-effectively? Coal has proven neither economically nor environmentally desirable. Natural

gas (NGCC) often appears cost-effective in projections, but when real-world capacity factors, heat rates, and moderate (33%) fuel price increase scenarios are considered, the advantage of NGCC over nuclear for baseload power narrows from 2.8 to 1.1 cents per kilowatt-hour (the change in heat rate to observed values worsens the effects of fuel price changes). Adding CCU systems to NGCC on top of that would raise its LCOE past the cost of nuclear—which itself is artificially inflated due to outdated regulations. Additionally, the cost structure for nuclear does not consider SMRs because they are a next generation technology with no existing cost data to reference. Other sectors like industrial and transportation, as well as Direct Air Capture, have even higher costs per ton of carbon captured than NGCC. Ultimately, policy decisions, market dynamics, and technological advancements will determine the mix of solutions guaranteeing U.S. energy security and independence.

For more information on sustainable energy solutions and carbon capture technologies, please contact Dr. Jeff Kleck at Jeff@OpenPowerEnergy.Net.

Citations

- EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks, 2022
- EPA, National Emissions and Removal, 2022
- FAS, U.S. Forest Carbon Data: In Brief, 2023
- EIA, Annual Energy Outlook, 2023
- EIA, Electric Power Monthly, 2023
- EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022 – Industrial Processes and Product Use
- IEA, Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019

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