UNDERSTANDING SCALES AND CAPTURE RATES FOR POINT-SOURCE CARBON CAPTURE TECHNOLOGY DEVELOPMENT

SUMMARY

The priority of the U.S. Department of Energy's Office of Fossil Energy and Carbon Management (FECM) is reaching the Administration's goals of a fully decarbonized power sector by 2035 and net-zero U.S. greenhouse gas emissions by 2050. To help achieve these goals, FECM invests in research, development and demonstration (RD&D) projects to reduce the cost, increase the efficacy and advance the deployment of commercial-scale point-source carbon capture technologies in the power and industrial sectors, coupled to permanent storage. FECM is developing technologies that can attain steady-state gross carbon capture efficiencies of 95% or higher.

In the process of advancing the readiness of a carbon capture technology for commercial deployment, a series of RD&D projects are commonly completed that have increasing levels of scale, system integration and operational realism.

Typically, small-scale projects are first completed in the laboratory, followed by mid-scale pilot projects in a controlled operational environment and finally full-scale demonstration projects in an actual, commercial, operational environment. Prudent investment of limited RD&D funds requires that costs be minimized by designing projects where research objectives are achieved at the least expensive scale and operational environment. Accordingly, the scale of a pilot or demonstration project is frequently less than what would be required to capture carbon from all of the host facility's emission sources.

Photo: Petra Nova Carbon Capture Facility

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RIGHT SIZING THE SCALE OF CARBON CAPTURE RD&D PROJECTS

For point-source carbon capture technologies, pilot- and full-scale RD&D projects are frequently conducted at an existing commercial plant. To cost-effectively meet the research objectives of a pilot-scale test, a project is usually sized such that only a small fraction of the plant's gas stream emissions is used.

For example, at a fossil-fueled power plant with multiple combustion units, the volume of flue gas from a single unit will typically exceed what is needed by a pilot project to validate the technology's maximum steady-state gross carbon capture efficiency, typically 95+%. Accordingly, only a slipstream, or fraction, of that flue gas would be utilized for testing. For highly modular technologies, a slipstream may even be sufficient for full-scale demonstration projects.

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Fossil Energy and Carbon Management

NATIONAL ENERGY TECHNOLOGY LABORATORY

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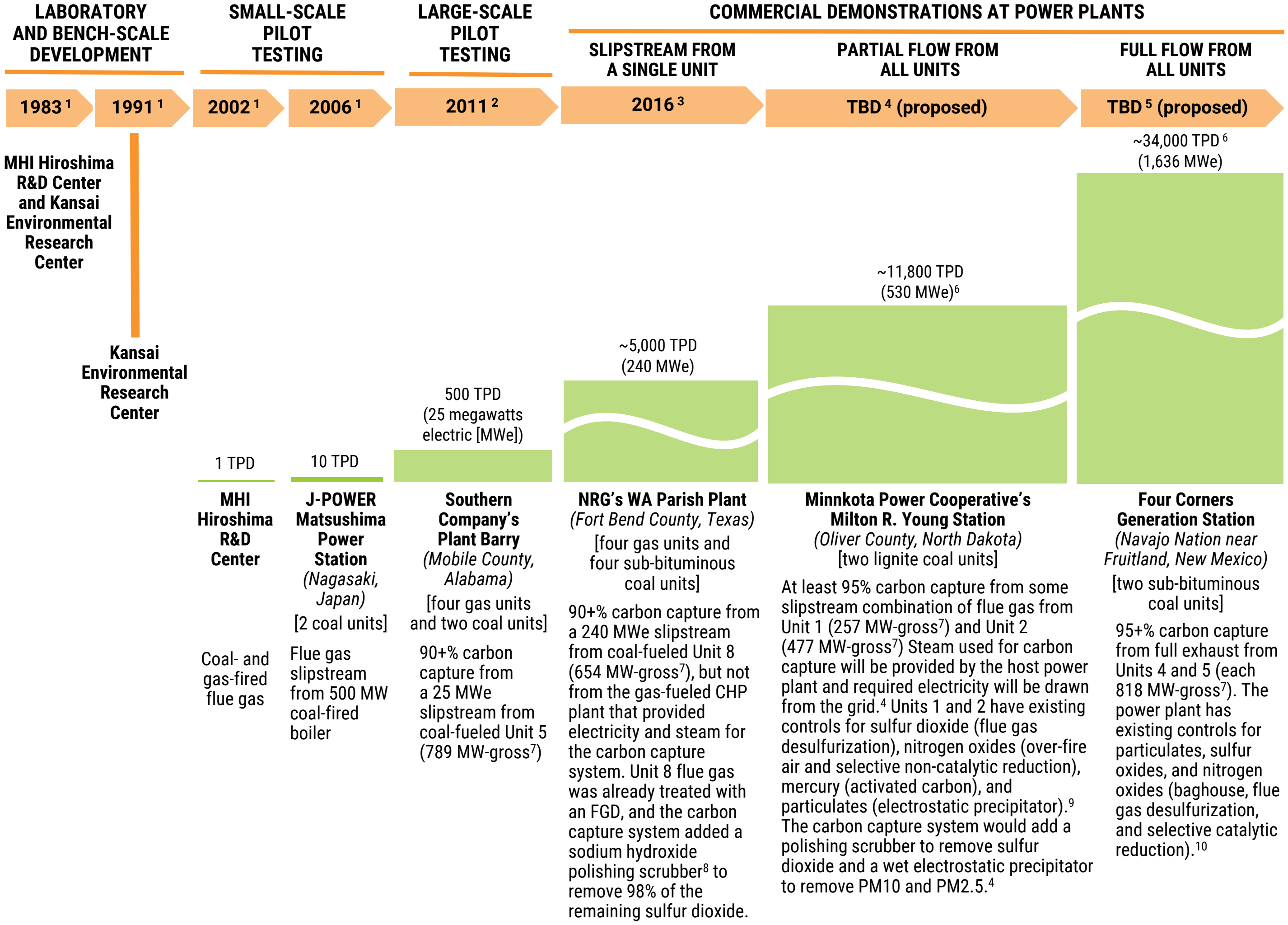
SCALING UP A CARBON CAPTURE TECHNOLOGY

As an example, consider Figure 1, which summarizes how the Kansai Mitsubishi Carbon Dioxide Recovery (KM-CDR) process was scaled up to capture CO_2 from coal-fueled power plants.

After laboratory development in the 1980s and 1990s, small-scale pilot testing commenced on coal-derived flue gas in the 2000s, concluding in 2006 with a 10 tonne per day (TPD) test using a slipstream from a coal-fueled boiler at the Matsushima Power Station in Nagasaki, Japan. This was followed in 2011 by a 500 TPD large-scale pilot test using a slipstream from coal-fueled Unit 5 at Plant Barry in Mobile County, AL. Finally, a ~5,000 TPD commercial demonstration was conducted in 2016 at the WA Parish Plant in Fort Bend County, TX using a slipstream from coal-fueled Unit 8.



MHI Hiroshima R&D Center

Coal- and gas-fired flue gas

J-POWER Matsushima Power Station
(Nagasaki, Japan)
[2 coal units]

Flue gas slipstream from 500 MW coal-fired boiler

Southern Company's Plant Barry
(Mobile County, Alabama)
[four gas units and two coal units]

90+% carbon capture from a 25 MWe slipstream from coal-fueled Unit 5 (789 MW-gross[7])

NRG's WA Parish Plant
(Fort Bend County, Texas)
[four gas units and four sub-bituminous coal units]

90+% carbon capture from a 240 MWe slipstream from coal-fueled Unit 8 (654 MW-gross[7]), but not from the gas-fueled CHP plant that provided electricity and steam for the carbon capture system. Unit 8 flue gas was already treated with an FGD, and the carbon capture system added a sodium hydroxide polishing scrubber[8] to remove 98% of the remaining sulfur dioxide.

Minnkota Power Cooperative's Milton R. Young Station
(Oliver County, North Dakota)
[two lignite coal units]

At least 95% carbon capture from some slipstream combination of flue gas from Unit 1 (257 MW-gross[7]) and Unit 2 (477 MW-gross[7]) Steam used for carbon capture will be provided by the host power plant and required electricity will be drawn from the grid.[4] Units 1 and 2 have existing controls for sulfur dioxide (flue gas desulfurization), nitrogen oxides (over-fire air and selective non-catalytic reduction), mercury (activated carbon), and particulates (electrostatic precipitator).[9] The carbon capture system would add a polishing scrubber to remove sulfur dioxide and a wet electrostatic precipitator to remove PM10 and PM2.5.[4]

Four Corners Generation Station
(Navajo Nation near Fruitland, New Mexico)
[two sub-bituminous coal units]

95+% carbon capture from full exhaust from Units 4 and 5 (each 818 MW-gross[7]). The power plant has existing controls for particulates, sulfur oxides, and nitrogen oxides (baghouse, flue gas desulfurization, and selective catalytic reduction).[10]

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1) Mitsubishi Heavy Industries (MHI) described the developmental history of their KM-CDR process in conference presentations in 2009 and 2018 and in a 2016 conference paper.
2) Southern Company Services and MHI described their carbon capture project at Plant Barry in a 2012 conference paper.
3) Petra Nova Parish Holdings described their carbon capture project in the 2020 Final Technical Report they submitted to the U.S. DOE.
4) Proposed project described in the April 2024 report, "Revised Draft Environmental Assessment for North Dakota CarbonSAFE: Project Tundra."
5) Enchant Energy described their proposed carbon capture project at the Four Corners Power Plant in a 2023 statement.
6) Estimated.
7) Nameplate gross generation capacities as reported to the U.S. Energy Information Administration on survey Form EIA-860.
8) See https://www.netl.doe.gov/sites/default/files/netl-file/Petra_Nova.pdf
9) See https://www.pkmcoop.com/wp-content/uploads/2019/06/Milton-R.-Young-Station-brochure.pdf
10) See https://www.powermag.com/scr-project-upgrades-two-units-at-four-corners/

Figure 1: Development of the Kansai Mitsubishi Carbon Dioxide Recovery (KM-CDR) Process for Coal-Fueled Power Plants

Right sizing these projects to treat slipstreams enabled their RD&D objectives to be achieved at a much lower cost than treating all the flue gas from a single unit or the entire facility.

As shown in Figure 1, two additional commercial demonstration projects have been proposed for the KM-CDR process. These additional projects will continue to reduce cost and performance risks during commercial deployment by further increasing the scale of carbon dioxide (CO_2) capture, perhaps culminating in the treatment of total facility emissions.

INTERPRETING CARBON CAPTURE RATES

The extent to which a carbon capture system removes CO_2 can be expressed in many ways. The calculation can be made on a gross or net basis, and the scope can be limited to the capture system itself or be broadened to encompass the entire host facility. Life cycle analysis (LCA) can also be used to factor in the effects of upstream and downstream emissions beyond the boundaries of the host facility. (For example, see Best Practices for Life Cycle Assessment of Direct Air Capture with Storage and the Carbon Dioxide Utilization LCA Toolkit.)

Some commonly used measures for quantifying the extent of carbon capture include:

- **Capture system's steady-state gross carbon capture efficiency (%)** - the gross quantity of CO_2 that the capture system is designed to remove at steady-state conditions, expressed as a percentage of the total CO_2 in the gas stream that is processed through it. For example, in a multiple-unit facility, the capture system may process only the gas stream emitted by a single unit, or even a fraction (slipstream) of the gas stream emitted by a single unit. This direct metric is the most commonly cited way to express the extent of carbon capture achievable by a given carbon capture technology. Note that the processed gas stream could be only one of multiple gas streams emitted by the host facility.
- **Capture system's steady-state gross carbon capture rate (kg/hour, tonnes/day or tonnes/year)** - the gross quantity of CO_2 that the capture system is designed to remove when operating at steady-state conditions over a given duration of time.
- **Capture system's steady-state net carbon capture efficiency (%)** - the net reduction in CO_2 emissions at steady-state conditions, expressed as a percentage of the CO_2 in the gas stream that is provided from the host facility for treatment. Net metrics account for scenarios in which additional CO_2 emissions are generated to produce (or replace) the energy (e.g., electricity, steam) consumed by the capture system. For example, if a combined heat and power (CHP) system is used to energize a carbon capture system, emissions from the CHP system should be factored into the net reduction of CO_2. Alternatively, if carbon capture is applied to a power plant, and that power plant is derated in order to energize the capture system, CO_2 emissions associated with generation of power to make up for the derate should be factored into the net reduction of CO_2 emissions.
- **Capture system's operational net carbon capture efficiency (%)** - the net reduction in CO_2 emissions during actual, non-steady-state, operational conditions, averaged over a given duration of time, expressed as a percentage of the CO_2 in the gas stream that is provided from the host facility for treatment. The carbon capture efficiency for an operational environment will typically be less than that for steady-state conditions due to a variety of factors, including part-load operation, off-design performance and outages (planned and unplanned).
- **Facility-wide measures** - Any of the above measures can also be computed for the entire facility. However, when reporting facility-wide metrics, one should note whether the capture system was designed to treat all, or only a portion of, the gas streams emitted by the host facility.

Figure 2 provides a generic example to illustrate how some of these metrics are calculated.

Confusing the above measures of carbon capture efficiency can lead to misunderstandings. For example, if a capture system processes only a fraction of a facility's emissions, one may erroneously conclude that the capture system is underperforming if they mistake the facility-wide carbon capture efficiency for the capture system carbon capture efficiency. Likewise, one may erroneously conclude that a carbon capture system is underperforming if the operational net carbon capture efficiency is mistaken for the steady-state net carbon capture efficiency.

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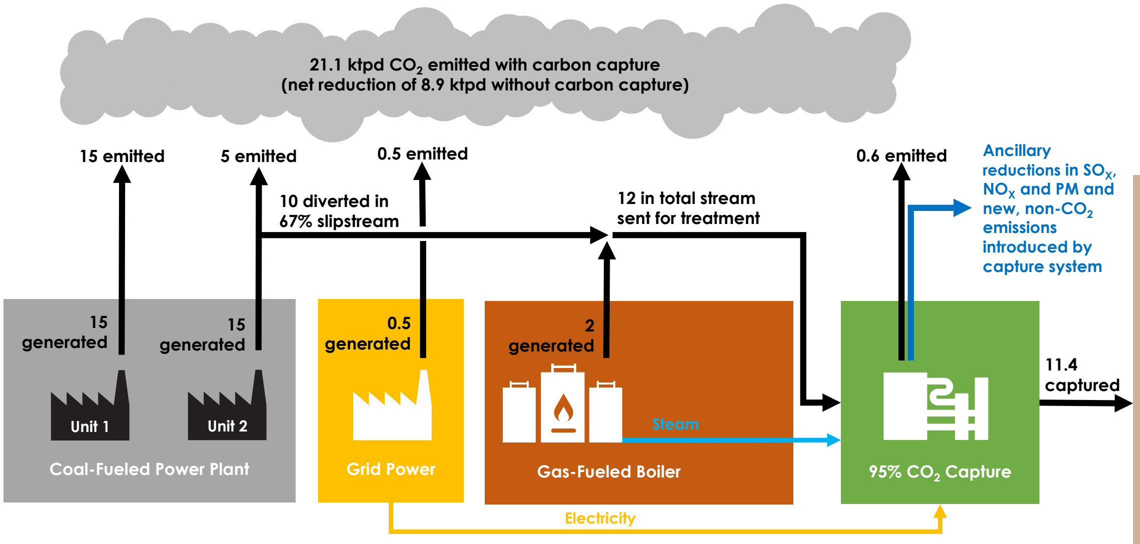

Only a portion of the Unit 2 exhaust gas (arbitrarily shown as 67% in this example) is diverted for treatment by the carbon capture system, with the balance of the facility emissions emitted without carbon capture.

Permitting considerations, host facility attributes, and other factors determine how electricity and steam are best provided to the capture system. In this example, electricity is provided by the grid (with associated CO_2 emissions). Steam is provided by an auxiliary gas-fueled boiler. (Alternatively, steam could be extracted from the coal-fueled power plant, but doing so would reduce its power output.) The gas-fueled boiler exhaust can be vented without carbon capture or be sent to the carbon capture system for treatment (as shown here).

95% of the CO_2 contained in the treated gas stream is separated by the carbon capture system and transported for permanent storage in the subsurface.

Capture system's steady-state gross carbon capture efficiency

11.4/12 = **95%** gross removal of CO_2 in total treated stream

Capture system's steady-state net carbon capture efficiency

(10-0.5-0.6)/10 = **89%** net CO_2 removal from Unit 2 slipstream

Facility-wide steady-state net carbon capture efficiency

(30-21.1)/30 = **30%** net CO_2 removal from host facility's total CO_2 generation

Natural gas boiler CO_2 emissions were extrapolated from Case B11A-BRwNGBlr.95 in the report, "Eliminating the Derate of Carbon Capture Retrofits"
Electricity grid CO_2 emissions were based on 2022 carbon intensity of 376 tonnes/GWh, reported by EIA at U.S. Energy Information Administration - EIA - Independent Statistics and Analysis

Figure 2: Carbon Capture Efficiencies for a Generic Carbon Capture Demonstration
(example CO₂ flows shown in kilotons per day [ktpd])

OTHER FACTORS TO TAKE INTO CONSIDERATION

Depending on the type of gas stream treated and the type of carbon capture technology used, the application of carbon capture can decrease or increase emissions of non-CO₂ pollutants within the plant boundary. In some cases, carbon capture can increase water consumption and/or create new solid or liquid waste streams within the plant boundary.

One example is amine solvents, which are used by many advanced carbon capture technologies. Amine systems typically include a pretreatment scrubber that reduces the concentration of sulfur oxides in the gas stream — often to 10 ppm or less — prior to removal of CO₂. The scrubber may also remove nitrogen oxides and particulate matter that would otherwise be emitted by the host facility. However, amine systems can introduce new types of environmental emissions, such as fugitive liquid and gas amine emissions and emissions of amine degradation products. Various design features may be employed to reduce the magnitude of such emissions.

The addition of carbon capture could also result in environmental impacts outside the plant boundary due to the supply chain of inputs to the capture system. These impacts can be quantified using life cycle analyses.

NETL is a U.S. Department of Energy national laboratory that drives innovation and delivers technological solutions for an environmentally sustainable and prosperous energy future. By leveraging its world-class talent and research facilities, NETL is ensuring affordable, abundant and reliable energy that drives a robust economy and national security, while developing technologies to manage carbon across the full life cycle, enabling environmental sustainability for all Americans.

Contact

John G. Wimer
Research and Innovation Center
John.Wimer@netl.doe.gov