A New U.S. Industrial Backbone

Exploring Regional CCUS Hubs for Small-to-Midsize Industrial Emitters

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HORIZON CLIMATE GROUP

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The EFI Foundation advances technically grounded solutions to climate change through evidence-based analysis, thought leadership, and coalition-building. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, the EFI Foundation conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. The EFI Foundation maintains editorial independence from its public and private supporters and sponsors.

Horizon Climate Group provides analysis, interactive tools, and easy to understand insight on energy, greenhouse gas emissions, and equitable climate solutions. Horizon's key areas of focus include industrial emissions quantification and solutions, energy systems planning, and transportation sector decarbonization. With a combined experience of over 20 years in climate, energy, and decarbonization, the team of analysts at Horizon specialize in life cycle GHG assessment, data analysis, geographic information systems (GIS), web & software development, graphic design, and data visualization.

Cover photo: fotolinchen

Previous Work on Carbon Management and Hubs

This report builds on the EFI Foundation's previous work on large-scale carbon management and net-zero hubs, including the following reports:

EFI Foundation, *Taking Root: A Policy Blueprint for Responsible BECCS Development in the United States,* June 2023, https://efifoundation.org/topics/carbon-management/taking-root-a-policy-blueprint-for-responsible-beccs-development-in-the-united-states/.

Energy Futures Initiative, Energy Futures Finance Forum (EF^3), *Turning CCS Projects in Heavy Industry and Power into Blue Chip Financial Investments,* February 2023, https://efifoundation.org/reports/turning-ccs-projects-in-heavy-industry-into-blue-chip-financial-investments/.

Energy Futures Initiative, *The U.S. Hydrogen Demand Action Plan*, February 2023, https://efifoundation.org/reports/the-u-s-hydrogen-demand-action-plan-2/.

Energy Futures Initiative, *CO2-Secure: A National Program to Deploy Carbon Removal at Gigaton Scale,* December 2022, https://efifoundation.org/reports/co2-secure-a-national-program-to-deploy-carbon-removal-at-gigaton-scale/.

Energy Futures Initiative, *Building the Gulf Coast Clean Hydrogen Market: Summary of Public Workshop and Private Roundtable*, September 2022, https://efifoundation.org/reports/building-the-gulf-coast-clean-hydrogen-market/.

Energy Futures Initiative, *Surveying the BECCS Landscape*, January 2022, https://efifoundation.org/reports/surveying-the-beccs-landscape/.

Labor Energy Partnership, *Workshop Summary: Ohio River Valley Hydrogen and CCS Hub Market Formation*, September 2021, https://efifoundation.org/reports/ohio-river-valley-hydrogen-and-ccs-hub-market-formation/.

Labor Energy Partnership, *Building to Net-Zero: A U.S. Policy Blueprint for Gigaton-Scale CO2 Transport and Storage Infrastructure*, September 2021, https://efifoundation.org/reports/building-to-net-zero/.

Energy Futures Initiative, *Workshop Summary: The Critical Role of CCUS: Pathways to Deployment at Scale*, December 2020, https://efifoundation.org/reports/the-critical-role-of-ccus/.

Energy Futures Initiative, *Rock Solid: Harnessing Mineralization for Large-Scale Carbon Management*, December 2020, https://efifoundation.org/reports/rock-solid/.

Energy Futures Initiative and Stanford University, *An Action Plan for Carbon Capture and Storage in California: Opportunities, Challenges, and Solutions*, October 2020, https://efifoundation.org/reports/an-action-plan-for-carbon-capture-and-storage-in-california/.

Energy Futures Initiative, *Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies*, September 2019, https://efifoundation.org/reports/clearing-the-air/.

Energy Futures Initiative, *Advancing Large Scale Carbon Management: Expansion of the 45Q Tax Credit*, May 2018, https://efifoundation.org/reports/advancing-large-scale-carbon-management/.

This report builds on the Horizon Climate Group authors' previous experience on large-scale carbon management and net-zero hubs, including contributions to the following reports:

Elizabeth Abramson, Dane McFarlane, Amy Jordan et al., *The Landscape of Clean Hydrogen: An Outlook for Industrial Hubs in the United States,* Carbon Solutions and Industrial Innovation Initiative, May 2023, https://industrialinnovation.org/wp-content/uploads/2023/05/The-Landscape-of-Clean-Hydrogen.pdf.

Elizabeth Abramson, Dane McFarlane, Amy Jordan et al., *An Atlas of Direct Air Capture: Opportunities for Negative Emissions in the United States,* Carbon Solutions and Great Plains Institute, March 2023, https://carboncaptureready.betterenergy.org/wp-content/uploads/2023/03/DAC-Hubs-Atlas-2023.pdf.

Dane McFarlane, Elizabeth Abramson, and Emma Thomley, *An Atlas of Carbon and Hydrogen Hubs for United States Decarbonization*, Great Plains Institute, February 2022, https://scripts.betterenergy.org/CarbonCaptureReady/GPI_Carbon_and_Hydrogen_Hubs_Atlas.pdf.

Elizabeth Abramson, Dane McFarlane, and Jeff Brown, *Transport Infrastructure for Carbon Capture and Storage: Whitepaper on Regional Infrastructure for Midcentury Decarbonization*, Great Plains Institute, June 2020, https://betterenergy.org/wp-content/uploads/2020/08/GPI_RegionalCO2Whitepaper.pdf.

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1. Executive Summary

The purpose of this report is to assess the potential of carbon dioxide (CO_2) emissions reduction from small-to-midsize U.S. industrial emitters through the formation of carbon capture, utilization, and storage (CCUS) hubs. The report's core findings are that there are sizable CO_2 emissions from these facilities and that they are clustered in several regions across the United States that could support the development of hubs.

Hubs can be important for realizing the emissions reduction opportunity of CCUS because their shared infrastructure can significantly decrease the economic, technical, and logistical barriers to CCUS deployment for small-to-midsize emitters.

The screening assessment identified 10 regions of the country with a high concentration of small-to-midsize CO_2 emitters and proximity to potentially attractive underground geologic storage capacity. Further in-depth analysis of four of these regions delineated key characteristics of the emissions sources, the initial step in assessing the feasibility of CCUS hub formation.

CO_2 emissions from the industrial sector account for about one-quarter of total U.S. greenhouse gas (GHG) emissions.[1] Decarbonizing industrial emissions is challenging because of differences in the size of individual sources, the variety of industrial processes and uses of energy within each process, and the combination of process emissions (e.g., waste products from steel and cement production) and emissions from fossil fuel combustion.

Industrial Decarbonization Through CCUS

There is a wide range of potential industrial decarbonization options. A recent U.S. Department of Energy (DOE) study identified four "pillars" of industrial decarbonization: energy efficiency; electrification; low-carbon fuels, feedstocks, and energy sources; and CCUS.[a,2]

Choosing specific technology solutions within these four pathways involves weighing multiple business objectives, including product quality, workforce requirements, asset values, market competitiveness, and innovation opportunities.[3] CCUS offers advantages such as addressing difficult-to-decarbonize combustion and process emissions, as well as harnessing existing infrastructure and workforces.[4]

Early CCUS projects have focused on power plants, larger industrial facilities, and those with relatively higher CO_2 concentrations. These projects typically use carbon capture technologies, such as amine scrubbers, which rely on large volumes of CO_2 to be economically and technically feasible. These large emitters also capture enough CO_2 to justify investment in transport and storage infrastructure. Small-to-midsize emitters typically have not been addressed in previous studies of CCUS because they do not meet these thresholds.

[a] DOE also found that other pathways beyond these pillars (e.g., non-energy emissions reduction) may be needed to reach net zero in industry.

Recent policy, technology, and business model developments, however, have changed the equation:

- The Inflation Reduction Act (IRA) raised the value of the Section 45Q tax credit for CO_2 capture and storage and extended the credit to smaller industrial CCUS projects.[5]
- Recent technology advances make smaller-scale applications of carbon capture viable, alongside the possibility of business models that could offer CCUS as a service to industrial emitters.
- Single large-scale CCUS projects under development could serve as anchor tenants for local and regional CCUS hubs that include small-to-midsize industrial units as well. These hubs could create the necessary economies of scale to support CO_2 transport and storage infrastructure, which those emitters would lack as standalone projects.

Key Study Findings

There are more than 3,000 small-to-midsize industrial CO_2 emitters in the United States aligning with key study criteria, constituting around 266 million metric tons of CO_2 emissions per year, or 25% of annual CO_2 from U.S. industrial point sources.[b,6,7,8]

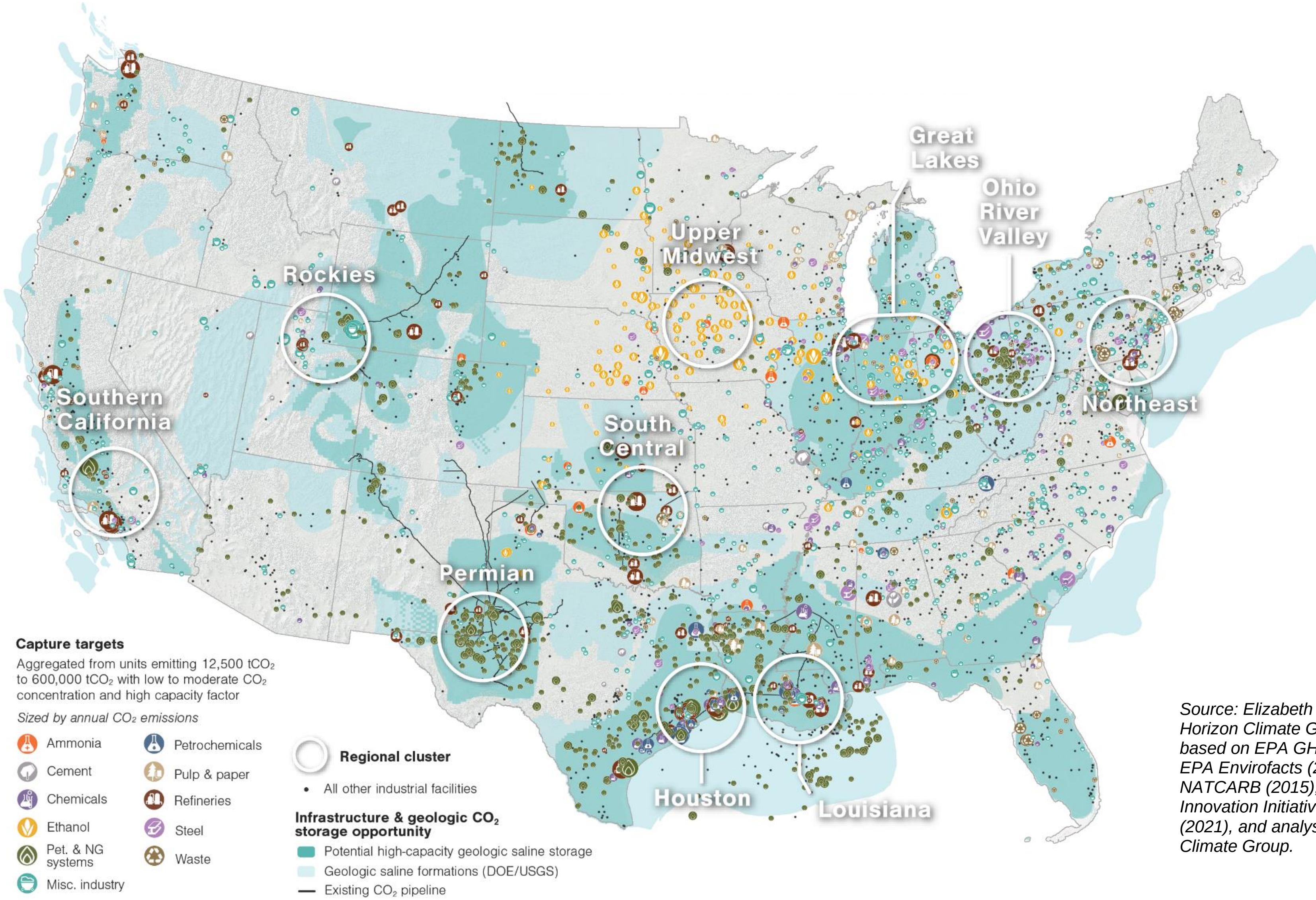
Small-to-midsize emitters of interest to this study, referred to as “capture targets,” are industrial units with annual emissions between 12,500 metric tons of CO_2 (tCO_2) and 600,000 tCO_2. The units were screened with additional criteria (e.g., CO_2 concentration level, capacity factor, unit type) to evaluate technical suitability for carbon capture.

- Nationwide, 41% of all industrial facilities are home to at least one industrial unit identified as a capture target in this study.
- The analysis assessed capture opportunities across 11 general industrial subsectors. Over half of the emissions from capture targets identified in this study come from facilities engaged in petroleum and natural gas production, transport, and processing, petroleum refining, ethanol production, and petrochemical production.
- The use of natural gas is the source of almost three-quarters of the total CO_2 emissions from identified capture targets.

This study identified 10 U.S. regions with a relatively high concentration of capture targets in areas that have (or are near areas with) favorable geological characteristics for underground CO_2 storage (Figure 1).

[b] All emissions data in this report are given in metric tons.

Figure 1
Small-to-midsize industrial capture targets for potential CCUS hubs



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), DOE NATCARB (2015), Industrial Innovation Initiative (2023), EIA (2021), and analysis by Horizon Climate Group.

Four of the 10 regions were selected for further detailed characterization of capture opportunities. These include southeastern Texas, centered on Houston; the Louisiana Gulf Coast; the eastern Ohio River Valley; and the southern Great Lakes region.

- These four regional clusters each have more than 70 small-to-midsize sources with combined annual emissions from capture targets totaling at least 8 million metric tons of CO_2 ($MtCO_2$) in each cluster and are located close to high-quality geologic storage. These conditions are the basic ingredients for formation of CCUS hubs with cost-effective CO_2 transport and storage.
- Capture targets in these four regional clusters emit around 72 $MtCO_2$ per year, approximately equivalent to the annual net emissions of Washington state.,[9]
- Two of the selected regional clusters are two-state regions but largely a single state (Texas and Louisiana); one regional cluster covers a three-state area (Pennsylvania, West Virginia, and Ohio); and the fourth covers a four-state area (Illinois, Indiana, Ohio, and Michigan). While the multistate regions will have more challenges in forming hubs, there are sufficient concentrations of small-to-midsize emitters within individual states to facilitate the initiation of intrastate efforts that could grow into multistate hubs.
- Individual states within these four study regions have varying degrees of state-level policies, regulations, and financial incentives that can enable hub formation. No state currently has a full complement of authorities and programs, but several have sufficient scope to enable the initiation of CCUS hub planning on an intrastate level. For example, states within three of the four study regions are currently seeking primary authority to permit underground injection needed for geologic CO_2 storage.[10]
- All four regions have several larger-scale CCUS projects in the development pipeline (operational, planned, or under development) that could serve as anchor tenants for a much larger CCUS hub buildout.[6,11,12]

Moving from Clusters to Hubs

The screening analysis shows clear patterns of clustering of small-to-midsize industrial emitters in specific regions that could form the basis of CCUS hubs. The hub concept offers several benefits that can facilitate and incentivize widespread CCUS deployment, including:

- **Shared resources.** This can include shared supply chain within a region as well as pooled funding of needed CO_2 transport and storage infrastructure. This can also include sharing of CCUS assets with natural gas-derived “blue” hydrogen hubs and sharing of transport and storage infrastructure with direct air capture (DAC) hubs.

- **Shared risks.** This allows for large-scale CCUS deployment to proceed even if one or more individual carbon capture projects do not.
- **Economies of scale.** Aggregation of captured carbon "supply" would enable economies of scale in the sizing of CO_2 transport systems and in the development of CO_2 storage facilities.
- **Economies of effort.** Regionwide CCUS deployment will enable not only scaling of supply chains and workforces, but also coordination of permitting and licensing, as well as coordinated, place-based public engagement efforts.

Previous EFI Foundation studies have identified five elements that will be needed to convert these concepts into action.[13] These include:

1. **A Governance Plan** to guide the deployment effort, including information sharing among participants and coordinated interaction with policymakers in the region.
2. **A Business Plan** that consolidates project-specific deployments, including scheduling, permitting, financing, management, and contracting
3. **An Infrastructure Development Plan** that provides details on the ownership, financing, permitting, and operation of common CO_2 transport and storage infrastructure.
4. **A Community and Workforce Plan** that provides a proactive strategy for public engagement, workforce recruitment and training, and ongoing public liaison.
5. **An Innovation Plan** that translates lessons learned into data to enable continuous enhancements in the implementation of the CCUS hub.

As noted earlier, these actions could be initiated on an intrastate level for those states with large clusters of small-to-midsize industrial emitters. This could facilitate a quicker and easier start to hub development that could evolve into a larger multistate CCUS hub.

Finally, the experience of other countries in forming CCUS hubs could provide further lessons for CCUS hub formation. These hubs are typically focused not only in areas with large clusters of industrial CO_2 emissions, but specifically in areas with concentrations of oil and gas facilities, providing infrastructure that can serve as a foundation for the buildout of CO_2 transport and storage. In particular, some of the hubs are repurposing existing natural gas pipelines for CO_2 transport or using depleted oil and gas reservoirs for CO_2 storage. The non-U.S. hubs also have the benefit of strong national policies and government cost sharing of the upfront investment required for hub development.

Recommendations

This report's screening analysis identified regional clusters of small-to-midsize industrial emitters that could form the basis of regional CCUS hubs. This screening, however, focused solely on technical factors. Additional analysis would be needed on several aspects to fully understand hub development potential, including:

- Techno-economic analysis to further refine the potential universe of hub participants and to develop initial estimates of the economics of hub development.
- More detailed geospatial analysis to begin to assess the extent of CO_2 transport and storage infrastructure, including possible repurposing of existing infrastructure or use of existing infrastructure rights of way.
- Further evaluation of geologic storage potential and sites within the identified cluster regions.
- Convening of interested parties within each region, including facility owners, policymakers, vendors, and stakeholder groups, to begin discussions of possible hub development.

Additional federal policy and programmatic actions could be considered by Congress and executive-branch agencies to further incentivize, accelerate, and facilitate industrial CCUS hub formation that includes small-to-midsize emitters.

Section 45Q enhancements. The recent changes to the Section 45Q tax credit have created the potential to extend CCUS deployment to small-to-midsize industrial facilities.[5] Previous EFI Foundation work identified several additional recommendations to build upon the new and improved 45Q incentive.[14] These include modifications to further facilitate transferability of the credit and amendments to expand eligibility for optional direct pay.

Targeted direct funding. The Bipartisan Infrastructure Law (BIL) and the IRA funded several new direct spending programs to support development of geologic storage and demonstration projects for carbon capture.[15] DOE could consider actions to integrate and further leverage these funding initiatives to enhance the prospects for industrial CCUS hub formation:

- Expanded use of DOE loan guarantee authorities to allow financing of multiple CCUS deployment projects for specific industrial applications.[14]
- Funding one or more demonstration "packages" of the same CCUS technology at multiple sites to accelerate learning and facilitate establishment of supply chains.
- Implementation of Phase IV of DOE's CarbonSAFE grant program for CO_2 storage and expansion of support for planning activities leading to hub formation, including pre-feasibility studies of small-to-midsize carbon capture projects within prospective hubs.
- Improved coordination among DOE funding programs for different carbon management value chain segments (capture, transport, and storage).
- Encouraging developers of blue hydrogen hubs and DAC hubs to accommodate opportunities for broader industrial CCUS hub development.

State and local governments could be encouraged to share in the funding support for these initiatives if they are designed and implemented in a way that provides a clearer potential path to the formation of a regional industrial CCUS hub that includes small-to-midsize emitters.

Class VI permitting. The federal government could seek to prioritize and expedite approval of state “primacy” over permitting for Class VI geologic CO_2 storage wells within the lead states of prospective industrial CCUS hub regions. The U.S. Environmental Protection Agency (EPA) also should accelerate the process of reviewing and approving Class VI wells under federal jurisdiction.

While the authority for delegation and permitting resides with the EPA, DOE could play a coordination and ombudsman role in working with those states interested in supporting industrial CCUS hub development that incorporates small-to-midsize emitters. The regional CCUS Permitting Task Forces authorized in the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act could play a role in facilitating permitting for regional CCUS hub formation.[16,17]

2. Industrial Decarbonization and the Role of CCUS

Greenhouse Gas Emissions from Industry

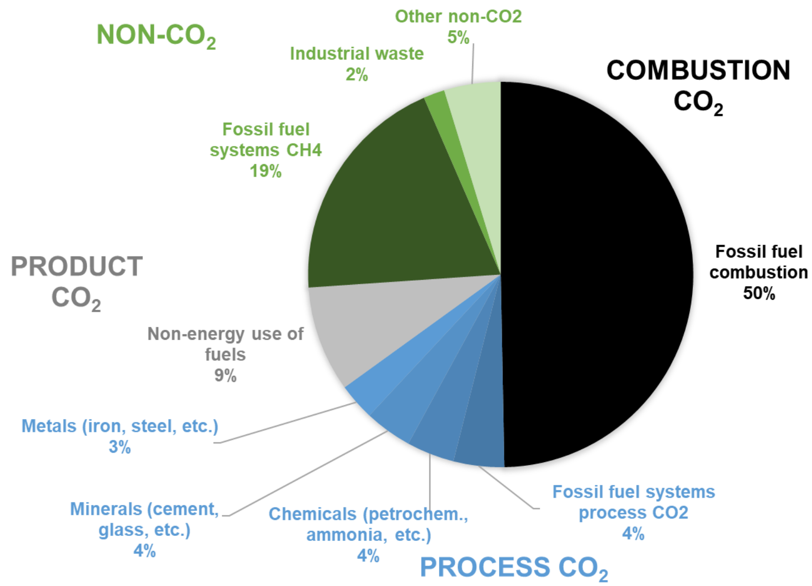
In 2021, U.S. GHG emissions from industrial sources reached 1,487 million metric tons of CO_2-equivalent ($MtCO_2e$), 23% of the country's total.[c,1] This percentage has remained relatively stable since 2000, while the total has decreased 10%.[1] In contrast, emissions from power generation decreased by 33% during the same period.[1]

Industrial emissions include more than 30 GHG-producing processes in fuel production, metals, minerals, chemicals, and manufacturing.[1] Emissions from industrial point sources include combustion of fossil fuels for process heat, mechanical energy, etc., and CO_2 "process emissions" from chemical reactions, such as those involved in cement and steel manufacturing.

CO_2 from fossil fuel combustion accounts for 50% of annual U.S. industrial emissions (739 $MtCO_2$), with natural gas being the primary fuel, followed by petroleum and coal (Figure 2).[1] CO_2 process emissions make up 16% (232 $MtCO_2$); CO_2 from non-energy use of fuels (e.g., lubricants), 9%; and non-CO_2 emissions, 26% (mostly methane from fossil fuel systems, mines, and wells).[18] The figures above exclude biogenic CO_2 emissions, such as from fermentation and biofuel combustion, which total more than 33 Mt.[19]

Figure 2

Industrial GHG emissions



Half of GHG emissions in the industrial sector are from fossil fuel combustion, while product and process emissions account for around 25% of CO_2 emissions. Non-CO_2 gases, such as methane, account for the remaining emissions in the sector. Source: See first figure mention in text for sources.

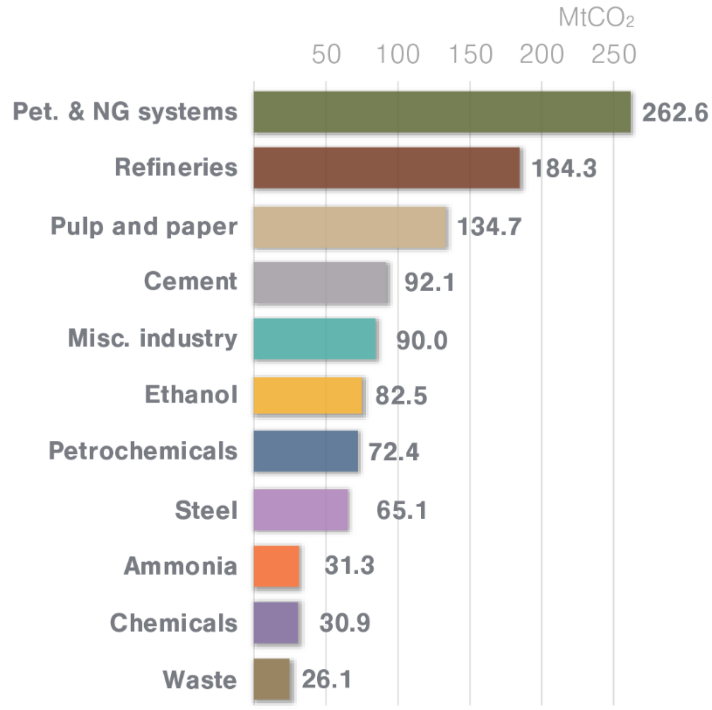
[c] Quantities of non-CO_2 GHGs are reported as CO_2-equivalent emissions, i.e., the quantity of CO_2 emissions that has the equivalent "global warming potential" (GWP) as the emitted amount of another GHG. Emissions data reported in tCO_2e may include both CO_2 and other GHGs, such as methane. EPA uses GWPs from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. "Total emissions" here represents gross emissions, excluding land use, land-use change, and forestry (LULUCF).

Petroleum and natural gas processing systems, refineries, pulp and paper processing facilities, and cement plants are the leading sources of CO_2 emissions within the industrial sector.[6,8] Together, these subsectors account for roughly 63% of annual industrial point source CO_2 emissions and 25% of total annual point source CO_2 emissions (see Box 1 for additional detail on emissions figures).[6,7,8] This report uses a simplified industry categorization system of 11 subsector categories to classify industrial facilities (Figure 3).

Industrial facilities vary widely in their size and equipment configuration, even within a single industrial subsector or within a single facility. This study focused on small-to-midsize industrial emitting units that are becoming increasingly attractive capture opportunities as capture technologies evolve. Across the U.S., small-to-midsize industrial process units, defined in this study as those emitting between 12.5 kilotons (kt; equal to 1,000 tons) of CO_2 and 600 ktCO_2 per year and dedicated to uses other than electricity generation, are present at nearly 70% of industrial facilities. These units account for roughly 700 MtCO_2 per year, or roughly 60% of emissions from all industrial point sources. Further screening of these units, detailed in Chapter 3 (see Page 22), resulted in a more refined subset of small-to-midsize units of particular interest for capture retrofit in this study.

Figure 3

Annual U.S. emissions from on-site process emissions, electricity generation, and fuel combustion, by industrial subsector



Industrial emissions reported in this figure come from 11 industrial subsector categories used to classify industrial facilities. Source: Elizabeth Abramson, Horizon Climate Group (2023) based on EPA GHGRP (2022), EIA (2021), and EPA Envirofacts (2023).

Box 1

EPA emissions data sources

This report uses three EPA databases of GHG emissions: the Inventory of U.S. Greenhouse Gases and Sinks (the Inventory), the Greenhouse Gas Reporting Program (GHGRP), and the Envirofacts database. The GHGRP collects annual emissions data from more than 8,000 facilities. The Envirofacts database collects data at the unit level on the facilities that report to the GHGRP and on some additional facilities. The Inventory combines data from several sources (including the GHGRP) to estimate the total annual emissions across the U.S. economy and for each state. Differences include:

- GHGRP and Envirofacts data report specific GHG emissions. The Inventory reports emissions totals in an aggregated CO_2-equivalent, including CO_2 along with non-CO_2 GHGs. The Inventory also includes more diffuse sources of emissions (e.g., oil wells, hydrofluorocarbon consumption).
- The GHGRP reports facility-by-facility data for biogenic CO_2 emissions, allowing them to be counted in industrial totals. The Inventory reports biogenic CO_2 through the land use, land-use change, and forestry (LULUCF) sector. Information on ethanol production capacity from the U.S. Energy Information Administration was used to calculate additional fermentation emissions from ethanol plants not reported to EPA.[8]
- The Inventory includes municipal landfills and wastewater treatment in a separate waste sector, whereas these facilities may be included in the industrial emissions numbers derived from the GHGRP. Some point sources might likewise be categorized as commercial buildings in the Inventory but are included in this report's industrial GHGRP data.

All data used in this report is from 2021 (the most recent year available for the Inventory at the time analysis was conducted) unless otherwise specified.

Industrial Decarbonization Pathways

The industrial sector is considered by many to be "hard to abate." While this view is often based on a concern that there is a lack of technological solutions (e.g., clean alternatives for high-temperature process heat), the challenges of industrial decarbonization involve a much broader range of considerations.

On a technological level, there are many approaches to address GHGs from the industrial sector.[14] DOE's *Industrial Decarbonization Roadmap* outlines four broad strategies: energy efficiency, electrification, low-carbon energy and feedstocks, and CCUS.[2] DOE's Roadmap also mentions non-energy strategies that can contribute to emissions reduction.[2] Figure 4 illustrates a number of technological approaches within these strategies.[2]

Energy efficiency includes energy management changes, infrastructure improvements, and efficiency technologies (e.g., combined heat and power, automation). Replacing thermal and thermochemical conversion processes with low-temperature or nonthermal alternatives (e.g., bioconversion) can also lower energy requirements.

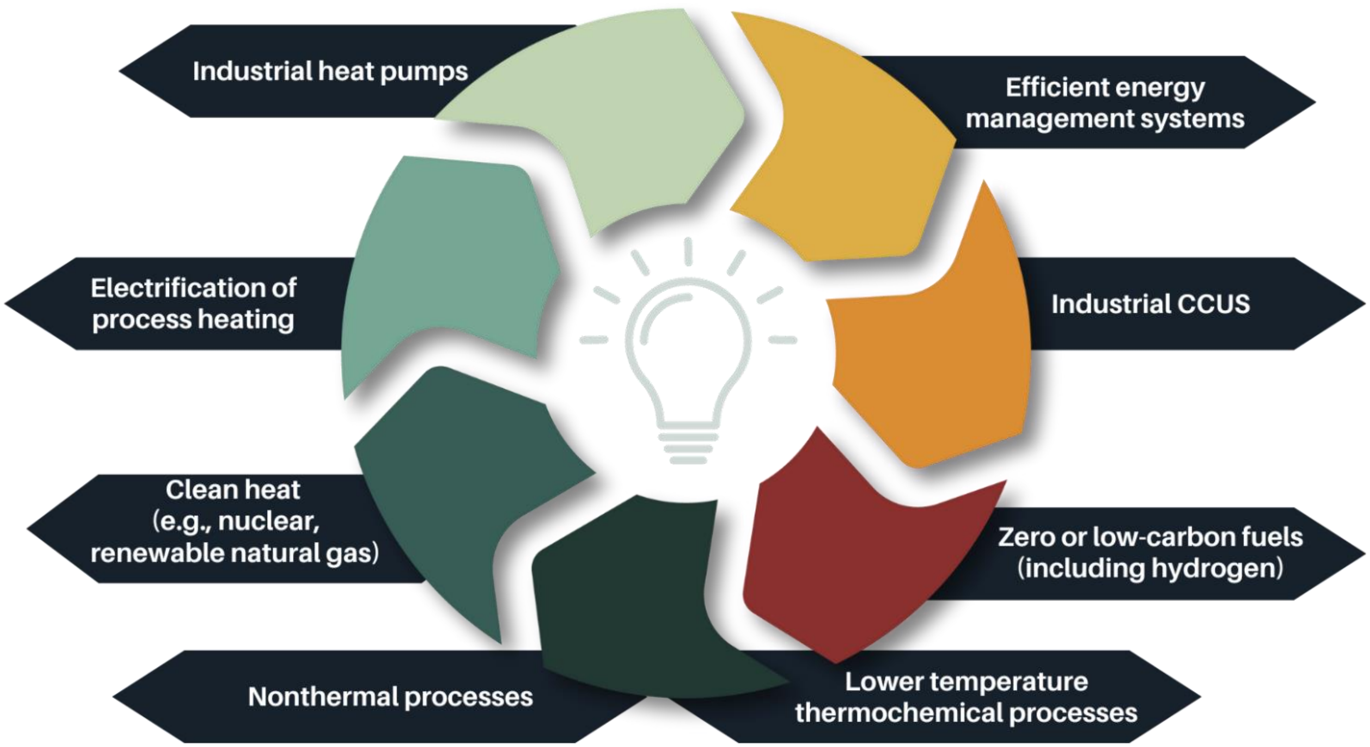
Electrification includes replacing combustion-based industrial process heating with electrified heating (e.g., induction, heat pumps, electric boilers, electric arc furnaces). Cost-competitive electrified heating, however, is not available for processes requiring higher temperatures.[2] Electrification can also replace fossil fuels in mechanical processes.[2]

Lower-carbon energy and feedstocks. Fuel switching from coal or petroleum to natural gas achieves incremental CO_2 reductions.[20] Larger reductions include the use of low-carbon fuels (e.g., hydrogen, biofuels). Non-energy feedstocks can similarly be replaced with low-carbon alternatives (e.g., cement produced from fly ash). Low-carbon sources of thermal energy, such as directly using nuclear or geothermal heat, also can replace fossil fuels.[2]

Non-energy strategies. Circular economy and material efficiency strategies could lower industrial emissions by decreasing the need for new products.[2] Industrial emitters also can decrease non-CO_2 emissions, such as by capturing methane from fossil fuel infrastructure and landfills or replacing hydrofluorocarbons with less-polluting alternatives.

Figure 4

Technology opportunities for industrial decarbonization



Several pathways within energy efficiency, electrification, low-carbon energy and feedstocks, and CCUS can contribute to industrial decarbonization. Source: EFI Foundation.

Innovation Opportunities

Choosing a particular industrial decarbonization pathway is a complex process that must consider several variables. Technical and economic feasibility of CO_2 reductions is an overarching factor. Some industry subsectors currently have few commercially viable pathways to decarbonization (e.g., high-temperature heat, cement kilning). Some existing alternatives (e.g., electrified steel manufacturing) have yet to achieve cost parity with higher-emissions counterparts.

Capital investment decision-making for industrial decarbonization involves balancing multiple business objectives, as illustrated in Figure 5. Decisions are made by private companies across several subsectors that are competing in global markets and constrained

Figure 5

Balancing industrial decarbonization strategies with other business objectives

To decarbonize the industrial sector, stakeholders must find a balance with other business objectives. Source: EFI Foundation.

by fiduciary duties to shareholders. Industrial equipment is capital-intensive, with life spans measured in multiple decades and slow turnover, raising the challenge of stranded assets.[d]

Technological Challenges

Technological innovation, including the potential for disruptive change, also can play a crucial role. New technologies for high-temperature process heating, advanced recycling, and use of hydrogen and biofuels could significantly change the calculus of industrial investment decision-making.

The Role of CCUS as a Strategy for Industrial Decarbonization

CCUS is a primary option to reduce industrial CO_2 emissions from both energy and process sources. CCUS solutions consist of a complex combination of:

- **Carbon capture** technologies, which use physical (e.g., membranes), chemical (e.g., solvents), and/or thermal processes (e.g., calcining) to separate CO_2 from other waste products at industrial facilities or power plants (see Figure 6).[14] These technologies can be retrofitted to existing facilities or integrated into the design of newly built facilities. The most widespread form of carbon capture is post-combustion capture using amine-based chemical solvents or physical solvents (e.g., methanol) to capture and separate CO_2 from a facility's flue gas (i.e., exhaust).[e,14,21]
- **Geologic carbon storage,** which involves injecting CO_2 underground or under the seabed in suitable geologic formations, including depleted oil and gas wells, deep saline reservoirs, unmineable coal seams, and reactive minerals such as basalt. These geologies can store CO_2 for centuries to millennia by trapping it physically (under impermeable caprock) or chemically (through the process of carbon mineralization).[22] Suitable geology is abundant in the United States, though only in some regions. Non-geologic storage options exist but are not discussed in this report.
- **Carbon utilization,** which disposes of captured CO_2 by putting it to an economically useful purpose. This can include using gaseous CO_2 (e.g., enhanced oil recovery, or EOR), converting it into durable products (e.g., concrete), or replacing more emissions-intensive fuels and products (e.g., "recycling" CO_2 into synthetic fuels). Utilization can make carbon capture more cost-effective, but it can also result in lower life cycle emissions savings.

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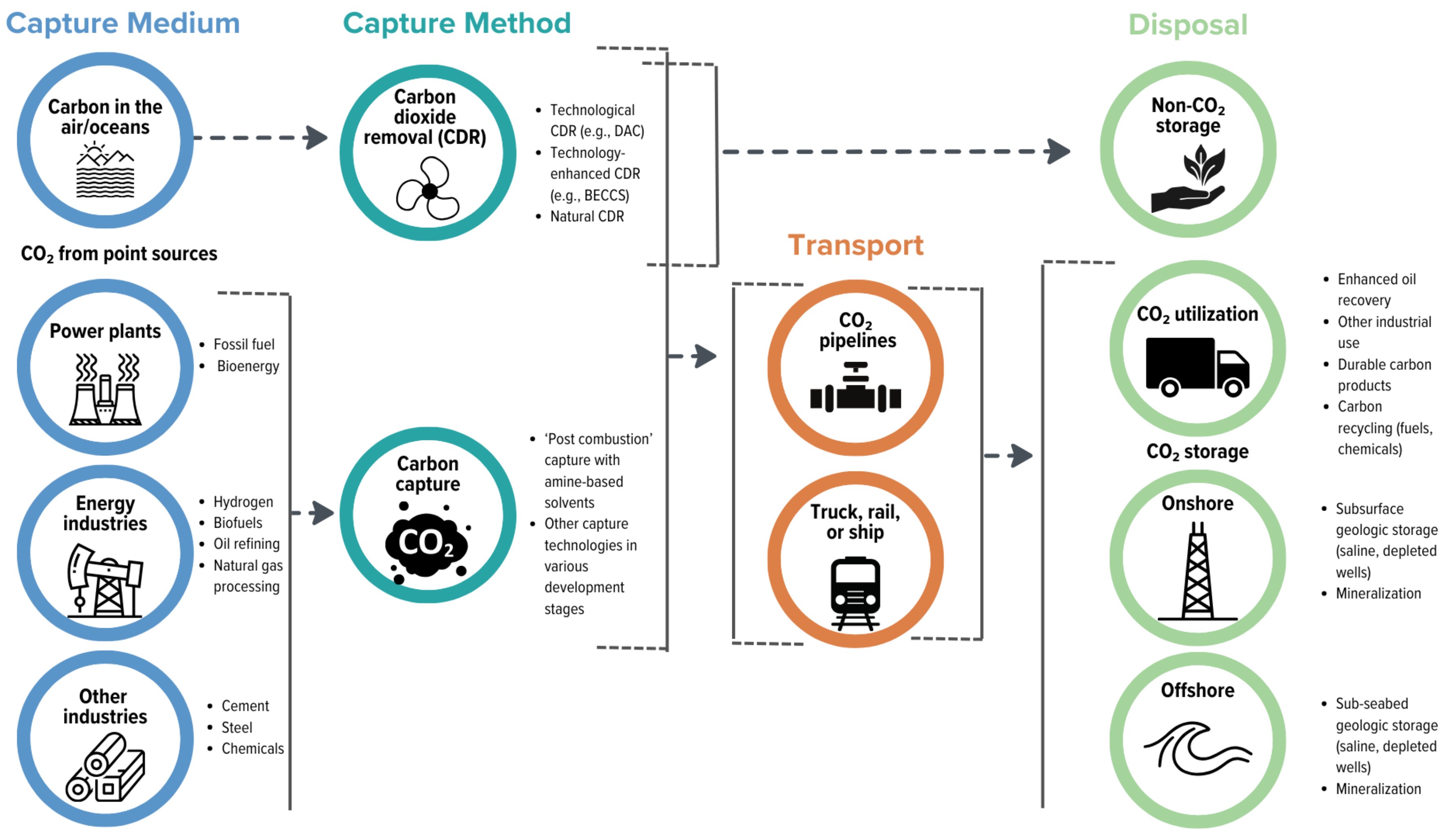
[d] Stranded assets are facilities, infrastructure, etc., that become obsolete before the end of their expected spans due to the low-carbon transition.

[e] Amines are a class of nitrogen-based chemical compounds, which are used in carbon capture because they react selectively with CO_2. These amines are dissolved in water to create solvents. Methanol, known commonly as wood alcohol, is a chemical that, when cooled to very low temperatures, can dissolve CO_2. Solvents containing CO_2 can be heated to release the CO_2 for transport.

Figure 6

Carbon management pathways



Carbon management includes a range of pathways. Adapted from: See first figure mention in text for sources.

- **Carbon transport,** which is sometimes needed to move CO_2 from capture points to utilization or storage sites. The most common mode is specialized pipelines. The United States already has about 5,000 miles of CO_2 pipelines, mostly used by the oil industry.[23] CO_2 can also be moved by truck, rail, or ship.

CCUS is closely related to carbon dioxide removal (CDR), which refers to processes that capture carbon directly from the atmosphere or oceans, rather than reducing emissions from a point source. Some CDR pathways use CCUS (e.g., bioenergy with carbon capture and storage, or BECCS) or similar processes (e.g., direct air capture), and the two sets of technologies can share infrastructure and participate in the same hubs.

CCUS technologies have been used in natural gas processing since 1929 and have been explored as a GHG mitigation option since the 1970s.[24] The basic technologies—amine capture, CO_2 pipelines, saline storage—are all widely commercialized at scale. They are not yet widely implemented, however, outside of a narrow set of applications (e.g., natural gas processing, ethanol production). Outside of those applications, CCUS remains costly, especially for first-of-a-kind (FOAK) projects, and relatively unproven. Other CCUS technologies (e.g., oxy-combustion capture, carbon mineralization) are at even earlier stages of development.

Advantages of CCUS

Principal factors that make CCUS an attractive solution for decarbonization include:

- Substantial scalability for emissions reduction, especially for industrial subsectors with limited decarbonization options (e.g., cement). It also paves the way for carbon removal and net-negative emissions.
- The ability to retrofit infrastructure to avoid stranded assets while preserving existing workforces and economically important facilities, creating new industries and jobs, and reducing air pollutants.[4,14]
- The ability to produce low-carbon energy or feedstocks for other sectors, such as firm power, synthetic fuels, zero-carbon biofuels, and clean hydrogen.

> **Principal factors that make CCUS an attractive solution for decarbonization include: substantial scalability[,] ability to retrofit infrastructure and avoid stranded assets [and] ability to produce low-carbon energy or feedstocks for other sectors.**

CCUS Risks and Challenges

CCUS has its own set of challenges related to the same themes of economics, technology, infrastructure, and policy affecting all pathways for industrial decarbonization. The EFI Foundation's 2023 report *Turning CCS Projects in Heavy Industry & Power into*

Blue Chip Financial Investments identifies five risks to deployment of these systems[14]:

Cost and revenue. CCUS has an inherent economic obstacle because it is essentially a pollution control system. Like other pollution control systems, it will not be economically incentivized except by durable policy, such as regulations that require it or put a price on emissions.[25]

Moreover, the incentive that does exist in the United States, the Section 45Q tax credit, may currently be insufficient. The cost of CCUS projects—other than for applications with highly concentrated CO_2—is higher than current revenue potential, including the subsidy provided by the newly increased tax credit, especially for FOAK projects.

Policy and regulation. Tax credits are difficult to monetize. Permitting authority is split between federal and state governments and inconsistent from state to state. Federal permitting processes are slow, and delays can scuttle projects. Federal policy does not address long-term liability.

Commercialization. CCUS technologies are not yet widely deployed in many industrial subsectors. This limited track record raises the cost of first-mover projects and makes finding investment more difficult. CCUS projects are also heterogeneous, differing from project to project and industry to industry, and require more capital expenditure and permitting than other pollution control devices (e.g., catalytic converters).[25]

Infrastructure. Capture projects depend on the existence of transport and storage (T&S) infrastructure and vice versa, creating a chicken-and-egg problem. Infrastructure buildout is also costly and subject to delays.

Stakeholder acceptance. CCUS projects often face resistance from frontline communities who harbor concerns about safety, cost, and environmental impact. Some groups believe CCUS is a “false solution” that will perpetuate GHG pollution and the use of fossil fuels, especially in disadvantaged areas.

CCUS projects are also heterogeneous, differing from project to project and industry to industry, and require more capital expenditure and permitting than other pollution control devices (e.g., catalytic converters).

> **[CCUS deployment] risks are magnified for some smaller emitters, which confront thinner margins, more risk from large upfront investments, and difficulty securing financing.**

These five risks are magnified for some smaller emitters, which confront thinner margins, more risk from large upfront investments, and difficulty securing financing. Many low-carbon technologies (e.g., CCUS) become more cost-competitive with economies of scale, which may not be possible for smaller emitters to achieve.

Recent legislation—including the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA)—has created new opportunities for industrial climate solutions, especially for CCUS and other large-scale carbon management technologies. Scaling up

CCUS, however, requires large amounts of new infrastructure—not just to capture the CO_2 from new or retrofitted facilities, but also to transport and store or utilize captured CO_2. One option for the scale-up of this new infrastructure is the creation of CCUS hubs.

Narrowing the Focus to Small-to-Midsize Emitters

Previous studies of CCUS hubs have often focused on emissions sources that are perceived as low-hanging fruit for carbon capture deployment: the largest units with the highest concentrations of CO_2 in their flue gas (power generation facilities and a subset of industrial emitters—e.g., ethanol, natural gas processing, cement).

Small-to-midsize units have traditionally presented two problems for CCUS development. First, standard amine scrubbing of flue gases was uneconomical unless done at a large scale (about 1 $MtCO_2$ per year or more). Second, tiny volumes would make permitting and building pipelines and storage prohibitively expensive. Consequently, larger emitters have been the primary or sole focus of previous studies of CCUS potential. Technological innovation, policy change, and the promise of hubs now offer potential solutions to these barriers.

Innovation makes carbon capture feasible for new types of units. Improved carbon capture processes, including modular designs, new solvents (e.g., amine-promoted buffer salts), and process intensification (e.g., rotating packed beds), make capturing carbon from smaller, lower-CO_2-concentration units more technologically and financially viable.[26,27] Further innovation, such as wholly new capture processes (e.g., pre-combustion capture), could open more possibilities.

New policies make CCUS at smaller industrial facilities more viable. Most consequentially, the IRA extended and modified the Section 45Q carbon oxide sequestration tax credit. The IRA increased the tax credit amount and lowered the minimum capture threshold for industrial facilities, reducing it from 100 $ktCO_2$ per year to 12.5 $ktCO_2$ per year.

> **Technological innovation, policy change, and the promise of hubs now offer potential solutions to CCUS development in small-to-midsize industrial units.**

Hubs can unlock economies of scale for small-to-midsize emitters. As explored further in Chapter 4 (see discussion of hub benefits on Page 66), one of the advantages of CCUS hubs is that multiple capture projects can benefit from sharing CO_2 T&S infrastructure. This is critical for small-to-midsize emitters, which, unlike larger counterparts, might not otherwise be able to shoulder the burdens (economic, permitting, etc.) of this infrastructure.

There are additional reasons why a focus on small-to-midsize industrial emitters is important from the perspective of achieving a deeply decarbonized economy:

These units make up a large quantity of emissions and a large proportion of total industrial emissions. This report focuses on small-to-midsize industrial units, representing 266 $MtCO_2$ nationwide per year, or about 25% of all industrial point-source emissions annually. CCUS designs may be easier to replicate for smaller units; using modular designs and focusing on units of similar type will enable rapid scale-up.

CCUS implementation for small-to-midsize units differs from implementation for larger emitters. Smaller and larger units differ at the engineering level, as do units with higher and lower CO_2 concentrations and emitters in different industries.[14] Consequently, emissions from smaller units at a larger facility—which could also be physically spread out—may not easily be combined into a single source for the purposes of CCUS.

Industrial emitters have different concerns than power plants. Industrial stakeholders have different prerogatives—balancing decarbonization with considerations such as product quality, supply chain risk, and competitiveness and trade—that will shape how they approach CCUS hub development. Carbon capture may also be a more favorable approach for industrial facilities, which tend to have higher utilization rates than fossil-fueled power plants (80% vs. 50%).[28,29]

3. Screening Analysis of Small-to-Midsize Industrial CCUS Clusters in the United States

Previous studies and proposals for carbon capture hubs have focused on early opportunities to retrofit capture equipment at industrial and power facilities with a high volume and/or high concentration of CO_2 emissions.

The initial minimum project thresholds for the Section 45Q tax credit required capture of 100 $ktCO_2$ per year for industrial projects and 500 $ktCO_2$ per year for electric power plants, in part because these larger volumes would likely see higher rates of capital utilization by maximizing CO_2 abatement.

These dynamics have traditionally meant that large units emitting high-CO_2-purity flue gas streams were the most economically feasible opportunities for capture retrofit. However, focusing capture retrofit on only large units leaves a large portion of the United States' industrial emissions unabated.

Emissions from small-to-midsize industrial process units account for 70% of total emissions from all industrial process units.[7] This report defines small-to-midsize process units as those emitting between 12.5 $ktCO_2$ and 600 $ktCO_2$ per year and not dedicated to electricity generation; 67% of all industrial facilities have at least one small-to-midsize process unit in this emissions range.

Recent progress in carbon capture technology, such as with rotating packed beds (which use centrifugal forces to increase capture efficiency) and modular designs, has opened new sections of industrial operations for carbon abatement in small-to-midsize units with low-to-moderate flue gas concentrations of CO_2.

These new capture technologies—along with enhancements to the 45Q tax credit—have enabled technically and financially feasible investments of carbon capture retrofits of small-to-midsize industrial equipment at facilities of all types and sizes. The 45Q tax credit enhancements drastically lowered annual capture thresholds to 18.75 $ktCO_2$ for electricity-generating facilities and 12.5 $ktCO_2$ for other industrial facilities.

This report identifies opportunities for capture at such facilities in regional clusters around the United States.

> **Recent progress in process intensification of carbon capture technology and enhancements to the 45Q tax credit open new opportunities for technically and financially feasible investments of carbon capture retrofits of small-to-midsize industrial equipment at facilities of all types and sizes.**

Analysis Parameters

The goal of this analysis is to assess the national landscape of opportunity for industrial carbon capture retrofit. It focuses on identifying promising capture candidates among small-to-midsize industrial units with low-to-moderate flue gas concentrations of CO_2 and high rates of utilization.

Data on all U.S. industrial facilities was gathered and screened to find units aligning with these criteria. The geographic distribution of these potential capture targets was then analyzed alongside other contextual factors to identify concentrated areas of opportunity for early movers in the development of CCUS hubs.

This section details the data sources and screening parameters used to identify capture opportunities and regional clusters. Limitations of this phase of analysis are also discussed.

Data Sources and Identification of Target Facilities

The EPA Envirofacts database was the primary source of data for this study. This database provides information on CO_2 emissions, fuel use, equipment type, and, in some cases, operating hours for industrial facilities across the United States.[7]

Most data in the Envirofacts database is reported at the individual industrial unit level, representing a single piece of industrial equipment at a given facility. In some cases, however, data is reported at the subpart level, which represents multiple aggregated units associated with a specific industrial process. Subpart-level reporting obscures detail on unit composition and emissions quantities from specific units, preventing the ability to identify unit-level opportunities for all facility types.

While the Envirofacts database reports the vast majority of combustion and process emissions from industry, it does not report biogenic fermentation process emissions from corn ethanol production. Data on ethanol production capacity were collected from the U.S. Energy Information Administration's U.S. Fuel Ethanol Plant Production Capacity dataset and were then used to estimate fermentation CO_2 emissions using a conversion factor published in previous studies.[8,30]

Analysis was conducted at the individual industrial unit level.

Equipment capacity factor, a measure of how often an industrial unit runs over a specified period of time, is a metric commonly used to assess candidates for carbon capture retrofit. Units with high capacity factors are typically better candidates for capture, as they maximize CO_2 capture quantity over a given period of time. Capacity factors were calculated by dividing a unit's annual operating hours by the total hours in a year.

In cases where a unit's operating hours were not provided in the Envirofacts database, this study gathered operating hours from the EPA's Greenhouse Gas Reporting Program (GHGRP) and from estimates based on the GHGRP and the National Renewable Energy Laboratory's (NREL) Industrial Energy Data Book, where available.[31,32,33] This study focused on units with capacity factors of at least 60%.

The expected CO_2 concentration of each unit's or subpart's emissions stream, also known as its molar fraction of CO_2, was determined by matching unit type and fuel use combinations to aggregated values from leading scientific literature.[34,35,36,37,38,39] In cases where peer-reviewed literature on CO_2 concentration could not be found for a particular unit type and fuel use pairing, CO_2 concentration information for a similar unit and fuel pairing was applied instead.

While units with high-purity flue gas streams nearing 100% CO_2 concentration are most efficient for some conventional capture technologies, this study focused on isolating units with CO_2 concentrations between 3% and 20%. This threshold was used to identify capture opportunities among the emitters that have not previously been the focus of widespread analysis but that are now increasingly attractive candidates for capture retrofit given recent advances in capture technology.

Each unit and industrial process subpart was assessed for technical carbon capture feasibility based on review of peer-reviewed literature.[40,41] Units without capturable emissions, such as thermal oxidizers and flares, were not targets of interest for this study and were excluded. Further, units dedicated to electricity generation inside industrial facilities were excluded from this analysis, along with any units at facilities identified as power plants.

Some industrial subsectors, such as aluminum manufacturing and chemical production, often have electrical generators on-site, co-located, or very close to the facility. However, electrical generators for industry, even those within the same fence line, may report emissions under a different identification number or be classified under a different subpart. Although these generators may be suitable candidates for capture retrofit, they are excluded from this study because of the difficulty of identifying all such facilities, and to keep the focus squarely on industrial processes.

Unit- and subpart-level data from the Envirofacts database was aggregated to the facility level and paired with the EPA GHGRP 2021 dataset. Each facility was categorized within 11 industry sectors to produce facility-level summaries of capture opportunity.[6,7] The industry categories are ammonia production, cement production, chemicals production, ethanol production, petroleum and natural gas systems, miscellaneous industry, petrochemicals production, pulp and paper production, refining, iron and steel production, and waste.

The petroleum and natural gas systems category is primarily composed of facilities that report under the EPA Greenhouse Gas Reporting Program's “Subpart W: Petroleum and Natural Gas Systems” industry classification. This includes facilities involved in the production, extraction, processing, transmission and compression, liquefication, storage, and distribution of petroleum and natural gas.

The miscellaneous industry category includes facilities that do not fall within another major industry category. It includes activities such as glass manufacturing, assorted metals and minerals processing, and food processing.

While a single facility may report multiple industrial processes, each facility was assigned a category based on the process for which the largest share of its emissions was reported, along with consideration of other reported information, such as the facility's North American Industry Classification System (NAICS) code.

The EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks is used as a supplemental data source in this study.[1] The Inventory, which provides national- and state-level summaries of GHG emissions by broad industrial and economic sectors, includes some facilities and emissions sources that do not report to the GHGRP and includes a wider range of gases not limited to CO_2. As such, the Inventory typically reports a higher total for industrial emissions than the sum of facilities reported to the GHGRP.

Screening Criteria

The following steps were taken to isolate capture targets of interest for this study.

First, industrial units and subparts were gathered, excluding units dedicated to electricity generation at industrial facilities and facilities identified as power plants. Second, units emitting below 12.5 ktCO_2 or above 600 ktCO_2 per year were removed. Third, unit types where capture is likely technically infeasible were removed. Next, units with a CO_2 concentration below 3% and above 20% were removed, targeting low-concentration emissions streams that have not been a traditional focus of prior study but that are well suited to emerging capture technologies. Finally, units with a capacity factor below 60% or an unknown capacity factor were removed.

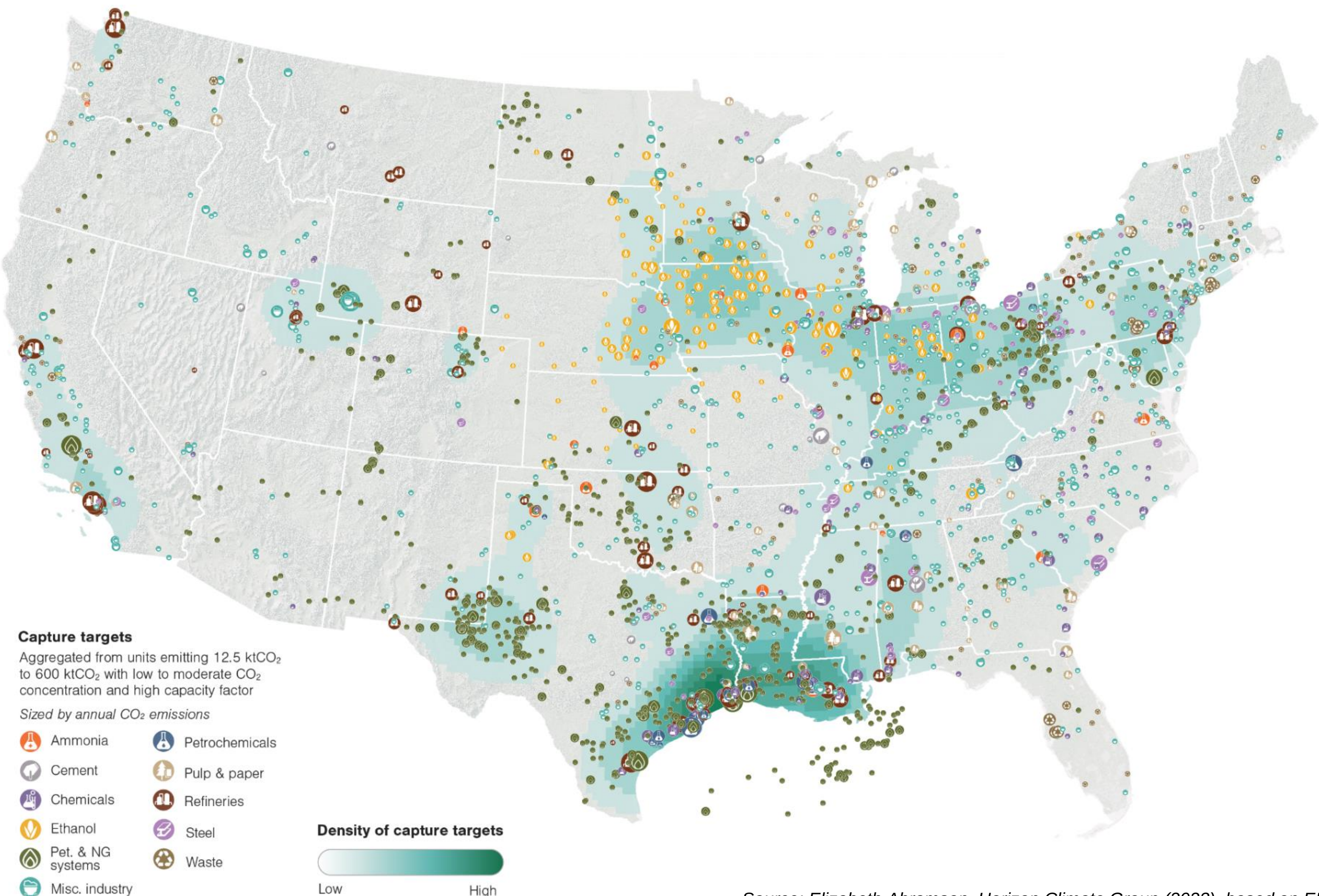
This screening resulted in a subset of small-to-midsize industrial units, referred to as "capture targets," with capturable emissions, that run frequently, and that have emissions and CO_2 concentrations well suited to the emerging technologies tailored to this type of industrial unit. Table 1 lists the screening criteria for capture targets, and Figure 7 shows the geographic density of capture targets across the United States, weighted by their emissions. Darker teal indicates areas where capture targets are geographically clustered and where there is a high concentration of emissions from those capture targets. These areas of high concentration informed the identification of regional CCUS clusters.

Table 1
Screening criteria for capture targets

Factor	Scale	Criteria
Emissions quantity	Unit	Units emitting **12.5 ktCO_2 to 600 ktCO_2** per year
Industry	Unit & facility	Industrial processes only, not electricity generation
Molar fraction of CO_2 in flue gas	Unit	Units with **3% to 20% CO_2 concentration**
Capacity factor	Unit	Minimum of **60% capacity factor**
Unit type	Unit	Unit types where capture is technically feasible

Figure 7

Geographic density of capture targets, weighted by emissions



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Beyond the core set of small-to-midsize units identified as capture targets through the screening process, this analysis also sought to examine the broader landscape of opportunity for industrial carbon capture retrofit. This entailed aggregating and mapping all other industrial units with technically feasible capture potential that fell outside the screening parameters of this study. These units are referred to as “other capture opportunities” in contrast to the “capture targets” that are the focus of this study. Many of these other opportunities have already been examined in previous studies of CCUS potential and are likely to take advantage of a different set of capture technologies.

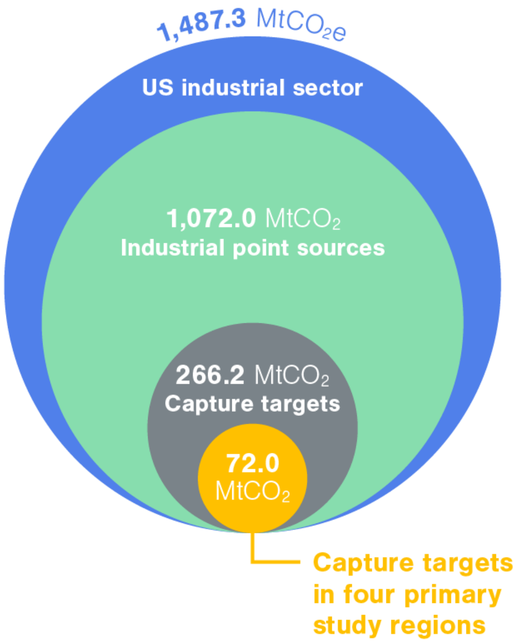
> **Capture target:**
>
> A unit emitting 12.5 ktCO_2 to 600 ktCO_2 per year with low-to-moderate CO_2 concentration and high capacity factor.
>
> **Other capture opportunity:**
>
> A unit where capture is technically feasible but the criteria for designation as a capture target were not met.

Overview of Screening Results

Nationwide, units identified as capture targets account for 266.2 MtCO_2 per year (Figure 8), with the largest shares coming from petroleum and natural gas systems (70.9 MtCO_2), refineries (49.2 MtCO_2), miscellaneous industry and manufacturing facilities (48.0 MtCO_2), ethanol production plants (21.3 MtCO_2), and petrochemical production facilities (19.2 MtCO_2).

Figure 8

Capture targets in context: Annual emissions within the industrial sector



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHG Inventory (2021), EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

The vast majority of units identified as capture targets are combustion sources falling under the general reporting category of “other combustion source” (OCS), which accounts for 76% of targets. Turbines and heaters account for 7% and 6% of units identified as capture targets, respectively, followed by boilers, which account for 3%.

Most units identified as capture targets are powered by natural gas (82%), followed by fuel gas (9%). Landfill gas (3%), coal (2%), biomass (1%), and municipal solid waste (1%) are the next most common fuel sources.

Limitations

This analysis is limited by incomplete data in publicly available datasets. While data was input manually where possible from supplemental sources, some gaps remain. Lack of complete data is most pronounced for capacity factor, where units often do not report their operating hours and where aggregation to the subpart reporting level prevents determination of a unit-specific capacity factor. Units also may lack fuel and unit type information or be obscured by unit aggregation, such as aggregation to “common pipe,” “group pipe,” and OCS classifications.

OCS is a catchall category that includes some unit types that are not well defined by other unit types, some units aggregated into groups, and some “normal” units that emitters may choose to report this way, obfuscating their data. The aggregation of individual combustion units into common and group pipes prevents identification of specific capture opportunities within those aggregations.

Many of the units bundled within common or group pipes could fall within the study's criteria for small-to-midsize emitters if assessed individually. However, the manual analysis required to identify information on individual units aggregated under OCS, common pipe, and group pipe classifications was beyond the scope of this study. Further, while some unit-level information can be gleaned from naming conventions, fuel types, and insider knowledge, operating details for some OCS units and common or group pipe reporters are often unobtainable.

Selection of Regions

This study set out to identify areas of highly concentrated potential for industrial CCUS across the country, focusing on small-to-midsize industrial emitters that could support a localized CCUS ecosystem anchored by larger industrial or power plant emitters.

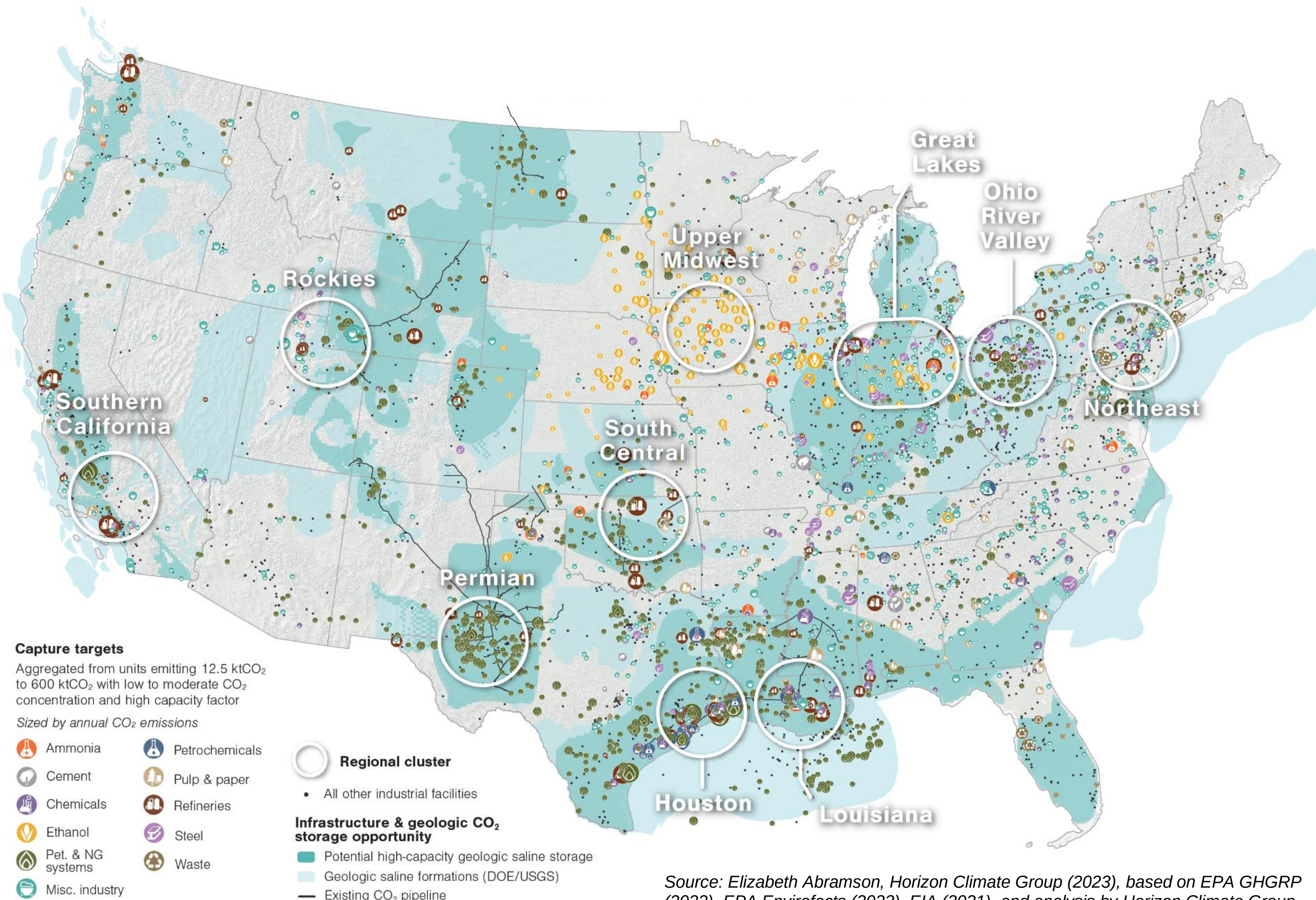
The geographic density of potential capture targets was examined alongside other factors that inform local readiness for CCUS hub development, including the presence of nearby high-capacity and low-cost geologic storage, favorable economic and political conditions, and the presence of existing CCUS-related activity and supportive infrastructure.

This study identified several locations across the country with promising characteristics for potential CCUS hub development, each with varied advantages and limitations (Figure 9).

This study provides a detailed profile of CCUS opportunities in four regional clusters that were identified as likely early movers: the Louisiana Gulf Coast, the Houston area, the Ohio River Valley centering on western Pennsylvania, and the Great Lakes region extending from Illinois to Ohio.

Figure 9

Small-to-midsize industrial capture targets for potential CCUS hubs



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

> **Four regional clusters [were] identified as likely early movers: the Louisiana Gulf Coast, the Houston area, the Ohio River Valley centering on western Pennsylvania, and the Great Lakes region extending from Illinois to Ohio.**

Within the four clusters selected for closer examination, the study identified 734 industrial units across 450 facilities as prime small-to-midsize capture targets, emitting a collective 72 $MtCO_2$ per year. The study identified 3,957 additional industrial units and subpart reporters in these four clusters that have technical potential for capture retrofit, but that fell outside of the screening parameters for capture targets in this study. These additional capture opportunities emit a collective 210 $MtCO_2$ per year.

A 100-mile radius was used to delineate the boundaries of potential hub regions for the purposes of this analysis, except in the Great Lakes regional cluster, where the boundaries were extended to include a broader area of potentially interconnected CCUS activity between Illinois and Ohio.

The 100-mile radius was selected as a reasonable distance for facilities to collaborate on local transport networks and to assess the density of opportunity within a defined geographic area. A single 100-mile cluster identified in this analysis could likely support one or more concentrated CCUS hubs.

Of course, real-world hub development will not be limited to a neat circle or to a strict distance radius. As such, the regional clusters identified in this report should be interpreted as general areas of concentrated CCUS opportunity for hub creation, while acknowledging that many suitable facilities falling outside of the regional cluster outlines could also be logical hub participants.

The four regional clusters selected for assessment each have advantages and limitations. However, all share the following characteristics, to varying degrees: dense geographic clustering of potential CO_2 capture sources, proximity to geologic CO_2 storage opportunities, a precedent of first-mover projects, and supportive state policy environments.

Clustering of Potential Capture Sources

The Louisiana and Houston regional clusters include some of the nation's most densely concentrated industrial areas (Figure 10). Industrial activity in these clusters is primarily composed of refining, petroleum and natural gas systems, and chemical and petrochemical production. Capture targets were identified at 74 facilities in the Louisiana cluster and at 124 facilities in the Houston cluster.

Geographic clustering can enable cost-saving coordination among facilities, particularly smaller emitters that may benefit most from the development of a localized CCUS hub. Further, with a large industrial workforce with transferable skills, this region has extensive opportunity to leverage local experience in developing a strong CCUS ecosystem.

The Great Lakes and Ohio River Valley clusters also are home to a robust industrial sector. Steel, ethanol, and refining account for the largest share of industrial emissions in the Great Lakes cluster. Steel, cement, and petroleum and natural gas systems make up the largest share of industrial emissions in the Ohio River Valley cluster (Figure 11).

In the Great Lakes cluster, capture targets were identified at 140 facilities, while capture targets were identified at 112 facilities in the Ohio River Valley cluster.

Favorable CO_2 Storage

The Louisiana and Houston regional clusters both have extensive local saline storage potential. Saline formations identified as having high CO_2 storage capacity and low injection costs extend throughout both regional clusters and the surrounding region.

The widespread availability of favorable geologic storage in this area can minimize logistical hurdles and costs associated with long-distance transport for facilities within the region. Further, the Houston and Louisiana regional clusters can become CO_2 storage destinations for long-distance CO_2 transport from facilities without local storage opportunities.

The primary high-capacity saline formations identified as destinations for CO_2 in the Houston and Louisiana clusters include:

- Miocene Sands
- Eocene Sands
- Oligocene Sands
- Washita-Fredericksburg Group
- Paluxy Formation

High-capacity saline formations are also present within the Great Lakes regional cluster, where the formations extend south into Illinois and Indiana and north into Michigan. A pocket of suitable storage in south-central Ohio could act as an additional local storage destination for the Great Lakes regional cluster and as a primary storage destination for facilities in the Ohio River Valley regional cluster.

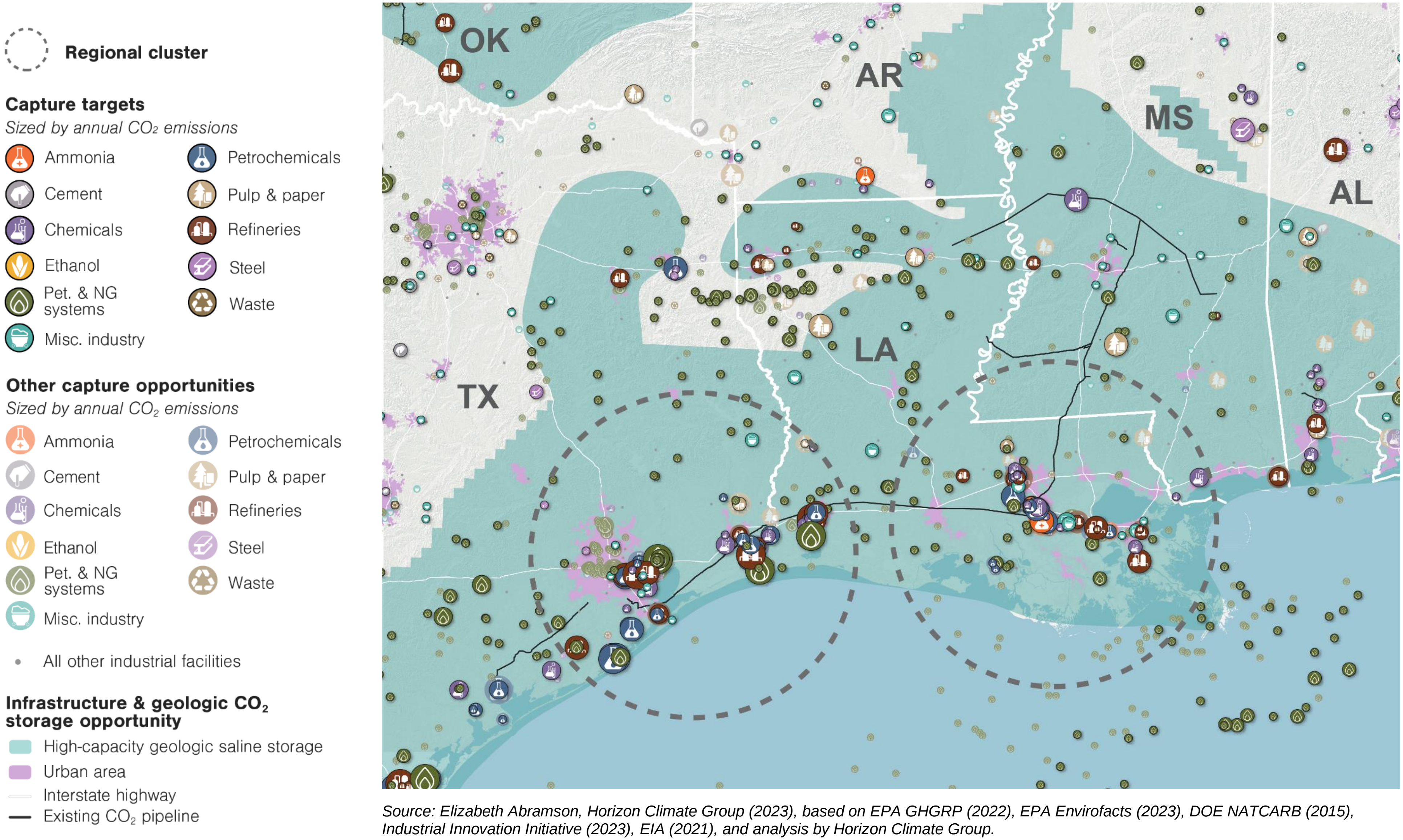
The primary high-capacity saline formations identified as destinations for CO_2 in the Great Lakes and Ohio River Valley clusters include:

- Mt. Simon Sandstone
- Knox Group
- St. Peter Sandstone

This study used geologic storage formation data published by the National Carbon Sequestration Database (NATCARB) at a 10-square-kilometer grid cell resolution, in conjunction with references drawn from existing published maps, to establish generalized regions of opportunity for high-capacity CO_2 injection and permanent storage.[42,43,44,45,46]

Figure 10

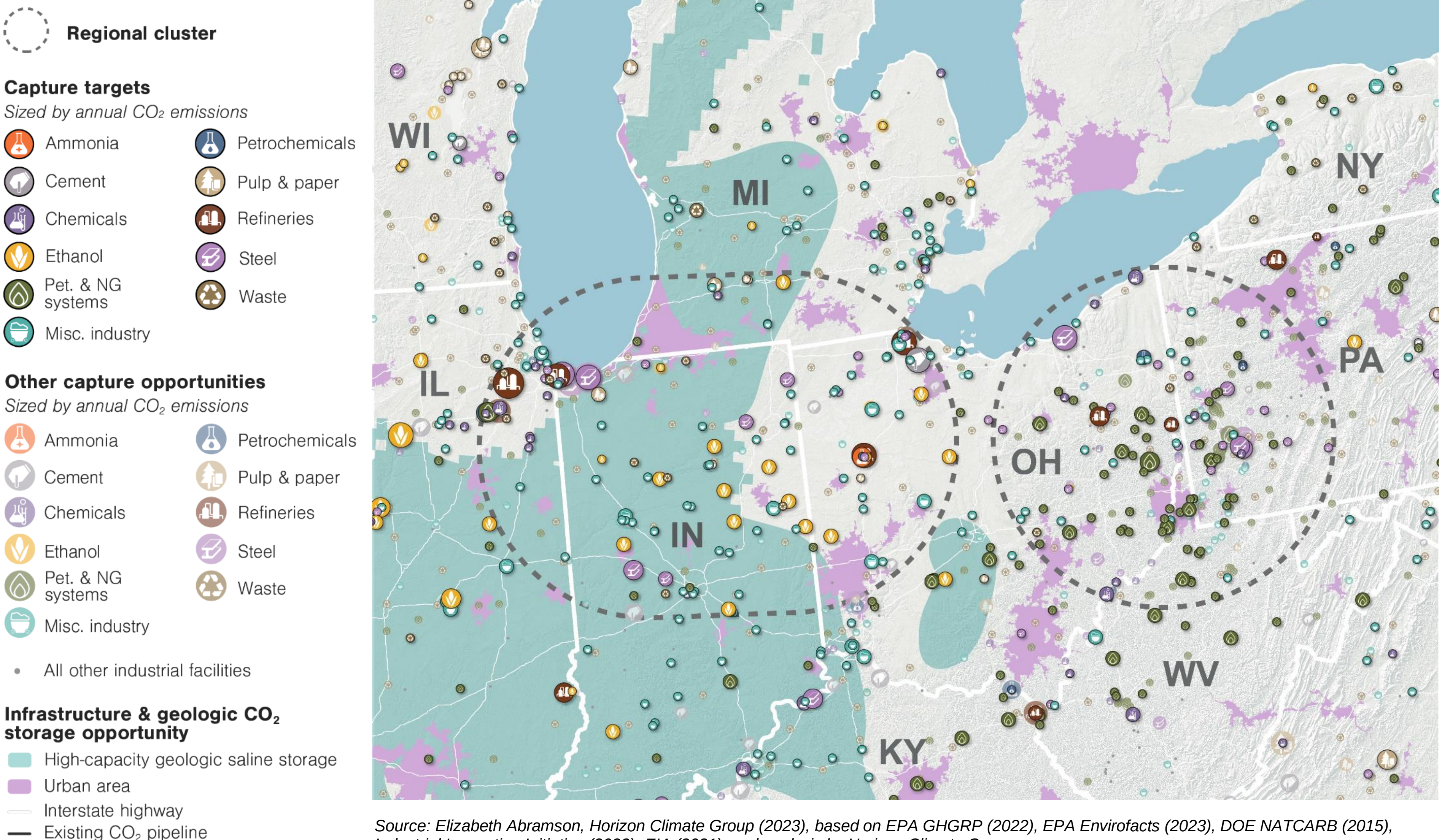
Small-to-midsize industrial capture targets and high-capacity storage in the Gulf Coast (Houston and Louisiana) regions



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), DOE NATCARB (2015), Industrial Innovation Initiative (2023), EIA (2021), and analysis by Horizon Climate Group.

Figure 11

Small-to-midsize industrial capture targets and high-capacity storage in the Midwest (Great Lakes and Ohio River Valley) regions



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), DOE NATCARB (2015), Industrial Innovation Initiative (2023), EIA (2021), and analysis by Horizon Climate Group.

Presence of First Movers

The four regional clusters studied in this report are all home to existing or announced CCUS projects in various stages of development that could serve as initial anchors for a CCUS hub (Figures 12 and 13). The following summaries represent the minimum number of identified projects in each location; other projects may also exist in these areas.[11]

Based on the reported capture sources and capacities of the projects for which such information is available, it appears that many of these projects are likely to target large emitters and use conventional amine solvent systems. However, if successfully executed, these projects will likely spur development of CO_2 pipelines and geologic sequestration sites that could be used by the small-to-midsize capture targets that are the focus of this study, thus simplifying and accelerating their project deployment.

The Louisiana cluster is home to 18 commercial CCUS projects that are currently planned or in development and at least two operational commercial projects. These projects include capture from a variety of sources, including iron and steel production, oil refining, chemical production, and petroleum and natural gas systems. Two-thirds of those projects are planning to permanently sequester their captured carbon in geologic formations.

The cluster's two operational commercial CCUS projects capture CO_2 from ammonia production operations. This cluster is also home to two CCUS pilot projects: one focused on capture from chemical production and the other on capture from hydrogen production. A Phase III Carbon Storage Assurance Facility Enterprise (CarbonSAFE) project focused on transport and storage for the industrial corridor between Baton Rouge and New Orleans has also been selected by DOE for funding (see Page 73 in Chapter 4 for a discussion of the CarbonSAFE program).

The Houston cluster includes two operational and 23 planned commercial CCUS projects. These projects include capture from gas processing, hydrogen production, and biomass processing, among other operations, as well as from direct air capture. Fourteen of the cluster's planned projects will permanently store their CO_2 in geologic formations. The Houston cluster also has an operational pilot project targeting capture from gas processing for use in industrial products and several planned pilot projects targeting capture from gas power, oil refining, and other operations.

A Phase III CarbonSAFE project developing a geologic storage hub within the Houston cluster has also been selected for funding. Existing CO_2 pipeline infrastructure across the Houston and Louisiana clusters establishes a precedent of CCUS activity in the region.

The Great Lakes cluster includes two planned commercial projects: one capturing CO_2 from ethanol production and the other capturing CO_2 from iron and steel production. This cluster also includes one operational and six planned CCUS pilot projects, capturing CO_2 from gas power generation, biopower generation, iron and steel production, and waste incineration, for uses including concrete production, chemical production, and mineralization. This cluster includes a Phase III CarbonSAFE project focused on developing a carbon storage hub in Northwest Indiana.

The Ohio River Valley cluster has one commercial CCUS project under development targeting CO_2 capture from coal power generation and one pilot CCUS project targeting CO_2 capture from iron and steel production. A Phase III CarbonSAFE project aimed at characterizing local geology for potential carbon storage has been selected for funding

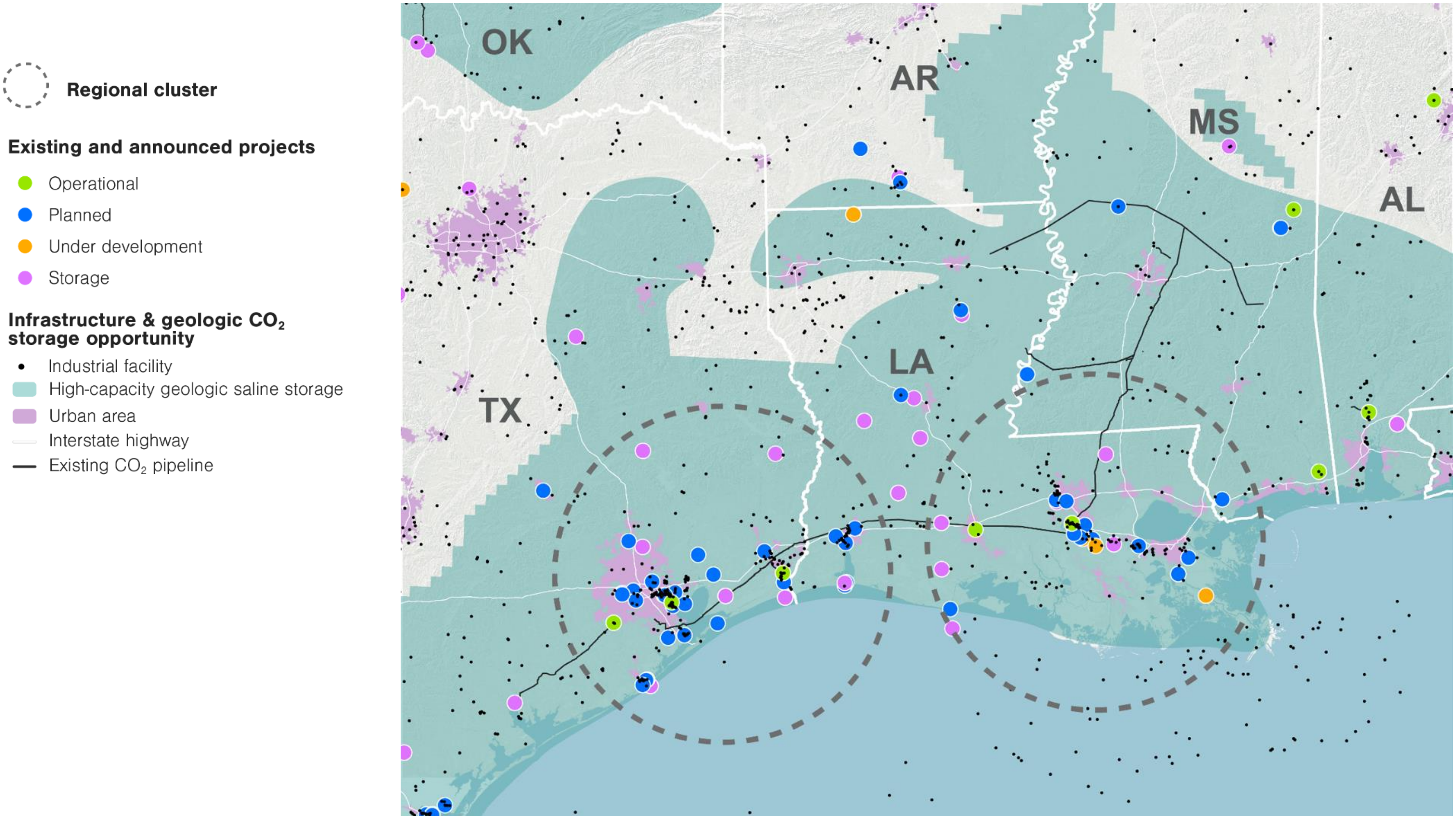
As of November 2023, Louisiana had 55 Class VI wells currently undergoing permitting (in 22 separate applications), the most of any state. Illinois had 22 wells under review (in addition to its two permitted wells); Texas, 19; Mississippi, eight; Indiana, four; and Ohio, one. Collectively, these states represent 64% of the active and pending Class VI wells under EPA jurisdiction and 59% of the nationwide total. Michigan, Pennsylvania, and West Virginia have no current applications.[10]

The Gulf Coast, Great Lakes, and Ohio River Valley have also been selected by DOE as Regional Clean Hydrogen Hubs.

With synergies between some forms of hydrogen production and CCUS, the establishment of these hydrogen hubs can complement the development of regional CCUS ecosystems.

Figure 12

Existing and announced CCUS projects in the Gulf Coast (Houston and Louisiana) regions



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), Rystad Energy (2023), DOE NATCARB (2015), Industrial Innovation Initiative (2023), and analysis by Horizon Climate Group.

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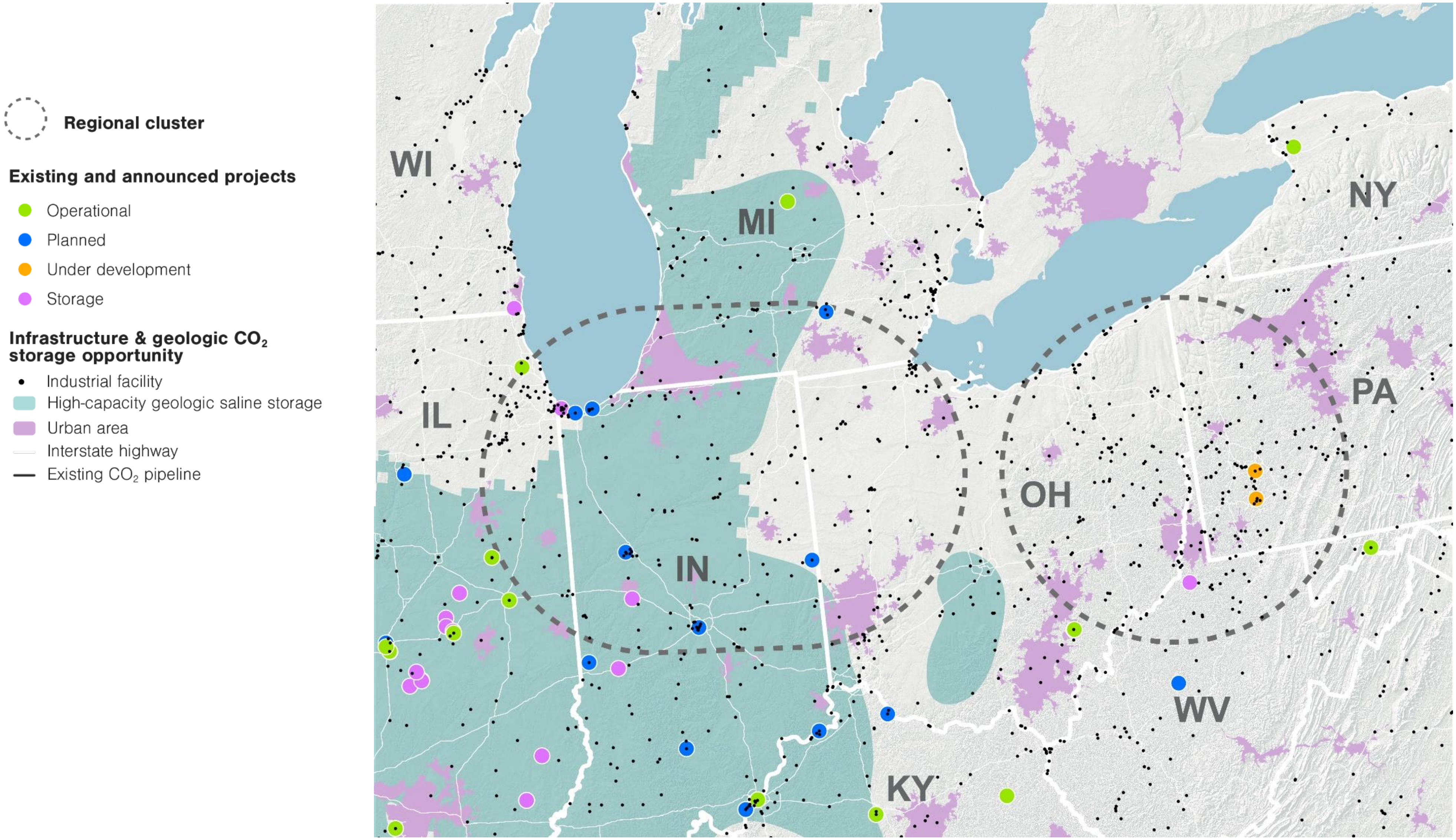
Figure 13

Existing and announced CCUS projects in the Midwest (Great Lakes and Ohio River Valley) regions



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), Rystad Energy (2023), DOE NATCARB (2015), Industrial Innovation Initiative (2023), and analysis by Horizon Climate Group.

Analysis and Takeaways by Region

The following section provides an analysis of CCUS hub opportunities in the Louisiana, Houston, Great Lakes, and Ohio River Valley regions.

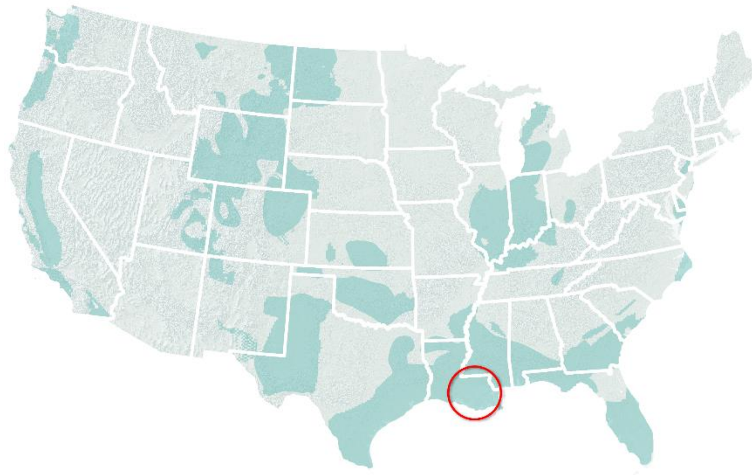
Louisiana Regional Cluster

With dense clustering of industrial activity, co-location with favorable geologic saline formations for CO_2 storage, existing CO_2 infrastructure, and supportive state policy, Louisiana has several important advantages for CCUS hub formation (Table 2).

Table 2
Louisiana regional cluster
At a glance

Primary states involved	Louisiana
Statewide industrial emissions	135.9 $MtCO_2e$ per year
Capture targets identified	107 units 74 facilities 12.0 $MtCO_2$ per year
Top capture target industries	Petrochemicals Refineries Chemicals
Geologic saline storage	Present throughout cluster
Existing CO_2 pipelines	Present

Source: EPA GHG Inventory (2021), EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.



Louisiana's industrial sector emits 135.9 $MtCO_2e$ per year, accounting for over 60% of the state's annual emissions (Table 3).[1]

Table 3
State of Louisiana
Emissions overview

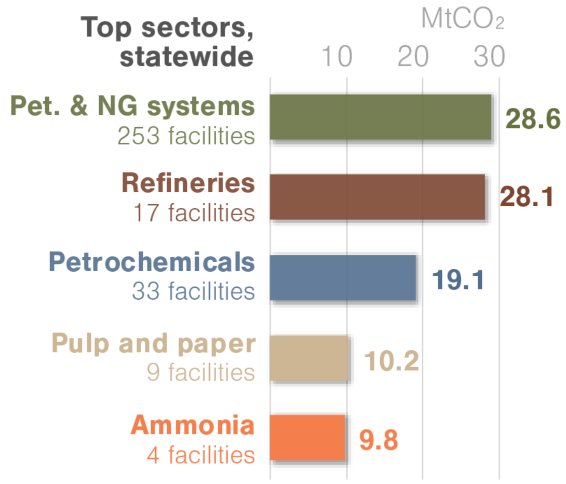
Sector	**Annual emissions** $MtCO_2e$
Industry	135.9
Transportation	39.1
Electric power	30.8
Agriculture	9.1
Commercial	6.6
Residential	3.0
Total	**224.6**

Source: EPA GHG Inventory (2021)

Within the state of Louisiana's industrial sector, the top five industries, by annual emissions, are petroleum and natural gas systems; refining; petrochemicals production; pulp and paper processing and production; and ammonia production.[f,6,7,8] Together, these sectors emitted 95.7 $MtCO_2$ in 2021, accounting for 70% of the state's industrial emissions of 135.9 $MtCO_2e$ (Figure 14).[1,6,7,8]

Figure 14

State of Louisiana: Top 5 industries by annual emissions



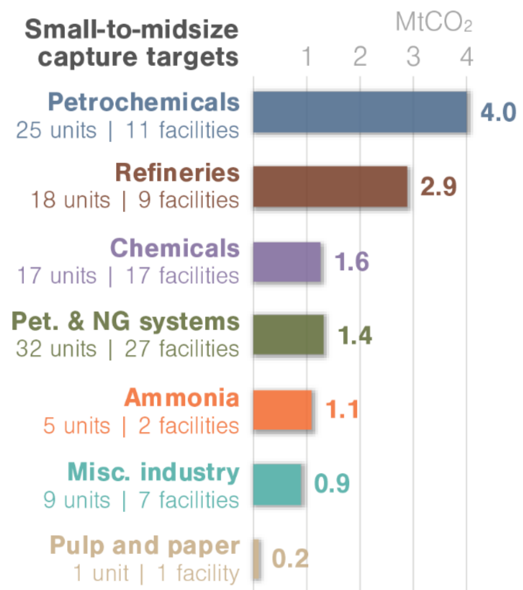
Note: Power generation was excluded from rankings. Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EIA (2021) and EPA GHGRP (2022).

Within the Louisiana cluster, this analysis identified 107 industrial units across 74 facilities as prime small-to-midsize capture targets (Figure 15). Together, these target units emit 12.0 $MtCO_2$ per year.

The petrochemicals sector accounts for the largest share of capture targets in this cluster, emitting 4 $MtCO_2$. Refineries, chemical production plants, petroleum and natural gas systems, and ammonia production plants also constitute a large share of the capture potential from target units in this cluster.

Figure 15

Louisiana regional cluster: Target units by sector and annual emissions



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

[f] See Page 21 for details on the petroleum and natural gas systems category.

Table 4 summarizes the typical characteristics of industrial units identified as capture targets in the Louisiana cluster. A typical unit identified as a capture target in the cluster emits 62 ktCO_2 per year, runs over 85% of the time, and has a molar fraction of 5% CO_2 in its flue gas stream.[g]

Table 4
Louisiana regional cluster
Target units by industrial sector: Profile of capture targets

Sector	# of Units	Annual emissions MtCO_2	Median annual emissions per unit ktCO_2	Median capacity factor	Median CO_2 concentration
Petrochemicals	25	4.0	103	82%	5%
Refineries	18	2.9	99	≥ 85%	12%
Chemicals	17	1.6	64	≥ 85%	5%
Pet. & NG systems	32	1.4	34	≥ 85%	5%
Ammonia	5	1.1	146	73%	5%
Misc. industry	9	0.9	122	74%	5%
Pulp and paper	1	0.2	156	≥ 85%	5%
Total	**107**	**12**	**62**	**≥ 85%**	**5%**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), Jordan & McFarlane (2023), and analysis by Horizon Climate Group.

Capture targets in the Louisiana regional cluster are densely concentrated along the corridor between Baton Rouge and New Orleans, with a variety of industries including chemical and petrochemicals plants, refineries, and ammonia production sites interspersed along this corridor (Figure 16).

Numerous petroleum and natural gas (NG) system facilities are located throughout the cluster both on- and offshore. An existing CO_2 pipeline running through the Louisiana cluster establishes a precedent for local CO_2 transport and storage. The Louisiana cluster's coastal ports can also enable the cluster to become an anchor for domestic and international CCUS markets.

[g] Capacity factors greater than 85% are desirable to maximize CCS equipment utilization and associated economic benefits. Due to uncertainty in some estimated capacity factors at the high range of the underlying datasets, capacity factor values at or above 85% are grouped and reported as "≥ 85%" in tables.

Figure 16

Small-to-midsize industrial capture targets and high-capacity storage in the Louisiana regional cluster

Regional cluster
100-mile radius

Capture targets
Sized by annual CO_2 emissions

- Ammonia
- Chemicals
- Pet. & NG systems
- Misc. industry
- Petrochemicals
- Pulp & paper
- Refineries

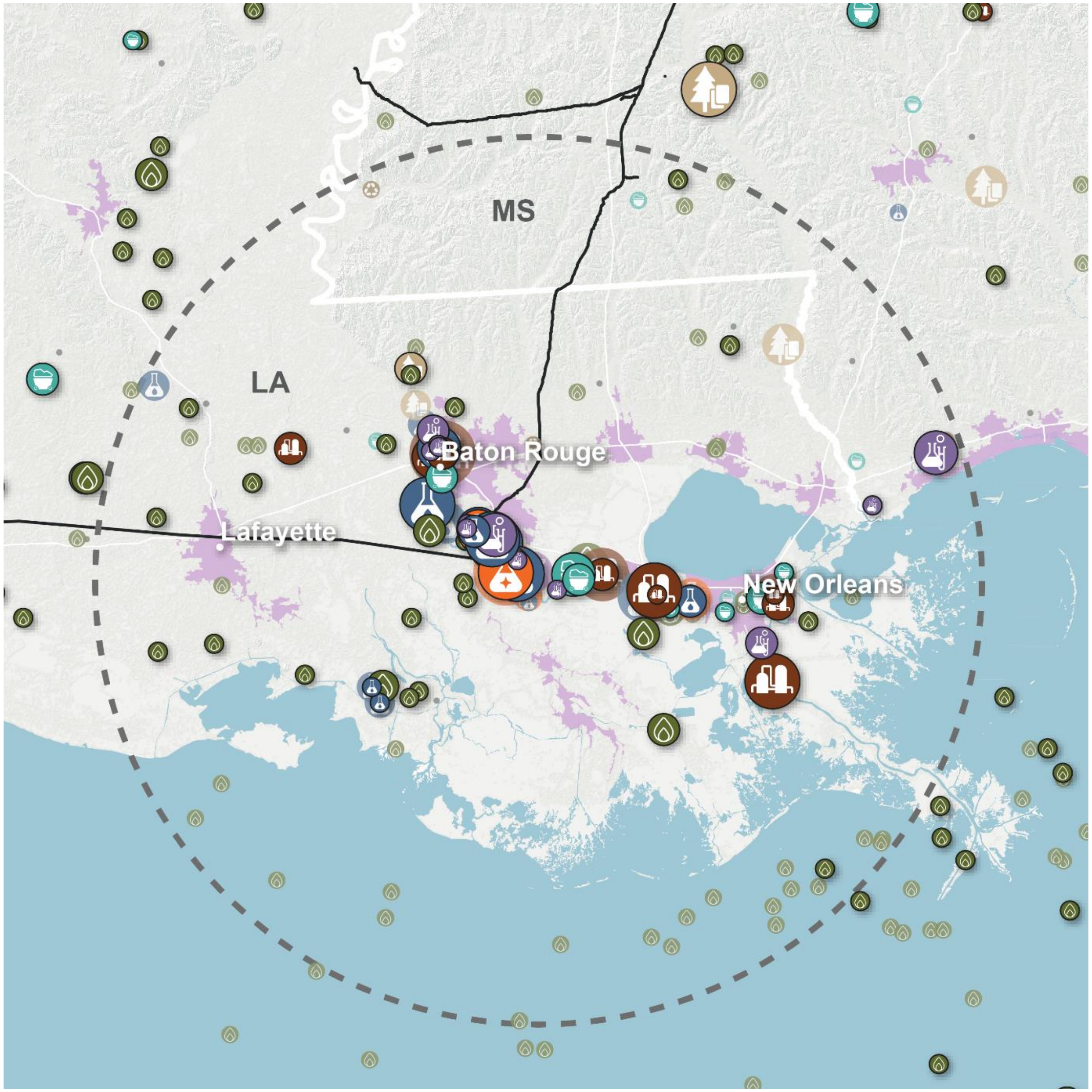
Other capture opportunities
Sized by annual CO_2 emissions

- Ammonia
- Chemicals
- Pet. & NG systems
- Misc. industry
- Petrochemicals
- Pulp & paper
- Refineries
- Steel
- Waste

- All other industrial facilities

Infrastructure

- Urban area
- Interstate highway
- Existing CO_2 pipeline

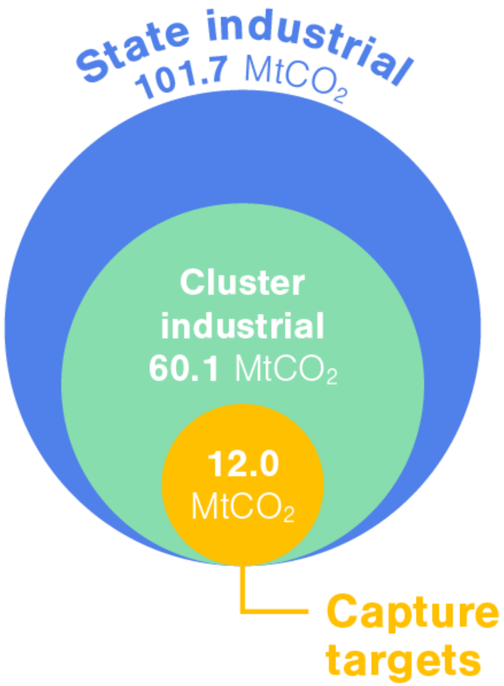


Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), DOE NATCARB (2015), Industrial Innovation Initiative (2023), EIA (2021), and analysis by Horizon Climate Group.

The industrial units identified as capture targets in the Louisiana cluster account for 12.0 MtCO_2 per year, or roughly 20% of the total 60.1 MtCO_2 emitted annually by all industrial facilities within the boundaries of the cluster. The 12.0 MtCO_2 emitted by these capture targets account for around 12% of the total 101.7 MtCO_2 emitted annually by industrial facilities across the state of Louisiana (Figure 17).

Figure 17

Louisiana regional cluster: Annual emissions in context



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table 5 summarizes industrial sector emissions in the state of Louisiana, in the Louisiana cluster, and from capture targets in the Louisiana cluster. As shown in this table, nearly all of the state's refining emissions come from the Louisiana cluster. Refining capture targets account for 2.9 MtCO_2 per year, or roughly 10% of the state's annual CO_2 emissions from refining. Petrochemical capture targets account for 4.0 MtCO_2 per year, or roughly 20% of annual statewide CO_2 emissions from petrochemical production.

Table 5

Louisiana regional cluster

Capture targets in context

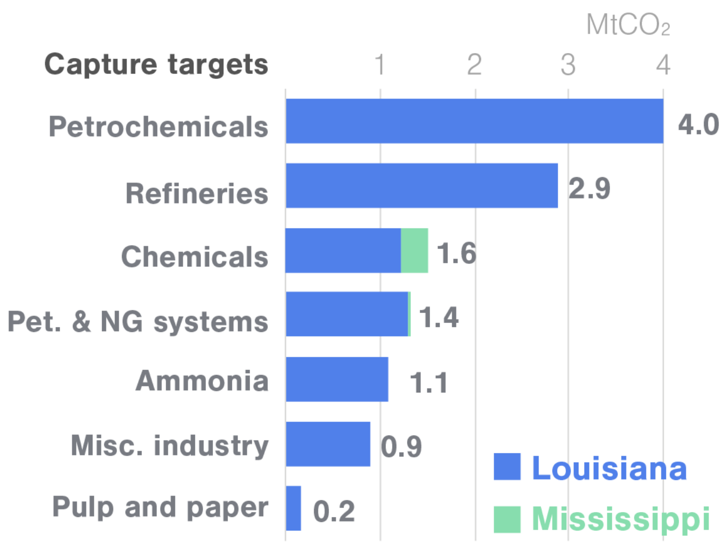
	Annual emissions MtCO_2		
Sector	**State**	**Regional cluster**	**Capture targets**
Pet. & NG systems	28.6	7.3	1.4
Refineries	28.1	21.2	2.9
Petrochemicals	19.1	14.4	4
Pulp and paper	10.2	2.4	0.2
Ammonia	9.8	9.8	1.1
Chemicals	3.1	2.5	1.6
Misc. industry	1.8	1.4	0.9
Steel	1.1	1.1	-
Waste	0.3	0.3	-
Total	**102**	**60**	**12**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

While centered in the state of Louisiana, the Louisiana cluster also includes a small portion of Mississippi. As shown in Figure 18, nearly all capture targets identified in the Louisiana cluster are within Louisiana, with only 415 ktCO_2 of the cluster's total 12 MtCO_2 per year emitted by units in Mississippi. A detailed overview of capture targets by sector and state within this cluster is available in Appendix Table A1.

Figure 18

Share of annual capture target emissions in the Louisiana regional cluster, by sector and state



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA Envirofacts database (2023), EIA (2021), and analysis by Horizon Climate Group.

Table 6 shows state policy related to CCUS in Louisiana, including the presence of permitting regulation, pore space and mineral rights law, and incentives of any kind for CCUS (beyond just industrial applications).

Across the states examined in this report, there are differences in their degree of policy development for CCUS.

States with existing CO_2 infrastructure—including Louisiana—often have established regulations for pipeline permitting, long-term liability, eminent domain, etc. Louisiana also has a nonbinding climate target and is the furthest along in the process of obtaining regulatory authority from EPA over geologic storage wells (Class VI primacy).[h] It would become only the third state to do so.

This regulatory environment—as well as Louisiana's existing industrial strengths—helps explain the state's high number of in-development CCUS projects and could make it a first mover for hub development.

[h] See Chapter 4 for a discussion of EPA's Underground Injection Control program and state primacy applications (on Page 74). Two classes of underground injection wells—Class II for EOR and Class VI for dedicated storage—are the primary ones related to CCUS.

Table 6
State of Louisiana
State CCUS policy

Permitting	**Permitting and inspection of CO_2 pipelines**	Yes[47]
	Eminent domain for CO_2 pipelines or storage	Yes[47]
	Class II primacy[48]	Yes
	Class VI primacy[49]	Applied: Rulemaking and Codification
Property ownership	**State assumption of long-term liability for CO_2 storage**	Yes (10 years or more after injections cease); trust fund composed of fees paid by operators[50]
	Mineral rights	Solid-state minerals belong to surface landowners; liquid and gas minerals do not[51]
	Pore space ownership	No existing laws; past court opinions support surface owner's right to pore space[52]
CCUS incentives	**Financial incentives for CCUS**	Tax exemption for the sale of man-made CO_2 for EOR[47]
	Clean energy standard with CCUS	No
	Carbon pricing/low-carbon fuel standard	No
	Climate targets	Net-zero GHG emissions by 2050[53]

Source: EFI Foundation analysis; see sources in table.

Houston Regional Cluster

The Texas Gulf Coast near the Houston metropolitan area is home to a high concentration of industrial operations in the refining, petroleum and natural gas system, chemicals, and petrochemicals sectors. Its proximity to existing CO_2 pipelines and potential CO_2 storage in geologic saline formations give the Houston area a head start in forming an industrial ecosystem of CO_2 capture, utilization, and storage (Table 7).

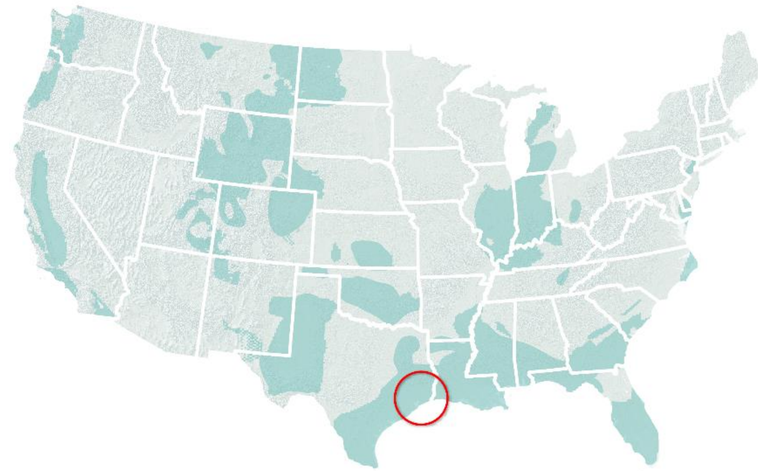


Table 7
Houston regional cluster
At a glance

Primary states involved	Texas and Louisiana
Statewide industrial emissions (Texas)	364.2 $MtCO_2e$ per year
Capture targets identified	311 units 124 facilities 36.6 $MtCO_2$ per year
Top capture target industries	Petroleum and NG systems Refineries Petrochemicals
Geologic saline storage	Present throughout cluster
Existing CO_2 pipelines	Present

Source: EPA GHG Inventory (2021), EPA GHGRP (2022), EIA (2021), analysis by Horizon Climate Group.

The industrial sector in Texas emits 364.2 $MtCO_2e$ per year, making it the leading GHG-emitting sector and accounting for over 40% of the state's annual emissions (Table 8).[1]

Table 8
State of Texas
Emissions overview

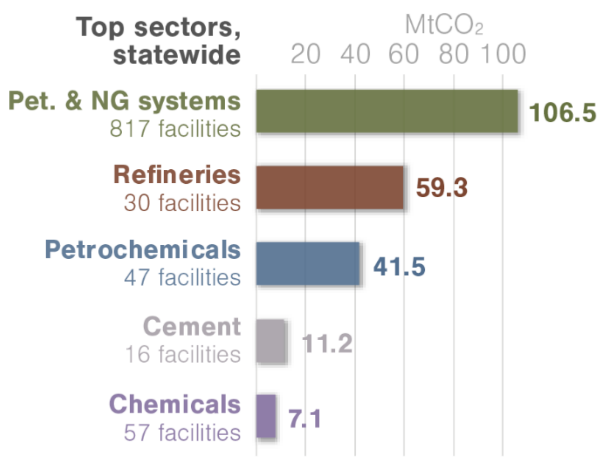
Sector	**Annual emissions** $MtCO_2e$
Industry	364.2
Transportation	209.7
Electric power	183.0
Agriculture	62.0
Commercial	35.9
Residential	18.3
Total	**873.1**

Source: EPA GHG Inventory (2021).

Within the industrial sector, the top five industries by annual emissions are petroleum and natural gas systems, refining, and, separately, the production of petrochemicals, cement, and other chemicals.[6,7,8,54] Together, these sectors emitted 225.5 $MtCO_2$ in 2021, accounting for 62% of the state's industrial emissions of 362.2 $MtCO_2e$ (Figure 19).[1,7]

Figure 19

State of Texas: Top 5 industries by annual emissions

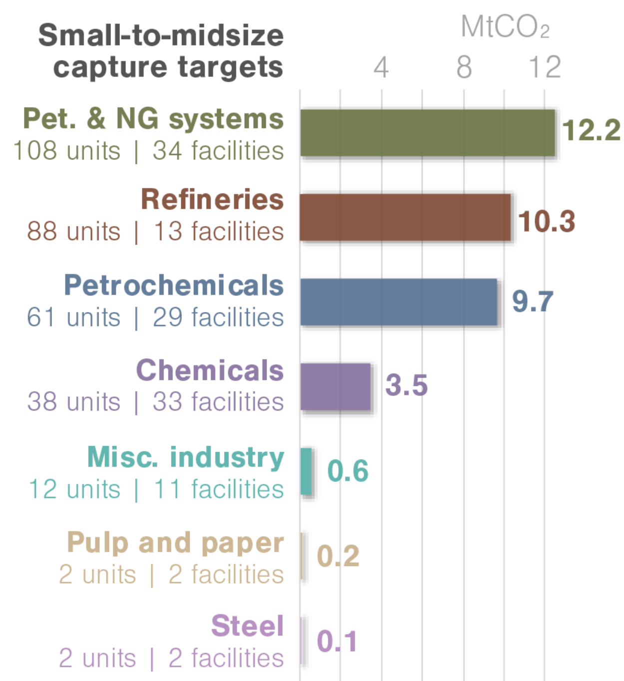


Note: Power generation was excluded from rankings. Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EIA (2021) and EPA GHGRP (2022).

Within the Houston cluster, this analysis identified 311 industrial units across 124 facilities as capture targets. Together, these target units emit 36.6 $MtCO_2$ per year. The largest share of capturable emissions comes from petroleum and natural gas systems, where capture targets identified within the Houston cluster account for 12.2 $MtCO_2$ per year. Refineries, petrochemicals, chemicals, and sectors that fall into the miscellaneous industry category also constitute a large share of the capture potential from target units in this regional cluster (Figure 20).

Figure 20

Houston regional cluster: Target units by sector and annual emissions



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table 9
Houston regional cluster
Target units by industrial sector: Profile of capture targets

Sector	# of Units	Annual emissions $MtCO_2$	Median annual emissions per unit $ktCO_2$	Median capacity factor	Median CO_2 concentration
Pet. & NG systems	108	12.2	95	80%	5%
Refineries	88	10.3	87	74%	12%
Petrochemicals	61	9.7	79	83%	5%
Chemicals	38	3.5	57	≥ 85%	5%
Misc. industry	12	0.6	39	≥ 85%	5%
Pulp and paper	2	0.2	94	71%	5%
Steel	2	0.8	38	≥ 85%	5%
Total	**311**	**36.6**	**77**	**81%**	**5%**

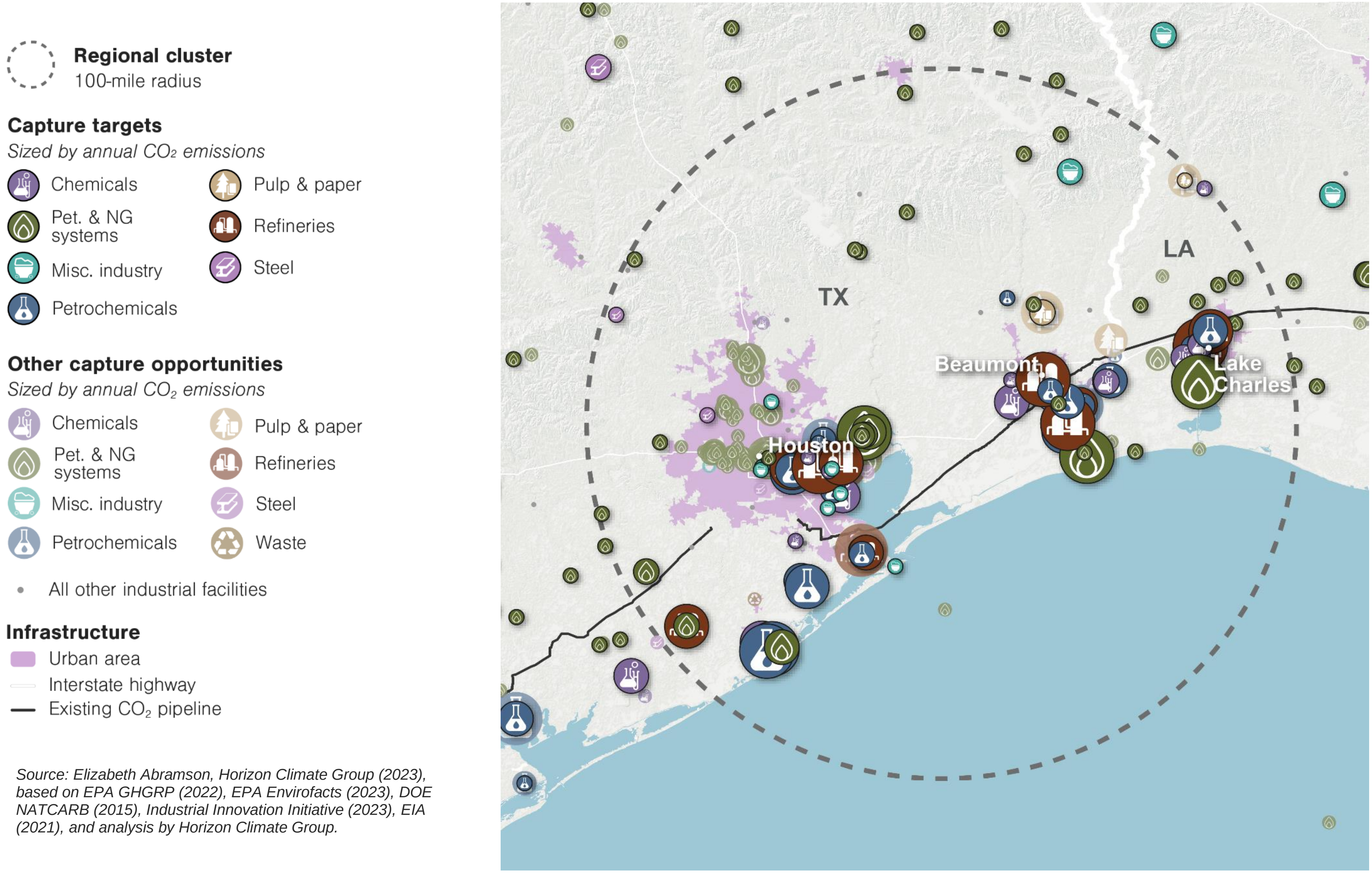
Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), Jordan & McFarlane (2023), and analysis by Horizon Climate Group.

Table 9 summarizes the typical characteristics of industrial units identified as capture targets in the Houston cluster. A typical unit identified as a capture target in the cluster emits 77 $ktCO_2$ per year, runs 81% of the time, and has a molar fraction of 5% CO_2 in its flue gas stream.

Identified capture targets in the Houston regional cluster are grouped around the cities of Houston, Beaumont, and Lake Charles (Figure 21). Each of these clusters has a mix of capture potential from industrial sectors including refining, petroleum and natural gas systems, and chemical and petrochemical production, among others. An existing CO_2 pipeline runs along the route between these clusters, establishing a precedent of local CO_2 transport and storage. With access to coastal ports, the Houston regional cluster is also well positioned to plug into domestic and international CCUS market chains.

Figure 21

Small-to-midsize industrial capture targets and high-capacity storage in the Houston regional cluster

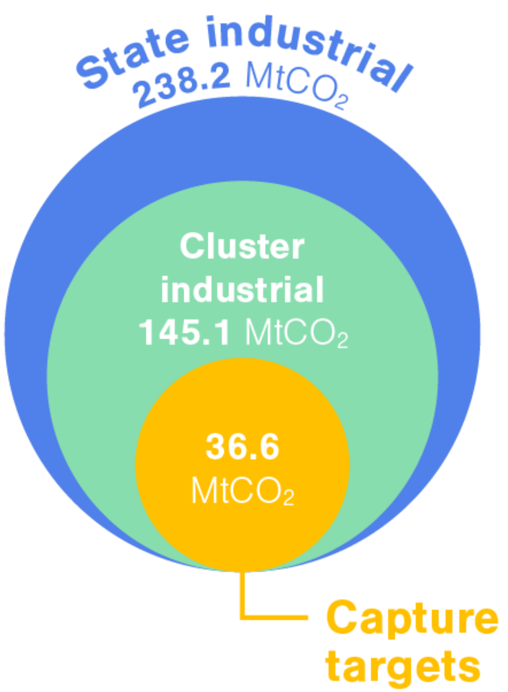


Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), DOE NATCARB (2015), Industrial Innovation Initiative (2023), EIA (2021), and analysis by Horizon Climate Group.

The industrial units identified as capture targets in the Houston cluster account for 36.6 $MtCO_2$ per year, or roughly 25% of the total 145.1 $MtCO_2$ emitted annually by all industrial facilities within the boundaries of the cluster. The 36.6 $MtCO_2$ emitted by these capture targets each year are equivalent to around 15% of the total 238.2 $MtCO_2$ emitted annually by industrial facilities in the state of Texas (Figure 22).

Figure 22

Houston regional cluster: Annual emissions in context



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

However, because the Houston regional cluster includes a portion of the state of Louisiana that contains several capture targets, this comparison of totals to the Texas state total should be used primarily for comparison of scale, rather than as a reflection of the regional cluster as a specific portion of state emissions.

Table 10 summarizes industrial emissions in the state of Texas, in the Houston cluster, and from capture targets in the Houston cluster.

Table 10
Houston regional cluster
Capture targets in context

	Annual emissions $MtCO_2$		
Sector	**State**	**Regional cluster**	**Capture targets**
Pet. & NG systems	106.5	55.0	12.2
Refineries	59.3	45.3	10.3
Petrochemicals	41.5	33.0	9.7
Cement	11.2	-	-
Chemicals	7.1	6.1	3.5
Pulp and paper	5.3	4.8	0.2
Misc. industry	3.3	0.7	0.6
Steel	1.8	0.3	0.8
Ethanol	1.4	-	-
Ammonia	0.7	-	-
Waste	0.2	0.3	-
Total	**238**	**145**	**37**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

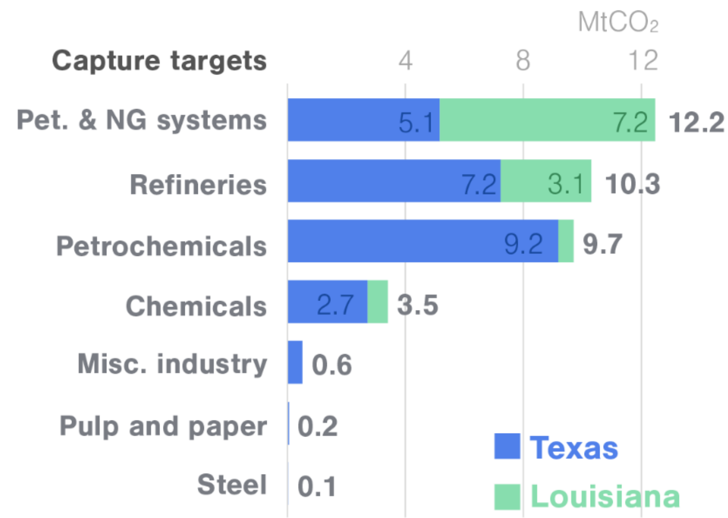
As shown in this table, refining, petroleum and natural gas systems, and petrochemicals production are the leading emissions sources in Texas, in the Houston cluster, and among capture targets in the Houston cluster. Refining capture targets account for 10.3 $MtCO_2$ per year, or roughly 23% of the 45.3 $MtCO_2$ emitted by all refineries in the Houston cluster annually. Petrochemical capture targets account for nearly a third of all annual petrochemical CO_2 emissions in the Houston cluster.

While centered in the state of Texas, the Houston regional cluster includes the southwestern portion of Louisiana. As shown in Figure 23, most emissions from petroleum and natural gas system capture targets in this cluster are in Louisiana. Likewise, a third of emissions from refineries identified as capture targets in the Houston cluster are in Louisiana.

A detailed overview of capture targets by sector and state within this cluster is available in Appendix Table A2.

Figure 23

Share of annual capture target emissions in the Houston regional cluster, by sector and state



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table 11 summarizes Texas' state policy for CCUS; Louisiana's state policy is included in Table 6. Like Louisiana, Texas has fairly well-developed CCUS policy (pipeline permitting, liability provisions, etc.) and is applying for Class VI primacy, though it is at an earlier stage in the process.

Table 11
State of Texas
State CCUS policy

Permitting	**Permitting and inspection of CO_2 pipelines**	Yes[55]
	Eminent domain for CO_2 pipelines or storage	Yes[55]
	Class II primacy[48]	Yes
	Class VI primacy[49]	Applied: Pre-Application Activities
Property ownership	**State assumption of long-term liability for CO_2 storage**	Yes (upon well closure); trust fund composed of fees paid by operators[50]
	Mineral rights	Separate from surface rights[56]
	Pore space ownership	No existing laws[52]
CCUS incentives	**Financial incentives for CCUS**	Reduced tax rates and state funding for capture projects and man-made CO_2 for EOR[47]
	Clean energy standard with CCUS	No
	Carbon pricing/low-carbon fuel standard	No
	Climate targets	No target

Source: EFI Foundation analysis; see references in table.

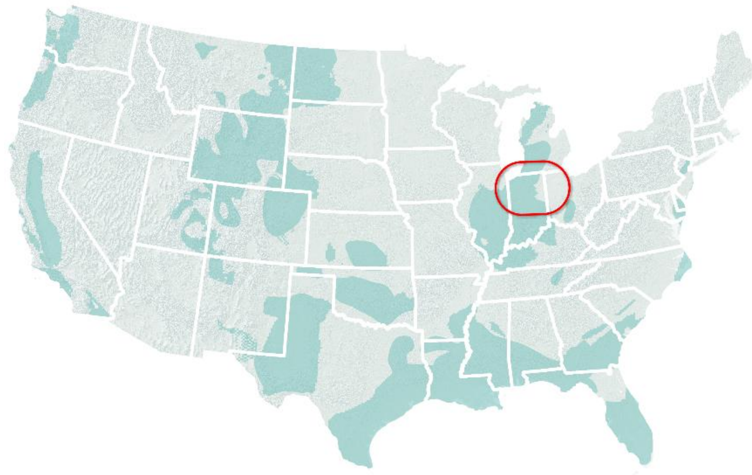
Great Lakes Regional Cluster

The Great Lakes is home to numerous facilities that refine petroleum and produce steel, ethanol, and cement. These sectors present a good opportunity for the creation of a carbon capture hub or hubs when considered alongside the nearby potential CO_2 storage in geologic saline formations in Illinois, Indiana, and Michigan (Table 12).

Table 12
Great Lakes regional cluster
At a glance

Primary states involved	Illinois, Indiana, Ohio, and Michigan
Statewide industrial emissions (Illinois, Indiana, Ohio, Michigan)	169.8 $MtCO_2e$ per year
Capture targets identified	189 units 140 facilities 15.0 $MtCO_2$ per year
Top capture target industries	Misc. industry Refineries Steel
Geologic saline storage	Present in some areas
Existing CO_2 pipelines	None

Source: EPA GHG Inventory (2021), EPA GHGRP (2022), EIA (2021), analysis by Horizon Climate Group.



Industry is the third-highest-emitting sector in Illinois, Ohio, and Michigan, and the second highest in Indiana. The industrial sector emits 41.6 $MtCO_2e$ annually in Illinois, 48.3 $MtCO_2e$ in Indiana, 52.8 $MtCO_2e$ in Ohio, and 27.1 $MtCO_2e$ in Michigan (Table 13).[1]

Table 13
Illinois, Indiana, Michigan, and Ohio
Emissions overview

State	Sector	Annual emissions $MtCO_2e$
Illinois	**Total**	**223.4**
	Transportation	59.2
	Electric power	53.6
	Industry	41.6
	Residential	24.1
	Agriculture	23.8
	Commercial	21.0

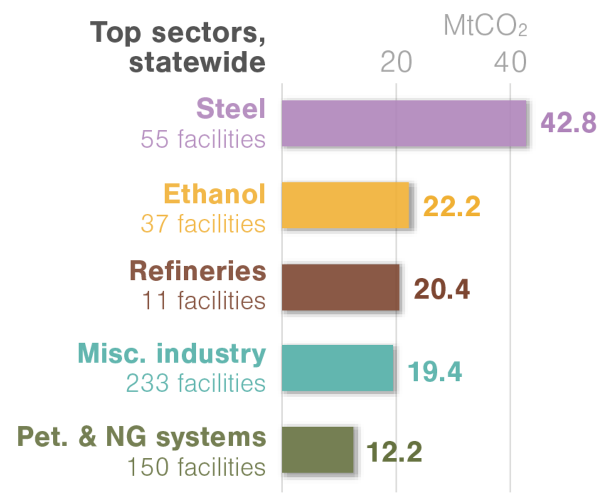
State	Sector	Annual emissions $MtCO_2e$
Indiana	**Total**	**193.6**
	Electric power	70.4
	Industry	48.3
	Transportation	41.3
	Agriculture	14.4
	Commercial	10.3
	Residential	9.0
Michigan	**Total**	**179.0**
	Electric power	53.9
	Transportation	47.9
	Industry	27.1
	Commercial	18.5
	Residential	20.2
	Agriculture	11.3
Ohio	**Total**	**235.4**
	Electric power	69.6
	Transportation	60.6
	Industry	52.8
	Residential	18.5
	Commercial	20.5
	Agriculture	13.4
Combined total		**831.4**

Source: EPA GHG Inventory (2021).

Within the industrial sector, the top five industries by annual emissions are steel, ethanol, refineries, miscellaneous industry, and petroleum and natural gas systems.[6,7,8] Together, these sectors emitted 117 $MtCO_2$ in 2021, accounting for 69% of the region's industrial emissions of 169.8 $MtCO_2e$ (Figure 24).[1,6,7,8]

Figure 24

States of Illinois, Indiana, Michigan, and Ohio: Top 5 industries by annual emissions



Note: Power generation was excluded from rankings. Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EIA (2021) and EPA GHGRP (2022).

Within the Great Lakes cluster, this analysis identified 189 industrial units across 140 facilities as capture targets (Figure 25). Together, these target units emit 15 $MtCO_2$ per year.

The largest share of emissions comes from the miscellaneous industry category, where capture targets identified within the cluster account for 3.5 $MtCO_2$ in annual emissions. Facilities in the miscellaneous industry category within the Great Lakes cluster include several glass manufacturing, food processing, and auto production sites, among other industrial facilities. Petroleum refining, steel production, cement, and ethanol production also constitute a large share of the capture potential from target units in this cluster.

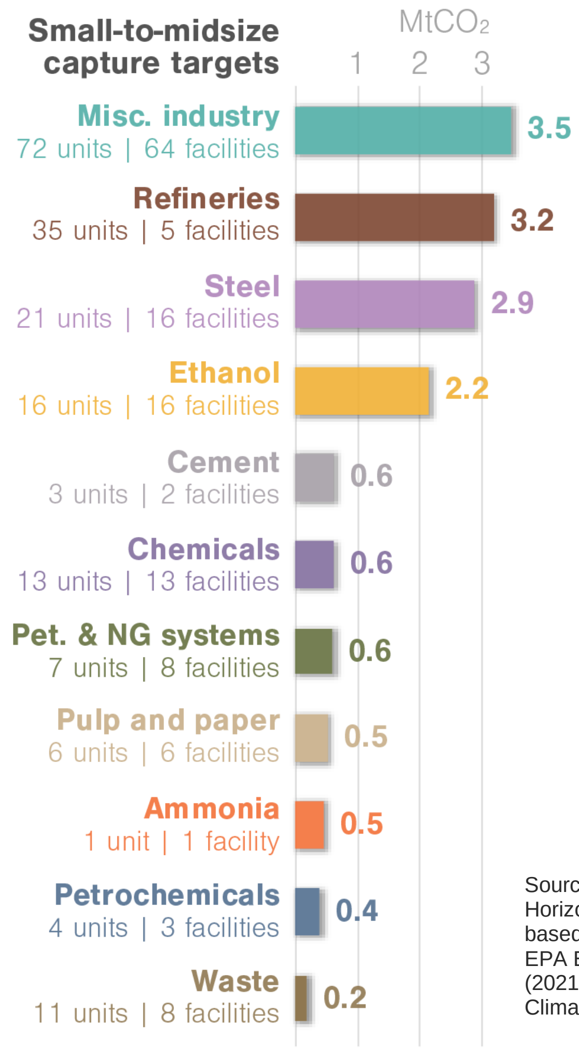
Table 14 summarizes the typical characteristics of industrial units identified as capture targets in the Great Lakes cluster. A typical unit identified as a capture target in the cluster emits 57 $ktCO_2$ per year, runs more than 85% of the time, and has a molar fraction of 5% CO_2 in its flue gas stream.

Capture targets in the Great Lakes regional cluster are dispersed throughout the region, with ethanol production and miscellaneous industry sites dotted throughout the region's more rural areas. Several refineries, iron and steel plants, and cement plants are clustered around urban areas such as Chicago, Illinois, and Toledo and Lima, Ohio. (Figure 26).

Capture targets in the miscellaneous industry in the Great Lakes regional cluster include glass manufacturing, food processing, and auto manufacturing sites. Access to shipping channels on Lake Michigan to the west and Lake Huron to the east provide an additional method for facilities in this region to engage with broader CCUS markets along with pipeline, rail, and road transport.

Figure 25

Great Lakes regional cluster: Target units by sector and annual emissions



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

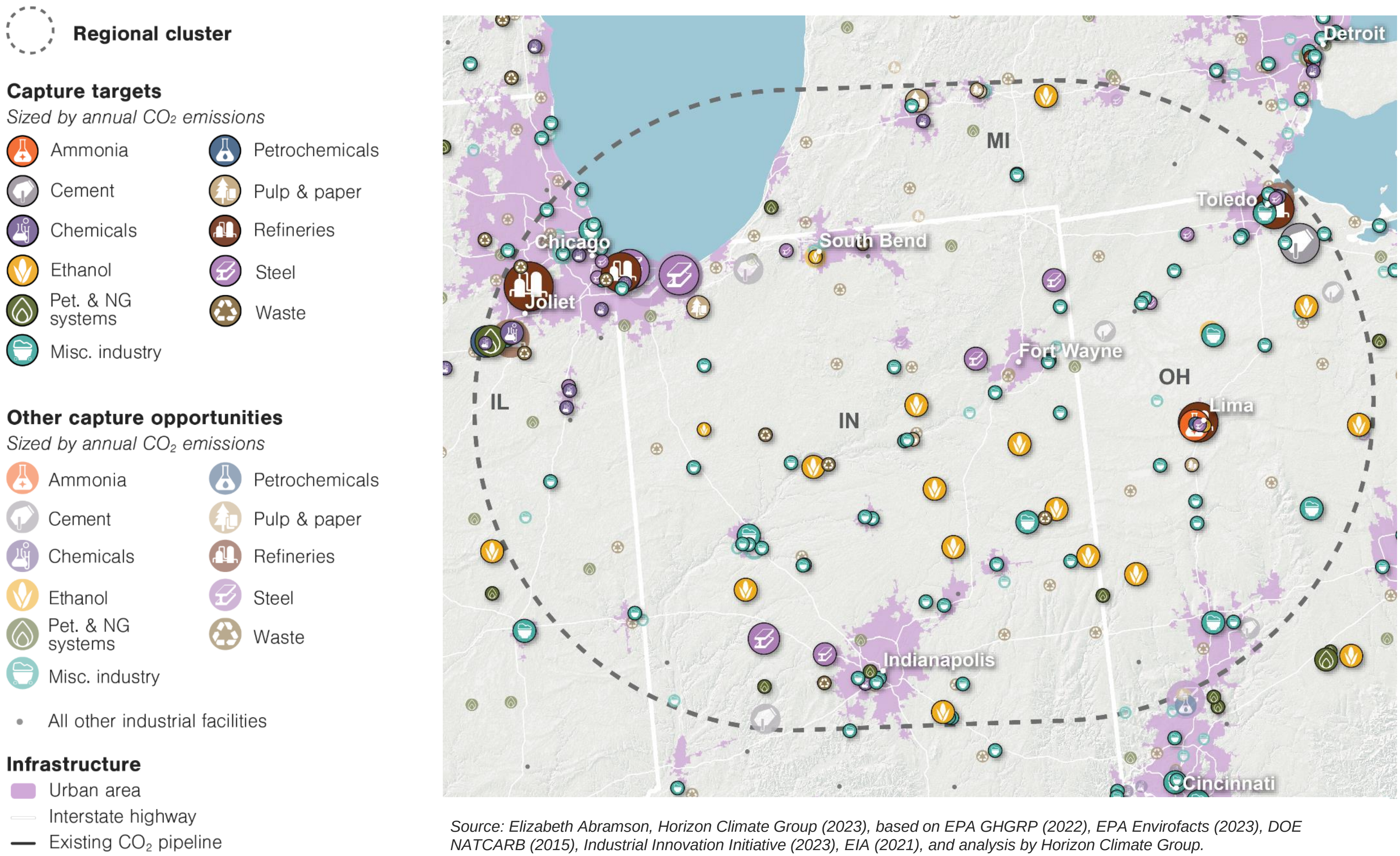
Table 14
Great Lakes regional cluster
Target units by industrial sector: Profile of capture targets

Sector	# of Units	Annual emissions $MtCO_2$	Median annual emissions per unit $ktCO_2$	Median capacity factor	Median CO_2 concentration
Misc. industry	72	3.5	39	≥ 85%	5%
Refineries	35	3.2	83	70%	12%
Steel	21	2.9	116	≥ 85%	5%
Ethanol	16	2.2	134	≥ 85%	5%
Cement	3	0.6	146	≥ 85%	13%
Chemicals	13	0.6	35	≥ 85%	5%
Pet. & NG systems	7	0.5	53	≥ 85%	5%
Pulp and paper	6	0.5	80	72%	5%
Ammonia	1	0.5	453	≥ 85%	5%
Petrochemicals	4	0.4	50	≥ 85%	5%
Waste	11	0.2	16	≥ 85%	5%
Total	**189**	**15**	**57**	**≥ 85%**	**5%**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), Jordan & McFarlane (2023), and analysis by Horizon Climate Group.

Figure 26

Small-to-midsize industrial capture targets and high-capacity storage in the Great Lakes regional cluster

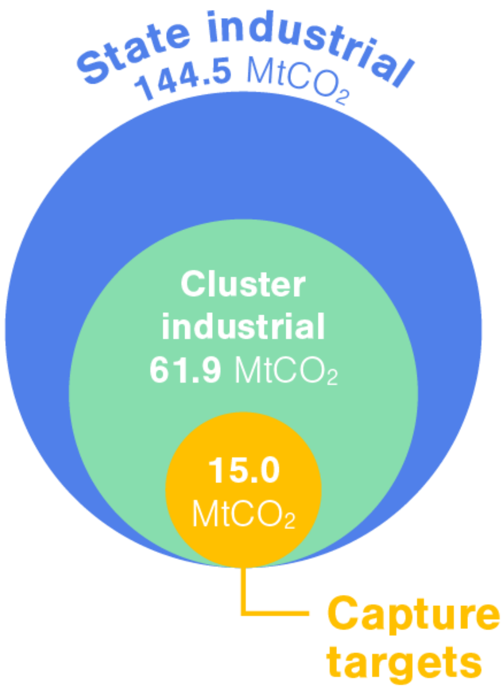


Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), DOE NATCARB (2015), Industrial Innovation Initiative (2023), EIA (2021), and analysis by Horizon Climate Group.

In total, the industrial units identified as capture targets in the Great Lakes cluster account for 15 $MtCO_2$ per year, or roughly 24% of the total 61.9 $MtCO_2$ emitted annually by all industrial facilities within the boundaries of the cluster. The 15 $MtCO_2$ emitted by these capture targets each year account for around 11% of the total 144.5 $MtCO_2$ emitted annually by industrial facilities in Illinois, Indiana, Ohio, and Michigan, the states in the Great Lakes cluster (Figure 27).

Figure 27

Great Lakes regional cluster: Annual emissions in context



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table 15 summarizes industrial sector emissions in the states of Illinois, Indiana, Ohio, and Michigan, in the Great Lakes cluster, and from capture targets in the Great Lakes cluster, by sector.

Table 15

Great Lakes regional cluster

Capture targets in context

	Annual emissions $MtCO_2$		
Sector	**States**	**Regional cluster**	**Capture targets**
Steel	42.8	22.7	2.9
Ethanol	22.2	7.7	2.2
Refineries	20.4	11.7	3.2
Misc. industry	19.4	5.3	3.5
Pet. & NG systems	12.2	3.8	0.5
Cement	11.4	6.0	0.6
Pulp and paper	5.1	0.5	0.5
Petrochemicals	4.4	1.7	0.4
Chemicals	3.2	0.8	0.6
Ammonia	2.1	1.4	0.5
Waste	1.4	0.3	0.2
Total	**141.5**	**62**	**15**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

The steel sector accounts for the largest share of industrial emissions across the four states and within the Great Lakes cluster itself. Steel sector capture targets within the Great Lakes cluster account for 2.9

$MtCO_2$ per year, or roughly 7% of emissions from the steel sector across the four states. Capture targets within the cluster account for around 10% of annual emissions from ethanol production and 16% of annual emissions from refining across the four states.

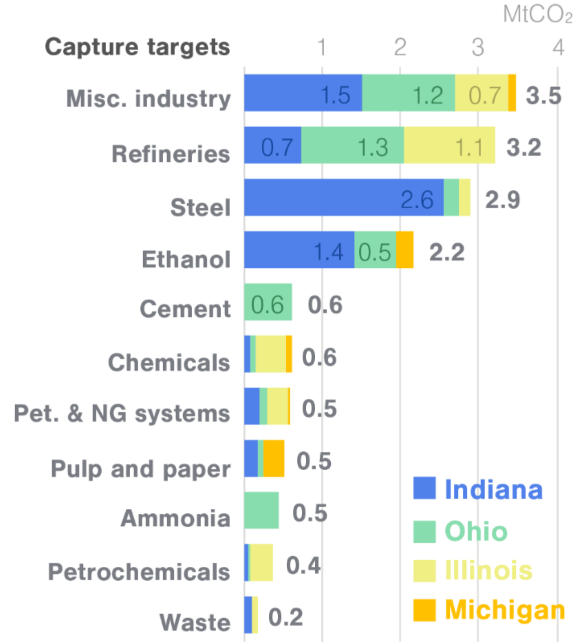
Figure 28 shows the breakdown of emissions from capture targets within the Great Lakes cluster, by state. Capture targets in the steel sector are largely concentrated in Indiana. Capture targets in the cluster's other leading sectors, such as refining, miscellaneous industry, and ethanol, are largely distributed across multiple states. A detailed overview of capture targets by sector and state within this cluster is available in Appendix Table A3.

Table 16 details state policy for CCUS development in three of the four states (Ohio is included in Table 21 at the end of the next section).

None of these states has applied for Class VI primacy, though this region has the first fully EPA-permitted Class VI wells (and another set of pending permits with completed applications). These states have relatively robust regulations for CO_2 infrastructure and some incentives for CCUS deployment. These incentives are largely limited to either power or EOR projects, reflecting policies that have not kept up with a shifting CCUS landscape over recent decades.

Figure 28

Share of annual capture target emissions in the Great Lakes regional cluster, by sector and state



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA Envirofacts database (2023), EIA (2021), and analysis by Horizon Climate Group.

Table 16
Illinois, Indiana, and Michigan
State CCUS policy

		Illinois	Indiana	Michigan
Permitting	Permitting and inspection of CO_2 pipelines	Yes[55]	No[51]	Yes[51]
	Eminent domain for CO_2 pipelines or storage	Yes[55]	Yes[51]	Yes[51]
	Class II primacy[48]	Yes	Yes	Yes
	Class VI primacy[49]	Not applied	Not applied	Not applied
Property ownership	State assumption of long-term liability for CO_2 storage	No	Yes (10+ years after injections cease); trust fund composed of fees paid by operators[50]	No
	Mineral rights	Separate from surface rights[57]	Separate from surface rights[51]	Separate from surface rights[58]
	Pore space ownership	Proposed law: Belongs to surface estate owner[52]	State law: Belongs to surface estate owner[52]	Case law: Belongs to surface estate owner[51]
CCUS incentives	Financial incentives for CCUS	State funding for coal power with capture and CCUS R&D[47,59]	State funding for coal power with capture[47,59]	State funding for coal power with capture; reduced severance tax rate for EOR projects using CO_2[47,59]
	Clean energy standard with CCUS	Yes[53]	Yes (voluntary)[60]	Yes[61]
	Carbon pricing/low-carbon fuel standard	No	No	No
	Climate targets	Reduce GHG emissions by at least 26% to 28% by 2025[62]	No target	Net-zero GHG emissions by 2050[53]

Source: EFI Foundation analysis; see references in table.

Ohio River Valley Regional Cluster

The tri-state area of Pennsylvania, Ohio, and West Virginia is home to a rich history of steel production and a wide variety of other industrial activity. A heavy presence of petroleum and natural gas systems and iron and steel production, as well as promising geologic storage formations to the west, anchor this region's potential to form a carbon capture hub or hubs (Table 17).

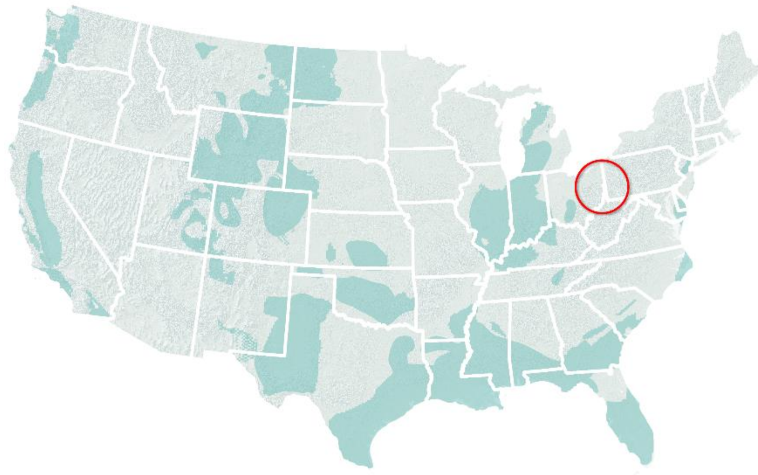


Table 17
Ohio River Valley regional cluster
At a glance

Primary states involved	Ohio, Pennsylvania, and West Virginia
Statewide industrial emissions (Ohio, Pennsylvania, West Virginia)	173.1 $MtCO_2e$ per year
Capture targets identified	127 units 112 facilities 8.3 $MtCO_2$ per year
Top capture target industries	Petroleum and NG systems Steel Misc. industry
Geologic saline storage	None
Existing CO_2 pipelines	None

Source: EPA GHG Inventory (2021), EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Industry is the second-highest-emitting sector in Pennsylvania and West Virginia, and the third highest in Ohio. Industry accounts for 31% of total annual emissions in Pennsylvania, 32% in West Virginia, and 22% in Ohio (Table 18).[1]

Table 18
Ohio, Pennsylvania, and West Virginia
Emissions overview

State	Sector	Annual emissions $MtCO_2e$
Ohio	**Total**	**235.4**
	Electric power	69.6
	Transportation	60.6
	Industry	52.8
	Commercial	20.5
	Residential	18.5
	Agriculture	13.4

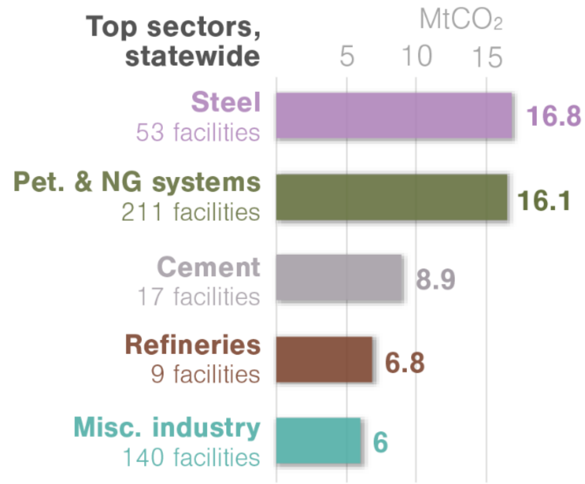
State	Sector	Annual emissions $MtCO_2e$
Pennsylvania	**Total**	**267.7**
	Industry	82.8
	Electric power	80.0
	Transportation	59.4
	Residential	19.5
	Commercial	16.8
	Agriculture	9.2
West Virginia	**Total**	**117.7**
	Electric power	60.1
	Industry	37.5
	Transportation	13.8
	Commercial	3.0
	Residential	2.0
	Agriculture	1.4
Combined total		**620.8**

Source: EPA GHG Inventory (2021).

Within the industrial sector, the top five industries in the Ohio River Valley cluster by annual emissions are steel, petroleum and natural gas systems, cement production, refining, and a mix of activities within the miscellaneous industry category.[6,7,8] Together, these sectors emitted 54.6 $MtCO_2$ in 2021, accounting for 32% of the three states' industrial emissions of 173.1 $MtCO_2e$ (Figure 29).[1,7,8]

Figure 29

States of Ohio, Pennsylvania, and West Virginia: Top 5 industries by annual emissions

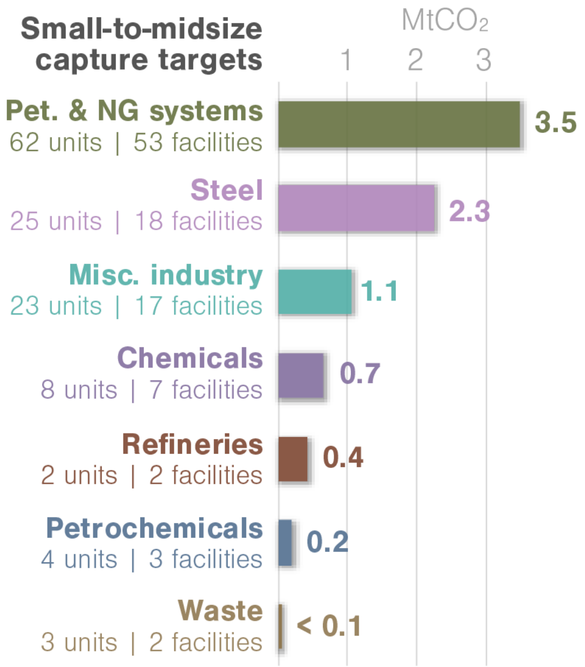


Note: Power generation was excluded from rankings. Source: Elizabeth Abramson, Horizon Climate Group (2023) based on EIA (2021) and EPA GHGRP (2022).

This analysis identified 127 industrial units across 112 facilities in the Ohio River Valley cluster as prime capture targets. Together, these target units emit 8.3 $MtCO_2$ per year. The largest share of emissions comes from petroleum and natural gas systems, where capture targets identified within the cluster account for 3.5 $MtCO_2$ per year. Steel production, chemical production, refineries, and facilities in the miscellaneous industry category also constitute a large share of the capture potential from target units in this cluster (Figure 30).

Figure 30

Ohio River Valley regional cluster: Target units by industrial sector and annual emissions



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table 19 summarizes the typical characteristics of industrial units identified as capture targets in the Ohio River Valley cluster. A typical unit identified as a capture target in this cluster emits 41 $ktCO_2$ per year, runs over 85% of the time, and has a molar fraction of 5% CO_2 in its flue gas stream.

Capture targets are dispersed throughout the Ohio River Valley regional cluster, with numerous petroleum and natural gas system capture targets centered on the intersection of the three states in this regional cluster (Figure 31).

Capture targets in the miscellaneous industry category in this cluster are a mix of metal production, glass production, food processing, and minerals production for construction materials. Capture targets in the iron and steel sector are visible around Pittsburgh and in Cleveland.

Table 19
Ohio River Valley regional cluster
Target units by industrial sector: Profile of capture targets

Sector	**# of Units**	**Annual emissions** $MtCO_2$	**Median annual emissions per unit** $ktCO_2$	**Median capacity factor**	**Median CO_2 concentration**
Pet. & NG systems	62	3.5	44	≥ 85%	5%
Steel	25	2.3	55	≥ 85%	5%
Misc. industry	23	1.0	37	≥ 85%	5%
Chemicals	8	0.7	57	≥ 85%	5%
Refineries	2	0.4	204	≥ 85%	5%
Petrochemicals	4	0.2	35	≥ 85%	5%
Waste	3	0.1	19	≥ 85%	5%
Total	**127**	**8.3**	**41**	**≥ 85%**	**5%**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), Jordan & McFarlane (2023), and analysis by Horizon Climate Group.

Figure 31

Small-to-midsize industrial capture targets and high-capacity storage in the Ohio River Valley regional cluster

Regional cluster
100-mile radius

Capture targets
Sized by annual CO_2 emissions

- Chemicals
- Refineries
- Pet. & NG systems
- Steel
- Misc. industry
- Waste
- Petrochemicals

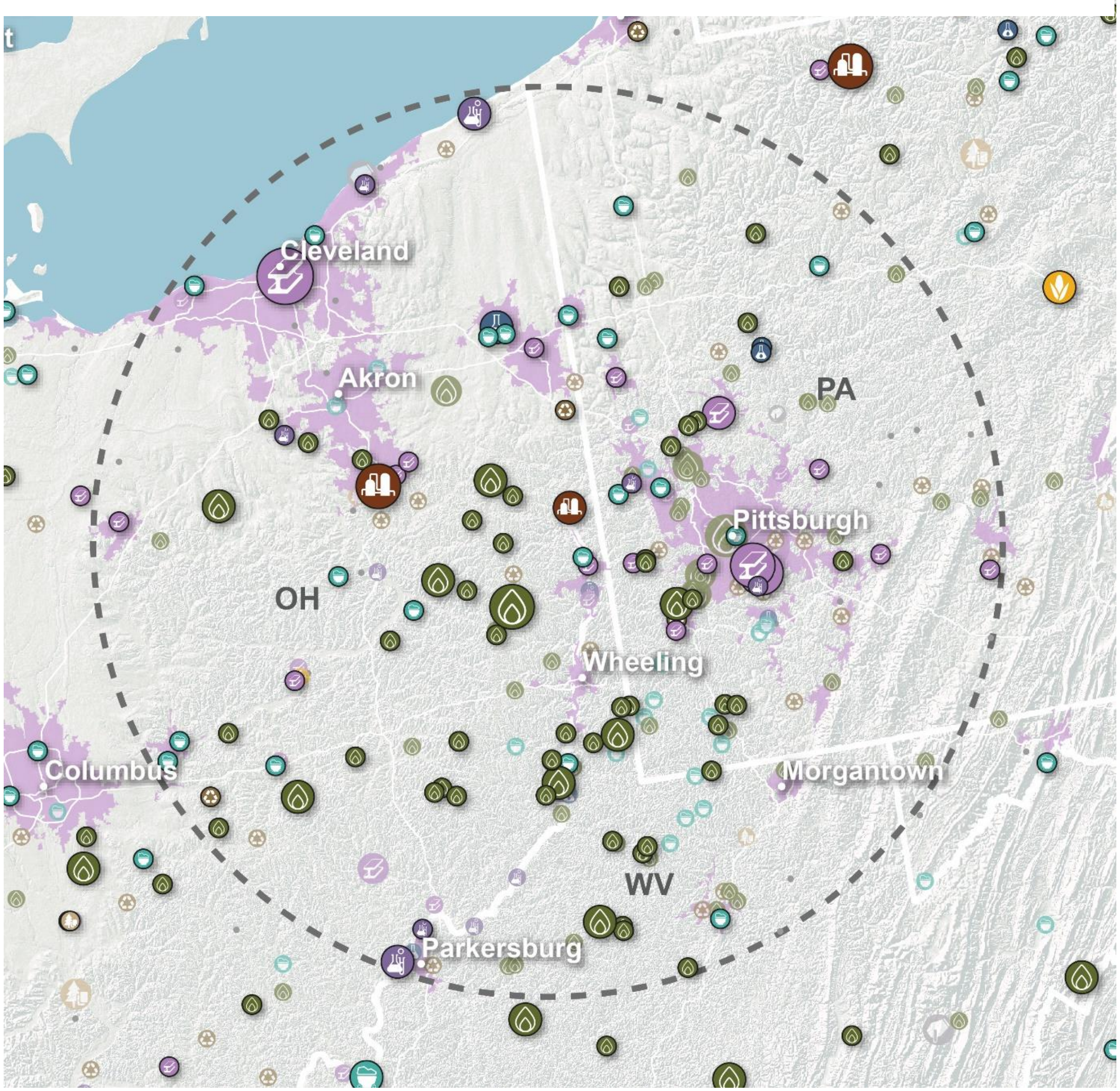
Other capture opportunities
Sized by annual CO_2 emissions

- Cement
- Petrochemicals
- Chemicals
- Pulp & paper
- Ethanol
- Refineries
- Pet. & NG systems
- Steel
- Misc. industry
- Waste

- All other industrial facilities

Infrastructure

- Urban area
- Interstate highway
- Existing CO_2 pipeline

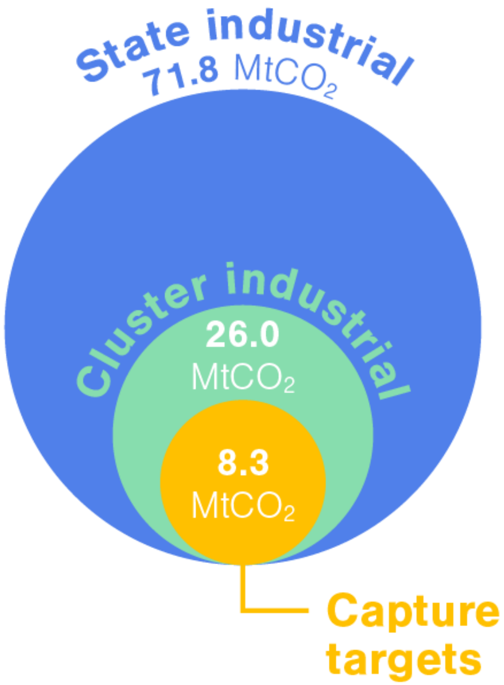


Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), DOE NATCARB (2015), Industrial Innovation Initiative (2023), EIA (2021), and analysis by Horizon Climate Group.

The industrial units identified as capture targets in the Ohio River Valley cluster account for 8.3 $MtCO_2$ per year, or roughly 31% of the total 26 $MtCO_2$ emitted annually by all industrial facilities within the boundaries of the cluster. The 8.3 $MtCO_2$ emitted by these capture targets each year account for around 12% of the total 71.8 $MtCO_2$ emitted annually by industrial facilities in Pennsylvania, Ohio, and West Virginia, the states in the Ohio River Valley cluster (Figure 32).

Figure 32

Ohio River Valley regional cluster: Annual emissions in context



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table 20 compares industrial sector emissions in the states of Pennsylvania, Ohio, and West Virginia, within the Ohio River Valley cluster, and from capture targets within the Ohio River Valley cluster, by sector.

Table 20

Ohio River Valley regional cluster

Capture targets in context

	Annual emissions $MtCO_2$		
Sector	**States**	**Regional cluster**	**Capture targets**
Steel	16.8	10.6	2.3
Pet. & NG systems	16.1	10.2	3.5
Cement	8.9	0.5	-
Refineries	6.8	0.7	0.4
Misc. industry	6.0	1.6	1.0
Pulp and paper	4.5	0.1	-
Ethanol	3.6	0.2	-
Chemicals	3.3	1.3	0.7
Petrochemicals	2.4	0.75	0.2
Waste	2.0	0.9	0.6
Ammonia	1.4	-	-
Total	**72**	**27**	**9**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

As shown in this table, petroleum and natural gas system capture targets in the Ohio River Valley cluster account for 3.5 $MtCO_2$ of annual emissions, representing 34% of annual CO_2 emissions from the sector within the cluster and 22% of annual CO_2 emissions from the sector across the three states. Steel sector capture targets in the Ohio River Valley cluster account for 2.3 $MtCO_2$ per year, or roughly 14% of the total 16.8 $MtCO_2$ emitted annually by steel facilities across the four states.

As shown in Figure 33, capture targets in the Ohio River Valley cluster are distributed among Pennsylvania, Ohio, and West Virginia, with the majority of emissions from petroleum and natural gas system capture targets located in Pennsylvania. Capture targets in the steel sector are split relatively evenly between Pennsylvania and Ohio. A detailed overview of capture targets by sector and state within this cluster is available in Appendix Table A4.

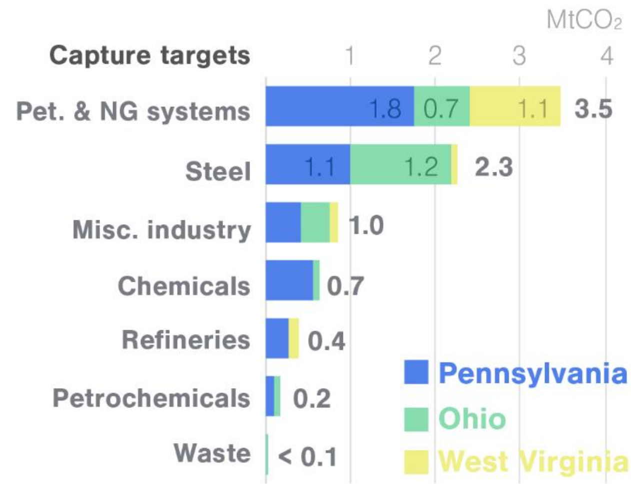
Table 21 details state policy in Pennsylvania, Ohio, and West Virginia. The latter, like Texas, is in the early stages of applying for Class VI primacy.

Pennsylvania is the only state among those analyzed in this report to pursue carbon pricing policy through the Regional Greenhouse Gas Initiative (RGGI), a multi-state cap-and-trade market in the Northeast. RGGI applies only to the power sector, however, and Pennsylvania's participation in it has been delayed by litigation.[63]

The states in this region have not established regulations for permitting CO_2 pipelines and have several other policy and regulatory gaps that could hamper development. Heterogeneity across this region (or others) in how states deal with siting and permitting could exacerbate difficulties for multistate hubs.

Figure 33

Share of annual capture target emissions in the Ohio River Valley regional cluster, by sector and state



Source: Elizabeth Abramson, Horizon Climate Group (2023), based on EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table 21
Ohio, Pennsylvania, and West Virginia
State CCUS policy

		Ohio	Pennsylvania	West Virginia
Permitting	**Permitting and inspection of CO_2 pipelines**	No[64]	No	No
Permitting	**Eminent domain for CO_2 pipelines or storage**	No[64]	No	No
Permitting	**Class II primacy**	Yes	No	Yes
Permitting	**Class VI primacy[49]**	Not applied	Not applied	Applied: Pre-application activities
Property ownership	**State assumption of long-term liability for CO_2 storage**	No	No[65]	Yes (10 years or more after injections cease); trust fund composed of fees paid by operators[50]
Property ownership	**Mineral rights**	Separate from surface rights[66]	Separate from surface rights[67]	Separate from surface rights[67]
Property ownership	**Pore space ownership**	No existing laws[52]	No existing laws[52]	Case law: Belongs to surface estate owner[52]
CCUS incentives	**Financial incentives for CCUS**	State funding for R&D[68]	State funding for R&D[47]	State funding for R&D[47]
CCUS incentives	**Clean energy standard with CCUS**	No[69]	No[70]	No[70]
CCUS incentives	**Carbon pricing/low-carbon fuel standard**	No	In process of joining RGGI[71]	No
CCUS incentives	**Climate targets**	No target	Reduce GHG emissions by 80% by 2050[59]	No target

Source: EFI Foundation analysis; see references in table.

4. CCUS Hubs for Small-to-Midsize Industrial Emitters

The CCUS Hub Concept

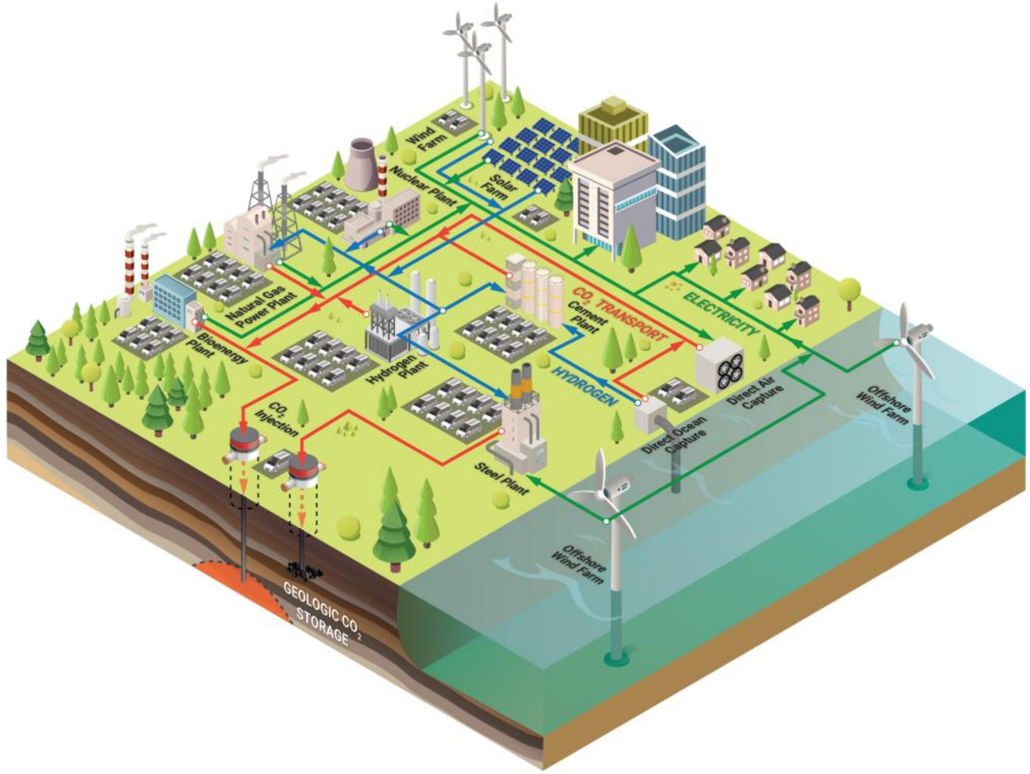
Net-zero industrial hubs have been proposed for several low-carbon technologies (e.g., zero-carbon electricity, clean hydrogen, CO_2 direct air capture).[13,72] Definitions of what constitutes a hub (or a CCUS hub in particular) vary.

For the purposes of this report, the essential quality of a hub is the presence of **shared, interconnected infrastructure and facilities**—which are usually new or repurposed—to enable deployment of emissions reduction solutions. These hubs are often modeled on—and may emerge from—existing industrial clusters or hubs, which have historically arisen around shared physical and human capital resources (e.g., clusters of refineries or biotech startups).

In the CCUS context, hubs are **groups of CO_2 capture sources that share transport and storage infrastructure** and/or utilization offtakers (Figure 34).[4,73]

Figure 34

Illustration of a CCUS hub



CCUS hubs connect CO_2 capture and removal sites that share transport and storage infrastructure. Source: See first figure mention in text for sources.

Benefits of CCUS Hubs

Regional hubs can be an essential element of CCUS development in the United States.[4] They can simplify national planning efforts, streamline processes for regulators, and provide stable sources of jobs. Their greatest value is to project developers.

Shared resources and risk. Hubs facilitate the pooling of resources among multiple stakeholders, addressing financial constraints.[13] Multiple capture projects could form a "buyers' club" for capture technologies or share contractors for T&S services or capture engineering and construction. This resource-sharing extends to informational and human capital. Diversifying a hub—multiple participants, capture sources, etc.—hedges against the risk that individual constituent projects will fail and expands the pool of available government funding.

Economies of scale and effort. Multiple parts of the CCUS value chain benefit from economies of scale. Building one high-capacity pipeline is more cost-effective than multiple smaller ones. Streamlining site exploration, geologic characterization, and permitting makes storage development easier. Small-to-midsize capture projects can ride in the slipstream of larger ones, helping transport and storage (T&S) providers fill their capacity without requiring additional infrastructure. Hubs facilitate economies of effort by allowing multiple projects to pursue pre-operations activities—permitting, community engagement, labor negotiations, site characterization, engineering/procurement/construction, ensuring regulatory compliance, securing government funding—through a centralized process.[74]

Storage-first development. Hubs evade the chicken-and-egg problem of mutually dependent capture, transport, and storage—and attendant delays or revenue shortages—by developing all three in sync. Hubs are also conveners, pairing up sources of CO_2 "demand" (utilizers or storage providers) with "supply" (capture sources). [4,13]

Place-based development. Hubs can be tailored to existing industrial clusters and local competitive advantages.[75] They can foster regional economic development and job creation. Furthermore, they can involve direct participation from local stakeholders (e.g., governments, universities), facilitating community engagement and new sources of funding or other support.

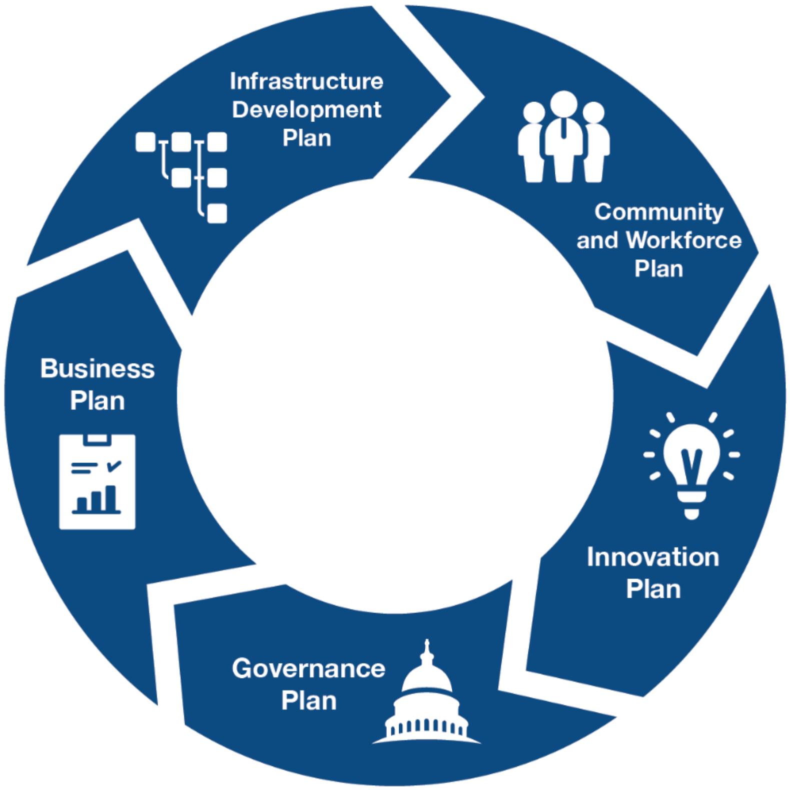
> **Regional hubs can be an essential element of CCUS development in the United States. They can simplify national planning efforts, streamline processes for regulators, and provide stable sources of jobs.**

Best Practices for CCUS Hub Development

The EFI Foundation has created a Regional Hub Design Strategy, based on research into prospective hydrogen hubs.[13] This strategy includes five elements (Figure 35).[13]

Figure 35

EFI Foundation's Regional Hub Design Strategy



CCUS hub development builds on five design plans for hub formation. Source: See first figure mention in text for sources.

Governance Plan. Effective governance is vital, requiring coordination across the entire CCUS value chain. Successful hubs often involve a consortium of stakeholders that pool capabilities, resources, and infrastructure.[13] These consortia need to set up legal and contractual frameworks early in the planning stage, clearly defining stakeholder responsibilities. An important aspect is appointing a single governing entity, either an existing participant or a new organization, such as a joint venture or new public utility. This entity will oversee major project functions, including project oversight and milestones, marketing and growth strategies, stakeholder liaison, monitoring and reporting, regulatory compliance, and data standardization and transparency.[13]

Business Plan. Business Plans will vary based on which segments of the carbon management value chain are included in a hub. Some "full-chain" hubs will include capture, transport, storage, and crosscutting entities working together. Capture-only hubs could form to tap into an existing T&S network; storage-focused hubs could develop common-carrier T&S infrastructure that contracts with capture sources. The introduction of carbon removal or utilization adds further complexity, offering additional revenue streams.

The contractual framework among participants is important to the Business Plan. Options include forming a joint venture to manage the hub and revenue collection, or hiring a contractor to construct and operate T&S infrastructure. In storage-focused hubs, the storage operator could establish a fee-for-service model, acting as a waste collection service for CO_2.

Regardless of the hub's configuration, certain best practices are universally applicable. Securing government support is vital (see Box 2), particularly for a capital-intensive technology such as CCUS.[13] Ensuring long-term project viability is also crucial, encompassing long-term contracts, strategies for growth, and large, consistent, durable financing.[13]

Infrastructure Development Plan. CCUS hubs require significant new infrastructure: retrofitted or new capture facilities, T&S infrastructure (especially pipelines and wells), enabling infrastructure (e.g., sensors, power for compressors), and more (optionally: utilization and carbon dioxide removal [CDR] facilities, distribution methods for products).

A strategy for siting and permitting is necessary before construction can start.[13] CCUS permitting is notoriously difficult, with overlapping authorities, unclear regulations that vary by jurisdiction, and under-resourced regulators. While hubs can potentially streamline this process, they cannot eliminate these challenges and may face further complications from interdependent permit delays.[13]

Infrastructure Development Plans encompass not only operational permits but also land and subsurface rights acquisition and frontline community engagement. Using existing infrastructure and workforce can reduce costs and ease permitting, benefiting local stakeholders (e.g., labor).[13]

Additionally, the Plan must address monitoring, reporting, and verification (MRV); long-term liability for CO_2 leakage or safety issues; and post-injection site care—all of which often require third-party verification or financial assurances to meet government mandates.

Box 2

The role of governments and public-private collaboration options for CCUS hubs

Federal, state, tribal, and local governments are major players in CCUS projects, acting as regulators and funders. Regulations across various domains (e.g., safety, siting and permitting, utility, environmental, financial) are critical to all CCUS projects and must be integrated into multiple facets of hub design.[13] While public financial support is not mandatory, it is often essential for feasibility because projects will rely on carbon markets, tax incentives, and government loans and grants.[14] Hub Business Plans should include strategies to access such funding.[13]

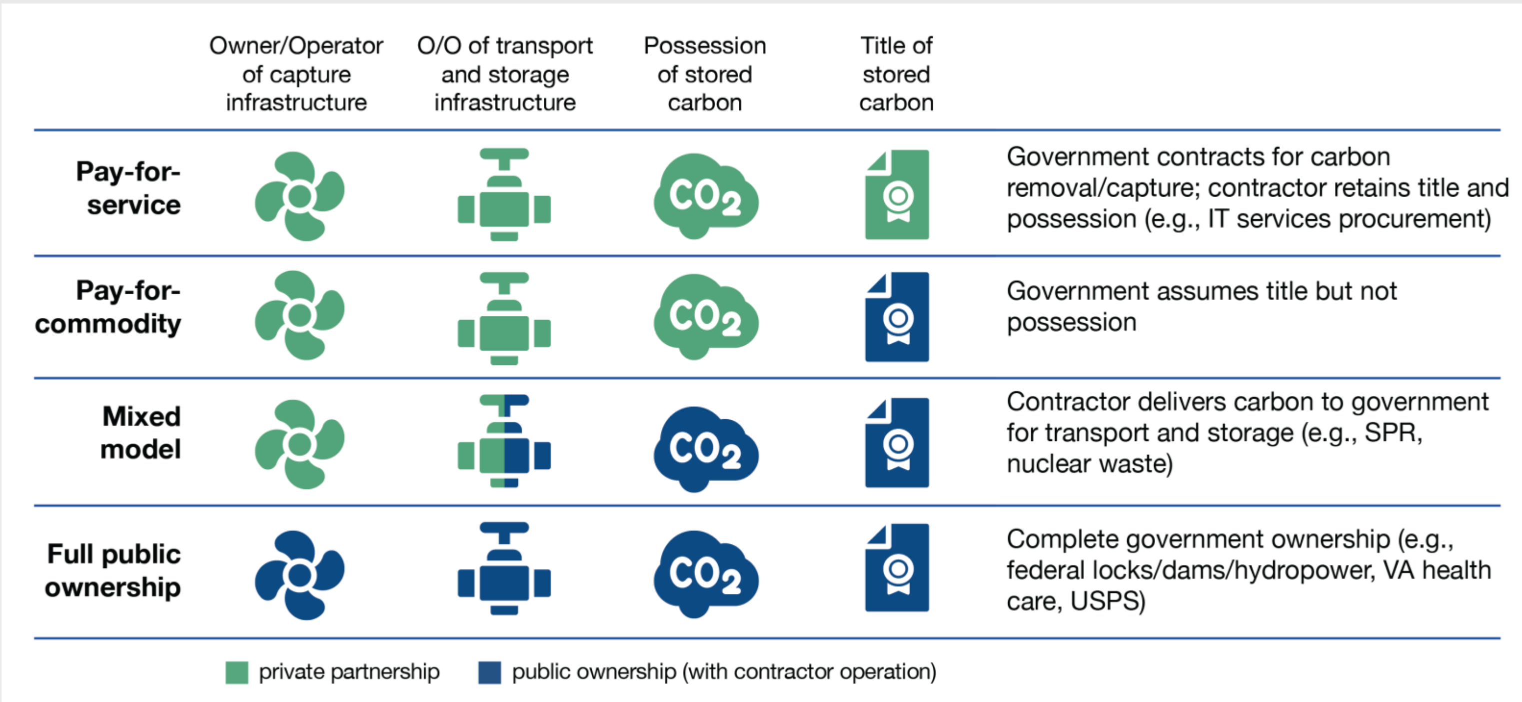
Governments also can play pivotal roles in CCUS development, acting as planners and conveners to promote diverse hubs in their geographic remits.[75] They can form public-private partnerships, contributing in various ways, from infrastructure ownership to research and development (R&D), project management, and community engagement.

All seven hydrogen hubs selected for funding by DOE, for instance, had at least one governmental entity as a project partner—including state agencies (some of which were lead hub conveners); city, county, and tribal governments; quasi-public development corporations; public universities and national laboratories; transit agencies and port authorities; and public utilities.[76,77]

Further, public-private partnership models might offer greater public ownership (Figure 36), including binding community benefits agreements for financial compensation, public authority or utility models for CO_2 transport and storage management, or government entities assuming long-term liability and post-injection site care responsibilities.[4,13,75]

Figure 36

Ownership and operation design options for a large-scale carbon management project



IT = information technology, SPR = Strategic Petroleum Reserve, VA = Department of Veterans Affairs, USPS = U.S. Postal Service. Adapted from: See first figure mention in text for sources.

Community and Workforce Plan. CCUS projects often face objections from environmental justice groups and frontline communities[i] because of concerns over increased air pollution and pipeline safety. Some also perceive CCUS as a "false solution" that could prolong polluting industries, fail to address climate change, exacerbate pollution in disadvantaged communities, and misuse taxpayer funds.[14,78,79,80,81]

It is important for hub development to address these concerns while also striving to maximize local co-benefits such as air pollution reduction and job creation.

DOE's Regional Clean Hydrogen Hubs, Direct Air Capture (DAC) Hubs, and CarbonSAFE programs (see section below on federal programs) require community benefits plans (CBPs) that can provide a good starting point for project developers. These CBPs must detail how applicants are advancing goals including "meaningful community and labor engagement" and investment in domestic workforces and disadvantaged communities.[82] DOE recommends metrics for CBP outcomes and encourages accords such as good neighbor agreements, community benefits agreements, and labor agreements.

Meaningful community engagement entails frontline community participation in decision-making; early, frequent, and continuous contact; not relegating community stakeholders to "sharing concerns" without real authority; transparency and accessibility of participation; and establishment of formal partnership agreements.[13] Additionally, hubs should prioritize harm reduction (e.g., emissions monitoring, leak detection, and safety culture) and community needs beyond decarbonization and economic development (e.g., air pollution, host community compensation).[13]

> **Hubs should prioritize harm reduction (e.g., emissions monitoring, leak detection, and safety culture) and community needs beyond decarbonization and economic development (e.g., air pollution, host community compensation).**

For workforce benefits, CCUS can preserve important supply chains and local economies, particularly in rural areas, while creating new industries and good-paying, long-term jobs (often in skilled trades).[4] Developers should focus on hiring local, displaced, and disadvantaged workers; developing workforce strategies; complying with federal wage and apprenticeship guidelines; and engaging with labor unions.[4,83]

Innovation Plan. Hubs are crucial for demonstrating the scalability of CCUS technologies. An essential aspect of this demonstration is an Innovation Plan, which should involve setting clear success metrics,

[i] "Frontline communities" are the people who are the most vulnerable and are the most adversely impacted by environmental and climate injustices. Similarly, "fenceline communities" are the populations that are immediately adjacent to the source of pollution. "Disadvantaged communities" are groups of people facing the most inequity related to energy, environmental issues, climate change, etc.—and the geographically discrete areas that are home to large populations of these groups.

implementing monitoring and evaluation, ensuring transparent internal and external data-sharing, and creating strategies for incorporating emerging technologies into the hub.[13]

Participation by research institutions and universities can improve the effectiveness of hubs' "learning by doing." Furthermore, a diverse range of hubs, varying in capture technologies, industrial applications, storage methods, and geographic regions, is vital for innovation.[75]

Major U.S. Federal Policies for CCUS Hub Development

Congress has supported CCUS at the federal level since 1997, and it expanded this support through recent legislation, including the BIL and IRA.[5,15,84] Congress highlighted the importance of CCUS hubs in the BIL, affirming that:[15]

> **… carbon capture, removal, and utilization technologies require a backbone system of shared carbon dioxide transport and storage infrastructure to enable large-scale deployment, realize economies of scale, and create an interconnected carbon management market.**

The **Section 45Q carbon oxide sequestration tax credit** is the most important incentive for U.S. CCUS development.[85] The credit rewards taxpayers for every ton of CO_2 stored or used in a project's first 12 years. The IRA extended 45Q through 2032 (for project start); increased the baseline credit value to $85 per t$CO_2$ (rivaling incentives abroad, including EU cap-and-trade allowances); lowered the project size threshold; and added direct pay provisions and incentives for prevailing wages and direct air capture.[86] Figure 37 summarizes the 45Q tax credit.[87]

Federal permitting is both crucial and challenging for T&S infrastructure development. EPA, under its Safe Drinking Water Act authority, permits onshore CO_2 storage through its Underground Injection Control program.

Although EPA has delegated regulatory control—known as "primacy"—for Class II (EOR) wells to 49 states, territories, and tribes, only North Dakota and Wyoming have received such authority for Class VI (dedicated geologic storage) wells as of October 2023. Louisiana, Texas, and West Virginia have also begun the process.[48] The slow pace of Class VI permit issuance and primacy approval causes delays and uncertainty for developers.[14]

The BIL granted the U.S. Department of the Interior authority over offshore CO_2 storage, but regulatory development (beginning with the Gulf of Mexico) has been delayed.[88,89]

Figure 37

45Q tax credit levels for projects beginning construction during 2023-2032 following IRA modifications

Minimum size of eligible carbon capture plant by type (tCO_2/yr)		Relevant level of tax credit from 2023-2026 ($USD/$tCO_2$)			
		Dedicated geological storage **with** prevailing wage and apprenticeship requirements	Dedicated geological storage without prevailing wage and apprenticeship requirements	Storage via EOR/utilization **with** prevailing wage and apprenticeship requirements	Storage via EOR/utilization without prevailing wage and apprenticeship requirements
Power plant	18,750*	$85	$17	$60	$12
Other industrial facility	12,500	$85	$17	$60	$12
Direct air capture	1,000	$180	$36	$130	$26
		Indexed to inflation after 2026			

**and capture capacity not less than 75% baseline emissions*

The IRA modified and expanded qualified facilities and credit levels for the Section 45Q tax credit. The modifications included incentives for prevailing wage and apprenticeship requirements. Adapted from: See first figure mention in text for sources.

Other federal entities, including the U.S. Department of Transportation and the Council on Environmental Quality (CEQ), play roles in areas such as pipeline safety and environmental justice.[23] Other regulatory power—such as pipeline siting and pore space ownership—rests mostly with states. A lack of CCUS-specific regulation or variation therein creates challenges for developers, especially with interstate projects.[14]

The **Carbon Storage Assurance Facility Enterprise (CarbonSAFE) initiative** is DOE's demonstration program for regional CCUS development. The goal of CarbonSAFE is to build on DOE's previous Regional Carbon Sequestration Partnerships program and guide commercial-scale CCUS projects from pre-feasibility studies through construction.[90]

The BIL granted the program $2.5 billion in additional funding; in 2023, DOE awarded nearly $700 million of that amount, including funding 16 Phase III (site characterization, planning, and permitting) projects (Figure 38), many of which are described as "hubs."[91,92,93,94]

Awarded projects cover a range of potential industrial applications, including ethanol, cement, pulp/paper, and mining. DOE has made the remaining BIL funds available for projects through Phase IV of CarbonSAFE, so future awards could include upfront deployment funding.[95] Alongside CarbonSAFE, DOE also awarded $9 million from BIL funds for three studies examining potential regional CO_2 transport networks (Figure 38).[92]

The BIL also funded DOE initiatives for **Direct Air Capture Hubs and Regional Clean Hydrogen Hubs**. Both natural gas-derived "blue" hydrogen and DAC require carbon storage. Industrial CCUS projects could join in these hubs, leverage their T&S networks, or glean strategies and best practices for hub development. Both programs have made their initial awards, shown in Figure 38. Blue hydrogen hubs in particular could benefit from co-location with other industrial CCUS projects, which could share resources and risks for CO_2 infrastructure development and also serve as potential hydrogen consumers.

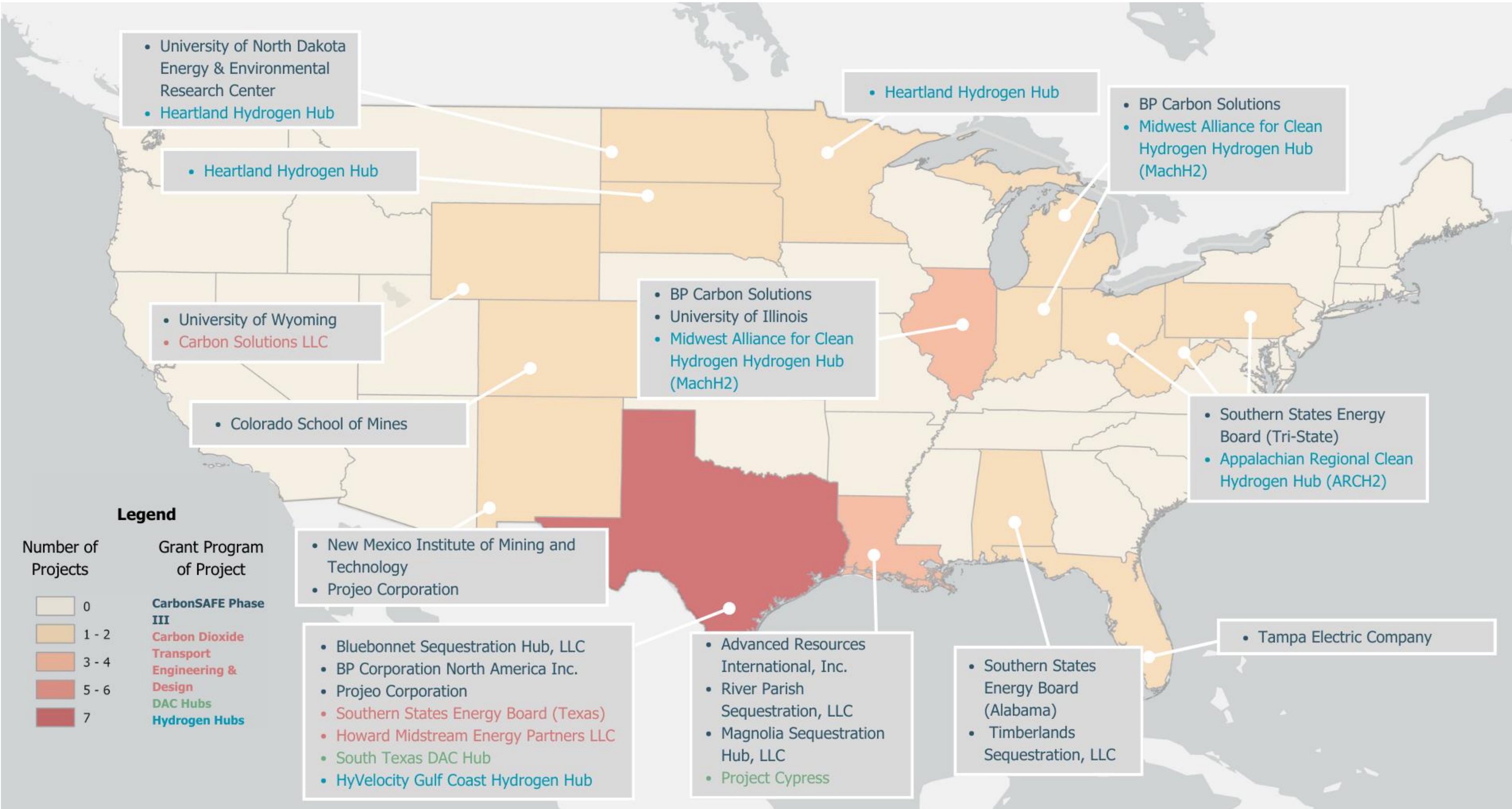
The **Carbon Dioxide Transportation Infrastructure Finance and Innovation (CIFIA)**, authorized in the BIL and expanded in the IRA, is a financing program modeled on similar programs for water and surface transportation infrastructure. CIFIA is specifically intended to help large, common-carrier CO_2 transport projects—including for hubs—overcome barriers that can make access to private capital difficult.[96,97] As of October 2023, DOE had yet to issue any commitments for CIFIA projects.[98]

The IRA, BIL, and other recent laws[j] provided **other potential sources of DOE funding** for industrial CCUS hubs. Funding for FOAK and other early technology demonstrations (e.g., Carbon Capture Large-Scale Pilot Programs, Carbon Capture Demonstration Projects Program, Industrial Demonstrations Program, Title XVII loan guarantees) can facilitate CCUS deployment at small-to-midsize units. Other funding could come from R&D programs at the Office of Fossil Energy and Carbon Management, the Section 48C qualifying advanced energy project tax credit (jointly administered by DOE and the Treasury Department), and demand-side mechanisms (e.g., the Carbon Utilization Program).[99,100]

[j] Including the USE IT Act and Energy Act of 2020 (both passed as part of the Consolidated Appropriations Act, 2021) and the Chips and Science Act.

Figure 38

DOE-announced hubs and related projects funded by the Bipartisan Infrastructure Law, by state



The Bipartisan Infrastructure Law provided funding for several carbon management and hydrogen programs at DOE that are focused on creating shared infrastructure and technology demonstration. These programs can provide a foundation for CCUS hub development for industrial applications. Source: See figure first mention in text for source.

5. Global Case Studies of CCUS Hub Development

There were 392 carbon capture and storage facilities in various stages of development across the globe in 2023, with the potential to capture 361 $MtCO_2$ per year.[101]

This figure, which includes 41 operational facilities, represents a 102% increase over the previous year, and CCUS development continues to accelerate. Within this broader development landscape, hubs are being considered across five continents: Africa, Asia, Europe, North America, and Oceania.[101]

This section explores five case studies of hubs from Europe and Canada that are already under development or in operation; these projects can provide lessons for CCUS development in the United States.

> **There were 392 carbon capture and storage facilities in various stages of development across the globe in 2023, with the potential to capture 361 $MtCO_2$ per year. This figure, which includes 41 operational facilities, represents a 102% increase over the previous year.**

The United Kingdom's East Coast Cluster and HyNet North West are two hubs under development that were selected as part of the U.K. government's Track-1 CCUS cluster sequencing strategy. Track-1 targets mid-2020s deployment, and Track-2 targets 2027 deployment.[102] The East Coast Cluster merges two CCUS hub projects—Net Zero Teesside (NZT) and Zero Carbon Humber (ZCH)—that share pipeline infrastructure transporting CO_2 to an offshore storage site.[102] NZT and ZCH are regions consisting of industrial clusters with companies in the power generation, hydrogen, and waste processing industries. The Northern Endurance Partnership (NEP)—a joint venture between BP, Equinor, and Total Energies—is developing the pipeline infrastructure for the project.

The HyNet hub is under development in northwest England/North Wales and is a hybrid hydrogen transport and CCUS project. The hub developer is Progressive Energy, and the pipeline developer is Eni UK. Companies supplying CO_2 for the hub are in the fertilizer, waste, and cement industries.[103] Both new-build pipelines and repurposed natural gas underground pipes will transport CO_2 into nearly empty offshore gas fields.[104]

Norway's Longship and Northern Lights are two facets of a geographically distributed carbon capture and storage hub. Longship will capture CO_2 from industrial sources: a cement factory in Brevik and a waste incineration facility in Oslo.[105] Gassnova, a state-owned enterprise, is the hub developer and coordinating body of the project. Gassnova ensures that the projects are developed according to the state's objectives, that the industrial partners are coordinated with one another, and that any regulatory issues the project encounters are resolved.[106] Northern Lights is the transportation and storage portion of the project and will transport liquid CO_2 from capture facilities in multiple countries to a terminal in Norway via ships. From there, CO_2 will be pumped through pipelines to a reservoir beneath the sea bottom. Equinor, Shell, and Total Energies are pipeline developers.

Denmark's Norne Carbon Storage Hub will consist of two onshore CO_2 storage facility sites in Denmark at the Port of Aalborg and the Port of Kalundborg. CO_2 will be transported to the storage facilities via pipelines and ships. Fidelis New Energy, Ross Energy, and Gas Storage Denmark are the hub developers. Companies in the power, cement, and steel sectors will supply CO_2 for storage.[107]

Canada's Alberta Carbon Trunk Line is a pipeline that carries CO_2 captured from the Sturgeon Refinery and the Nutrien Redwater fertilizer plant to EOR projects in central Alberta in Canada. The CO_2 is stored underground in repurposed oil reservoirs. Enhance Energy is the developer for the storage site, and Wolf Midstream is the developer for the pipeline.[108]

Table 22 summarizes the global case studies of CCUS hub development and includes further information on the projects such as capture sources, governance structure, and funding arrangements.

Key Takeaways from Global Case Studies

Most of the profiled CCUS hub projects received upfront government funding while being developed and owned by private companies. In some cases, projects may be partially government-owned, such as Norway's Longship project, or entirely privately owned with no government funding, such as Denmark's Norne project. These hubs are largely being developed intentionally as hubs, rather than emerging organically from existing industrial clusters.

CCUS projects and storage facilities are typically located in preexisting industrial hubs and oil or gas reservoirs, while transportation facilities are newly built. Many of the companies implementing CCUS projects, and therefore providing the CO_2 for storage, tend to be existing players in high-emitting sectors such as oil refineries, cement, waste processing, and chemicals manufacturing. However, a natural gas power plant is being built in the U.K.'s East Coast Cluster in Teesside to connect to the storage hub. Transportation infrastructure can consist of any combination of ships transporting liquified CO_2 and underground pipelines. The U.K. HyNet hub is using repurposed natural gas pipelines in addition to new-build pipelines.

CCUS hubs can be localized or geographically distributed. Some CCUS hubs, such as the U.K.'s East Coast Cluster, consist of clusters of capture projects located close to one another and connected to a storage site by pipeline infrastructure. In other cases, such as Norway's largely state-owned Longship and Northern Lights, the projects can be farther apart from one another—including across national borders—with the CO_2 transported separately to the storage site in ships.

A rise in the carbon price in the EU's Emissions Trading Scheme—as well as an expansion to other emitting sectors—is driving demand for CCUS in European countries. In addition to upfront government cost sharing, CCUS projects in the countries profiled in the global case studies are incentivized by carbon trading or carbon pricing mechanisms. CCUS deployment in the United States, by comparison, is primarily fostered by tax incentives at the federal and state levels.

National initiatives to build CCUS hubs are integral to broader national climate strategies. The U.K., Denmark, and Canada, in particular, include CCUS deployment in their national strategies to reduce carbon emissions, and the U.K. and Canada have carbon capture targets.

Table 22
Global case studies of CCUS hub development

Project	East Coast Cluster (Net Zero Teesside and Zero Carbon Humber)	HyNet North West	Longship/Northern Lights	Norne Carbon Storage Hub	Alberta Carbon Trunk Line
Location	United Kingdom	United Kingdom	Norway	Denmark	Canada
Status	Teesside in front-end engineering and design (FEED); Humber in pre-FEED[102]	Pre-construction phase; final investment decision expected in 2024[109]	Under construction[110]	Under construction[107]	Completed/in operation
Operation date	2027[102]	2027[109]	2024[110]	2027[111]	2020[112]
Transport type	Pipeline[102]	Pipeline[109]	Ships and pipeline[110]	Ships and pipeline[107]	Pipeline[108]
Storage type	Offshore saline aquifer[102]	Offshore depleted gas fields[109]	Temporary storage facility before being piped to a saline aquifer[110]	Onshore natural caprock formation[113]	Onshore depleted oil reservoirs[108]
Storage capacity	450 $MtCO_2$[102]	10 $MtCO_2$ per year[109]	Over 5 $MtCO_2$ per year[110]	Over 20 $MtCO_2$ per year by 2030[114]	14.6 $MtCO_2$ per year[108]
CO_2 emitter industries	Electricity generation, hydrogen, bioenergy, waste-to-energy, oil refinery, fertilizer[115]	Hydrogen, cement, waste management, fertilizer[116]	Cement, waste-to-energy, fertilizer[117]	Biomass power, heating plants, cement, steel[113]	Fertilizer, oil refining, chemicals manufacturing[112]
Project ownership structure	Pipeline and storage to be developed by the Northern Endurance Partnership (NEP), consisting of BP (as lead operator),	Progressive Energy is the hub developer; Eni UK is the pipeline and storage developer[103]	Gassnova–a state-owned enterprise–is the hub developer and coordinating body of the project[106] Pipeline and storage are being developed by	Storage sites are being developed by Fidelis New Energy, Ross Energy, Gas Storage Denmark, and Ramboll[107]	Pipeline is constructed, owned, and operated by Wolf Midstream; storage/EOR site is owned and operated by Enhance Energy[108]

	Equinor, and TotalEnergies[102]		Equinor, Shell, and TotalEnergies Northern Lights has commercial agreements with international customers of its carbon storage services[110]		
Liability of CO_2 storage	Operator; liability can be transferred after 20 years if conditions are met[118]	Operator; liability can be transferred after 20 years if conditions are met[118]	Northern Lights DA will share liability among partners[4]	TBD[119]	Operator; liability can be transferred to the government after closure; operator required to contribute to stewardship fund[4]
Government incentives for CCUS: capital costs	50% of capital costs for industrial carbon capture projects are funded by the CCUS Infrastructure Fund (CIF)[120] T&S network may receive partial government funding from the CIF but is otherwise similarly funded to other regulated utilities, with revenue supplemented by user payments[121] Funding for power-sector carbon capture projects is similar to a contract-for-difference (CfD) structure[122]		The government will cover 75% of the capital costs of the capture facilities and 80% of the transportation and storage projects[123]	Energy Technology Development and Demonstration Program: technology-neutral funding for demonstration and deployment public-private projects in the energy sector; funding varies from 25% to 100%[124,125]	Federal government covered capital costs via Canada Pension Plan Investment Board, Federal EcoETI and Clean Energy Fund Programs[126] Province of Alberta's Carbon Capture and Storage Funding Act covers up to 75% of the total incremental cost of CCUS projects and up to 40% of project costs pre-completion[127]
Government incentives for CCUS: operational costs/other	CCUS Infrastructure Fund (CIF) for cluster sequencing program[128] UK CCUS Innovation Programme[128] Net Zero Hydrogen Fund[128] Fund for early CCUS deployment[129] Emission Trading Scheme (UK ETS)[130]		R&D funding and direct subsidies for CCUS[132] EU ETS	Subsidy funds for CCUS deployment and tenders: NECCS Fund (subsidy per $MtCO_2$ captured and stored between 2025-2032); CCUS Fund (subsidy per $MtCO_2$ captured and stored between	Fund for deploying decarbonization technologies, including CCUS[135] Canada Growth Fund and Energy Innovation Fund for CCUS R&D[136]

	Target to capture 20-30 $MtCO_2$/yr by 2030[129] National emissions reduction target that includes CCUS[131]			2025-2048, uses CfD to adjust for CO_2 allowance price fluctuations, targets consortia of smaller CO_2 sources)[133] Funds to the Geological Survey of Denmark and Greenland to investigate potential storage sites, establish six regional clusters[134] EU ETS INNO-CCUS/EU Innovation Fund: broader innovation funds that include CCUS[133]	Target to capture 15 $MtCO_2$/yr by 2030[129] Announced federal CCUS investment tax credit[136] Federal clean fuel regulations[136] Alberta's carbon pricing system[136] Alberta Carbon Capture and Storage Funding Act covers up to 75% of the total incremental project costs and up to 40% of project costs pre-completion[127]
Stakeholder consultation strategy	Public consultation; evaluation by independent panel of inspectors[137]	Public consultation[138]	Public consultation; meetings with municipal authorities [113,139]	Public consultation[113]	Public consultation; MRV program[140]

6. Conclusion and Next Steps: What Is Needed to Advance CCUS Hubs for Small-to-Midsize Industrial Emitters in the United States?

The initial screening analysis presented in this report illustrates the technical potential for the formation of regional CCUS hubs in the United States for small and midsize industrial emitters.

CCUS is a central technology option for industrial decarbonization and is vital to U.S. efforts to reach net zero by midcentury. The formation of industrial CCUS hubs can allow for more efficient deployment by facilitating economies of scale and effort, pooling resources and risks, and bringing a variety of stakeholders into the development process.

These hubs can be built around existing clusters of small and midsize emitters, not just the large facilities that could more easily pursue carbon capture without the benefit of shared infrastructure. Other clean energy hubs in the United States and CCUS hubs around the world can provide examples of how to develop these hubs using varying business models and governance structures, while navigating the pitfalls of infrastructure deployment and maximizing innovation, workforce, and community benefits.

The formation of industrial CCUS hubs can allow for more efficient deployment by facilitating economies of scale and effort, pooling resources and risks, and bringing a variety of stakeholders into the development process.

Recommendations for Federal and State Policymakers

Recent action in Congress and the administration, such as the BIL and IRA, have set the table for expanded CCUS deployment, including the potential to apply the hub concept to large clusters of small-to-midsize industrial emitters.

There are several steps federal and state policymakers can consider to jump-start an initiative for CCUS hubs for small and midsize industrial producers. For example, the following recommendations are drawn from the EFI Foundation's existing work; further study of hubs for smaller emitters could expand on these recommendations and suggest new ones.

Congress should consider ways to make 45Q easier to monetize, and expand access to the tax credit and other potential incentives. Despite the improvements to the 45Q tax credit in the IRA, it still has limitations that present areas for improvement or expansion. As proposed in the recent Energy Futures Finance Forum (EF^3) report, Congress and the Treasury Department could expand the options for deploying capital by targeting monetizability of tax credits (e.g., the implementation and expansion of direct pay and transferability options).[14]

Section 45Q also could be amended to reward new technologies for capture and long-term storage (e.g., biomass pyrolysis, mineralization), as proposed in the EFI Foundation's *Taking Root*.[141]

New or expanded state incentives—such as clean energy standards, low-carbon fuel standards, and government procurement of low-carbon materials—could also accelerate CCUS deployment.

DOE should consider ways to better target its existing funding sources to augment the 45Q tax credit to focus on CCUS hub formation. Previous research by the EFI Foundation has shown that the 45Q tax credit alone may be insufficient to cover the costs of early deployments of CCUS, including in important industrial subsectors.[14] At the same time, examples both stateside and abroad have shown how more expansive incentives (e.g., carbon pricing in the EU, U.K., and Canada) and upfront cost sharing by national governments can spur hub development.

The Labor Energy Partnership's *Building to Net-Zero* report suggested that DOE should use existing authority (CarbonSAFE, which has now been supplemented by CIFIA) to provide funding and financing support for the planning of CCUS hubs.[k,4] Leveraging CarbonSAFE for hub development could include advancement of promising projects to Phase IV (permitting and construction support); extending funding support for hub implementation planning (e.g., governance, financing); pre-feasibility studies of small-to-midsize capture project deployments within the hub; and seed funding for hub analysis (e.g., recruiting small-to-midsize emitters that could help fill out the storage capacity of a potential hub). DOE is already taking steps toward the latter through a new initiative, announced in December 2023, to fund the establishment of regional carbon storage partnerships that will provide technical assistance to CCUS developers.[142]

The EF^3 report on making CCUS more investable recommended expanded use of DOE loan guarantees to allow financing of multiple CCUS deployment projects for a particular industrial application.[14] This recommendation would be particularly beneficial for CCUS technology applications for small-to-midsize industrial emitters, where multiple deployments can build a strong experience base and enable the establishment of a robust supply chain.

New technology demonstration could also potentially be achieved through other programs funded in the BIL, such as the Carbon Capture Demonstration Projects Program. Coordination among DOE's programs for different carbon management segments (capture,

[k] The EFI Foundation's previous research suggested that $3.2 billion in additional funding might be needed to support three to five early carbon capture projects in each of six key industries. Hubs that include development of shared transport, utilization, and storage infrastructure could require additional funding beyond that.

transport, utilization, storage) could assist in providing the necessary start-up funding for FOAK hubs that include a diversity of industrial and other facilities.

The BIL's hydrogen and DAC hubs could also incorporate industrial CCUS projects into their shared infrastructure, including small-to-midsize emitters.

The EF[3] report also pointed out the importance of being able to combine federal cost sharing and loan guarantees to leverage limited resources and improve project outcomes. DOE could expand eligibility for existing programs by allowing financing through the Title XVII program for projects receiving grant funding.[14]

Federal and state governments should consider approaches for streamlining permitting while facilitating meaningful community engagement. The EFI Foundation's previous work has suggested several steps that state and federal policymakers could take to accelerate siting and permitting for CCUS.

States could develop a coordinating body for CCUS regulation; state environmental regulators could require analysis and public disclosure of capture project effects on air pollutants; Congress could grant a federal agency power over interstate permitting for transport and storage infrastructure; EPA and Congress could work to bring more experts into the Underground Injection Control program to accelerate permitting and primacy applications.[4,14]

These efforts could be pursued through pilot projects that focus on small and midsize industrial CCUS hub formation.

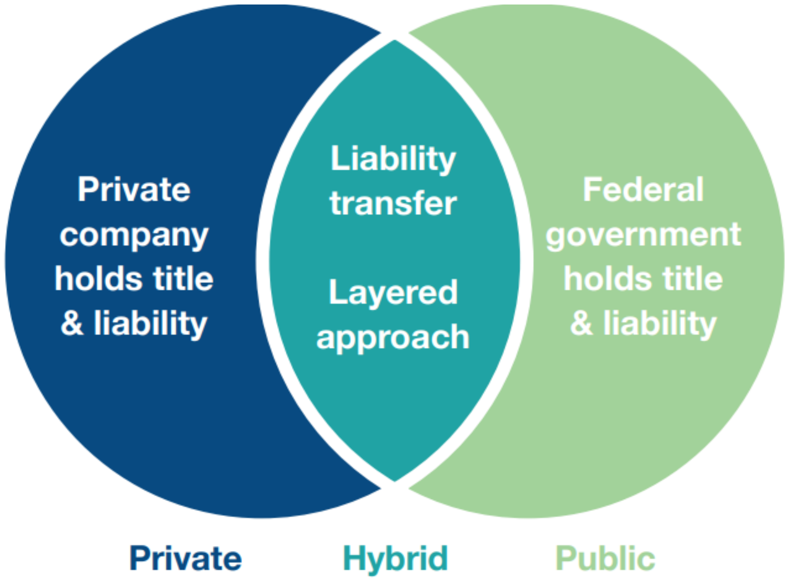
While the authority for delegation and permitting resides with the EPA, DOE could play an advisory role as well. DOE could provide technical support to both states and developers navigating CCUS permitting regulation, serving in a coordination and ombudsman role.

One venue for this coordination could be the new regional CCUS Permitting Task Forces, authorized in the USE IT Act and formally established in 2023 through a memorandum of understanding between DOE and CEQ.[16,17] These two task forces, each of which will cover a yet-to-be-determined geographic region, are charged with improving regional coordination and addressing gaps in federal and state regulation; they could play a meaningful role in facilitating permitting for regional CCUS hub formation.[143]

Congress should explore a "utility model" for CO_2 transport and storage or other forms of public-private partnership. CCUS hubs could be opportunities to explore new forms of public-private collaboration that maximize benefits for communities and obviate concerns about liability, eminent domain, etc.

The EFI Foundation's previous reports—including the *CO2-Secure* report on CDR—have proposed several potential forms this could take, including public infrastructure ownership (e.g., a "utility model" for CO_2 T&S) and/or government backstops for long-term liability (Figure 39).[4,14,75]

Figure 39
Liability for stored CO_2



Liability for stored CO_2 can be assumed by the public sector, the private sector, or in a hybrid, "layered" approach in which the costs for an incident are borne by the private operator up to a certain dollar amount. After this threshold is reached, additional costs are borne by both the private entity and the government. Source: See first figure mention in text for sources

Recommendations for Industry

Initiate CCUS hub development within state boundaries. The complexity of CCUS hub development makes it difficult to build infrastructure that crosses state lines. As the experience of early hub development has shown, longer pipeline projects increase the risk of obstacles that can torpedo a project.[144] The four case studies presented in this report show that some states have a sufficient cluster of small-to-midsize emitters and CO_2 storage potential to support intrastate CCUS hubs as the initial phase of interstate hub development.

Large-scale CCUS demonstration and deployment projects could serve as anchor tenants for formation of CCUS hubs for small-to-midsize industrial emitters. Industrial CCUS efforts often focus on large-scale deployment at very large facilities (e.g., petroleum refineries or petrochemical complexes) or clusters of a single industry (e.g., ethanol facilities). There also are a number of one-off, single demonstration projects (e.g., steel, cement) that are in planning and development. These projects can serve as anchor tenants for small and midsize emitters to join to form regional hubs.

Opportunities for Further Analysis

This screening analysis has identified regional clusters of small-to-midsize industrial emitters that could form the basis of regional CCUS hubs. This screening, however, focused solely on technical factors. Additional analysis would be needed in several dimensions to fully understand local hub development potential, including:

- Techno-economic analysis to further refine the potential universe of participants in a hub and to develop initial estimates of the economics of hub development.
- More detailed geospatial analysis to begin to assess the extent of CO_2 transport and storage infrastructure, including possible repurposing of existing infrastructure or use of existing infrastructure rights of way.
- Further evaluation of geologic storage potential and sites within the identified cluster regions.
- Convening of interested parties within each region, including facility owners, policymakers, vendors and stakeholder groups to begin discussions of possible hub development prospects.

Finally, a similar technical characterization analysis could be conducted for other regions among the 10 initially identified.

Appendix

Table A 1
Louisiana regional cluster
Capture targets by sector and state

	# Units			Annual emissions $MtCO_2$		
Sector	**Louisiana**	**Mississippi**	**Total**	**Louisiana**	**Mississippi**	**Total**
Ammonia	5	-	**5**	1.1	-	**1.1**
Chemicals	15	2	**17**	1.2	0.4	**1.6**
Misc. industry	9	-	**9**	0.9	-	**0.9**
Pet. & NG systems	31	1	**32**	1.4	< 0.1	**1.4**
Petrochemicals	25	-	**25**	4.0	-	**4.0**
Pulp and paper	1	-	**1**	0.2	-	**0.2**
Refineries	18	-	**18**	2.9	-	**2.9**
Total	**104**	**3**	**107**		**0.4**	**12.0**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table A 2
Houston regional cluster
Capture targets by sector and state

	# Units			Annual emissions $MtCO_2$		
Sector	**Texas**	**Louisiana**	**Total**	**Texas**	**Louisiana**	**Total**
Chemicals	30	8	**38**	2.7	0.8	**3.5**
Misc. industry	12	-	**12**	0.6	-	**0.6**
Pet. & NG systems	67	41	**108**	5.1	7.2	**12.2**
Petrochemicals	58	3	**61**	9.2	0.5	**9.7**
Pulp and paper	1	1	**2**	0.1	0.1	**0.2**
Refineries	73	15	**88**	7.3	3.1	**10.3**
Steel	2	-	**2**	0.1	-	**0.1**
Total	**243**	**68**	**311**	**25.0**	**11.6**	**36.6**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table A 3

Great Lakes regional cluster

Capture targets by sector and state

	# Units					Annual emissions $MtCO_2$				
Sector	**Illinois**	**Indiana**	**Michigan**	**Ohio**	**Total**	**Illinois**	**Indiana**	**Michigan**	**Ohio**	**Total**
Ammonia	-	-	-	1	**1**	-	-	-	0.5	**0.5**
Cement	-	-	-	3	**3**	-	-	-	0.6	**0.6**
Chemicals	8	2	1	2	**13**	0.4	0.1	0.1	0.1	**0.6**
Ethanol	-	11	1	4	**16**	-	1.4	0.2	0.6	**2.2**
Misc. industry	13	38	3	18	**72**	0.7	1.5	0.1	1.2	**3.5**
Pet. & NG systems	1	4	1	1	**7**	0.3	0.2	< 0.1	< 0.1	**0.5**
Petrochemicals	2	1	-	1	**4**	0.3	0.1	-	< 0.1	**0.4**
Pulp and paper	-	2	3	1	**6**	-	0.2	0.3	0.1	**0.5**
Refineries	11	10	-	14	**35**	1.2	0.7	-	1.3	**3.2**
Steel	3	14	-	4	**21**	0.1	2.6	-	0.2	**2.9**
Waste	4	7	-	-	**11**	0.1	0.1	-	-	**0.2**
Total	**42**	**89**	**9**	**49**	**189**	**3.0**	**6.9**	**0.7**	**4.5**	**15.0**

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

Table A 4
Ohio River Valley regional cluster
Capture targets by sector and state

	# Units				Annual emissions $MtCO_2$			
Sector	**Ohio**	**Pennsylvania**	**West Virginia**	**Total**	**Ohio**	**Pennsylvania**	**West Virginia**	**Total**
Chemicals	6	2		8	0.6	0.1	-	0.7
Misc. industry	14	7	2	23	0.5	0.4	0.1	1.1
Pet. & NG systems	30	14	18	62	1.8	0.7	1.1	3.5
Petrochemicals	1	3		4	0.1	0.1	-	0.2
Refineries	1		1	2	0.3	-	0.1	0.4
Steel	9	15	1	25	1.1	1.2	0.1	2.3
Waste	2	1		3	< 0.1	< 0.1	-	0.1
Total	**63**	**42**	**22**	**127**	4.5	2.5	1.4	8.3

Source: EPA GHGRP (2022), EPA Envirofacts (2023), EIA (2021), and analysis by Horizon Climate Group.

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