CARBON CAPTURE AND STORAGE OPPORTUNITIES IN THE MID-ATLANTIC

A TECHNICAL REPORT

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ABOUT THE GREAT PLAINS INSTITUTE

A nonpartisan, nonprofit organization, the Great Plains Institute (GPI) aims to accelerate the transition to net-zero carbon emissions for the benefit of people, the economy, and the environment. Working across the US, we combine a unique consensus-building approach, expert knowledge, research and analysis, and local action to find and implement lasting solutions. Our work strengthens communities and provides greater economic opportunity through creation of higher-paying jobs, expansion of the nation's industrial base, and greater domestic energy independence while eliminating carbon emissions.

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ABOUT CARBON SOLUTIONS LLC

Carbon Solutions LLC is a low-carbon energy startup using cuttingedge research and development and software and services to address energy challenges, including carbon capture and storage, geothermal energy, wind energy, biofuels, energy storage, and the hydrogen economy. Carbon Solutions aims to accelerate low-carbon energy infrastructure development in the US. The Carbon Solutions business vision is focused on three integrated pillars: research and development that advances low-carbon energy science, software development that generates unique tools and data, and services that apply our research and development and software to address emerging energy challenges for our clients.

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Executive summary

To meet midcentury climate goals, the United States must decarbonize its industrial sector and energy production. Deploying carbon capture equipment and developing carbon dioxide (CO_2) transport infrastructure to carry captured CO_2 emissions to permanent storage locations will play an essential role in economywide decarbonization. The Mid-Atlantic region, composed here of Delaware, Kentucky, Maryland, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia, and the District of Columbia, is a major hub of industry, manufacturing, and energy generation, providing industrial goods and energy to the densely populated northeastern states and to the rest of the United States.[1]

This analysis identified 789 facilities in the Mid-Atlantic that are eligible for the federal 45Q tax credit.[2] Section 45Q provides a tax credit for capturing CO_2 from industrial or power sources and permanently storing the captured CO_2 in a geologic formation or utilizing it for developing products. The 45Q tax credit is a key financial mechanism for the deployment of carbon capture technologies, which can be received when captured CO_2 is stored permanently.

From these facilities, a subset of 286 facilities with CO_2 emissions greater than 100,000 metric tons per year were selected to include in this analysis. This emissions threshold was used since projects with greater emissions reduction potential will likely benefit from economies of scale and are likely the best candidates for retrofitting a facility with carbon capture.

This subset of facilities emits 370.0 million metric tons of CO_2 per year ($MtCO_2$/yr.), of which 304.7 $MtCO_2$/yr. are considered suitable for capture in this study. The 286 facilities with emissions greater than 100,000 metric tons of CO_2 per year (tCO_2/yr.) account for 87 percent of total CO_2 emissions from the Mid-Atlantic region.

This analysis also identified 102 facilities as near-term capture opportunities. These 102 facilities have flue gas streams that allow for efficient capture and enhanced economic conditions for a positive return on investment over a 15-year period, given current technologies and economic incentives. Facilities are also considered near-term opportunities if they provide a critical service with no alternative opportunities for carbon reductions, are deemed economically robust, and have large CO_2 emissions. These near-term opportunities emit a combined 264.4 $MtCO_2$/yr., of which 220.5 $MtCO_2$/yr. is considered capturable.

The SCO_2T^{PRO} geologic storage model, developed by Carbon Solutions, is used to calculate the total storage capacity of onshore and offshore geologic reservoirs and to identify low-cost areas in this region to serve as storage hubs for captured emissions. Reservoirs identified using SCO_2T^{PRO} have an estimated geologic storage potential of 500 billion metric tons of CO_2 using multiple geologic formations, with most of the storage potential in offshore formations.

This analysis also used the *SimCCS*^{PRO} model, a CO_2 transport infrastructure model from Carbon Solutions, to explore the infrastructure required to construct an optimized transport network between capture opportunities and permanent geologic storage.[3] The near-term scenario includes 102 facilities connected to potential saline geologic storage by 4,655 miles of new pipeline infrastructure. The midcentury scenario includes 286 facilities connected to potential saline geologic storage by 6,721 miles of new pipeline infrastructure.

1 Batch, "A *Labored* Mid-Atlantic Region Defined, Not Discovered: Suggestions on the Intersections of Labor and Regional History."

2 26 USC 45Q: Credit for carbon oxide sequestration.

3 Middleton et al., "SimCCS."

Introduction

To limit the global average surface temperature from rising to 1.5°C above pre-industrial levels, carbon dioxide (CO_2) emissions must reach net zero around 2050, according to the Intergovernmental Panel on Climate Change.[4] For the United States to meet its climate targets, a host of technologies must be deployed to decarbonize the industrial and power sectors.[5]

One of these technologies, carbon capture and storage, involves capturing CO_2 at a facility before it is emitted to the atmosphere. The captured CO_2 is then transported to permanent storage locations, typically geologic reservoirs deep in the subsurface. Carbon capture has a long history of deployment in gas processing facilities but in recent years has been employed at ethanol, ammonia, and power facilities. Further advancements in the technology and policy incentives have led to new opportunities in additional industrial sectors discussed in this report.

The Mid-Atlantic region, defined in this report as Delaware, Kentucky, Maryland, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia, and the District of Columbia, offers significant opportunities for decarbonization through carbon capture. This analysis will provide an overview of capture, transport, and storage opportunities in the Mid-Atlantic and offer two scenarios for economywide deployment of carbon capture in the near term and into the midcentury.

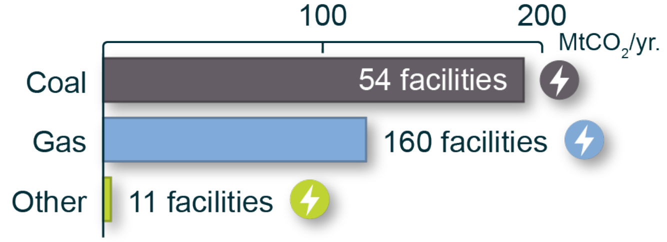
Mid-Atlantic emissions profile

SECTOR EMISSIONS PROFILES

Within the Mid-Atlantic region, 1,081 facilities reported CO_2 emissions to the US Environmental Protection Agency (EPA) Greenhouse Gas Reporting Program (GHGRP) in 2021.[6] Broadly, these facilities can be divided into two groups: electricity generation and industrial facilities. The largest contribution to the total CO_2 emissions in this region is from electricity generators, with a combined 312.9 million metric tons per year ($MtCO_2$/yr.) from coal-, gas-, and other-fired power plants (figure 1).

A variety of industrial sectors are present in the Mid-Atlantic and contribute 114.3 $MtCO_2$/yr. to the Mid-Atlantic region's emissions profile (figure 2). Roughly half of industrial emissions are related to on-site stationary combustion, with the remaining industrial emissions attributed to various processes within each sector. The steel, cement, and petroleum refinery sectors are the highest contributors to the Mid-Atlantic industrial emissions profile, with each sector contributing greater than 15 $MtCO_2$/yr. Facilities in the waste, pulp and paper, gas processing, metals, minerals, and other sectors are often small emitters of CO_2, but as a whole, each sector is a large contributor to the region's total CO_2 emissions.

Figure 1. Power plants in the Mid-Atlantic that reported CO_2 emissions to US EPA GHGRP.



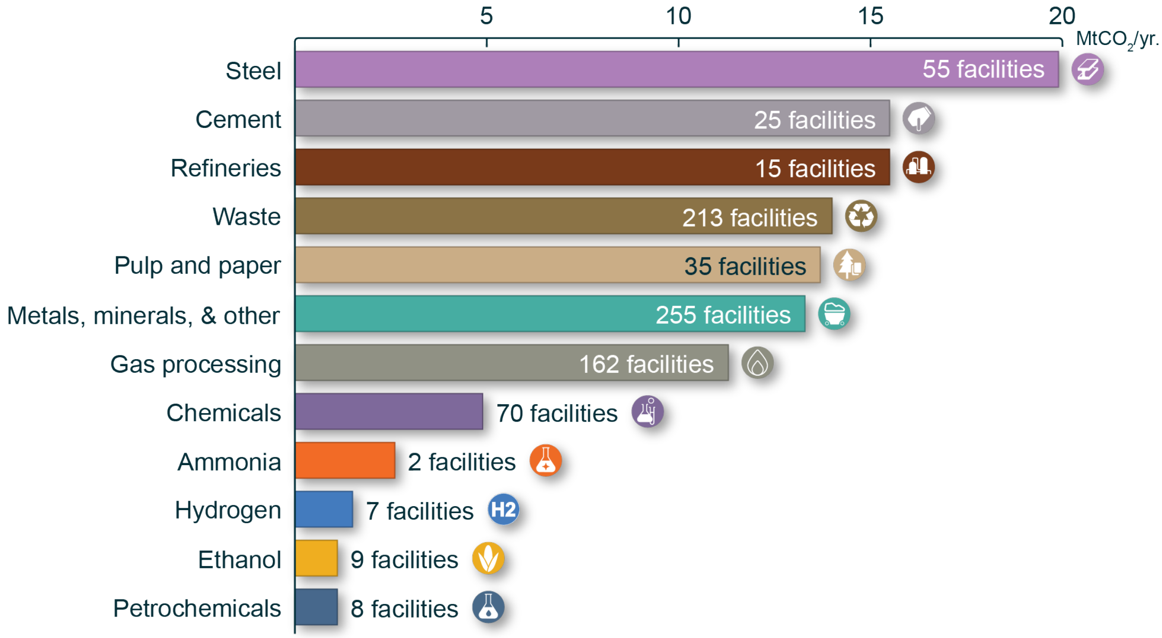
Source: EPA GHGRP, 2021.

4 Lee et al., "Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change."

5 US Department of State, "The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050."

6 US Environmental Protection Agency Office of Atmospheric Protection, "Greenhouse Gas Reporting Program (GHGRP)."

Figure 2. Industrial sources in the Mid-Atlantic that reported CO_2 emissions to US EPA GHGRP.



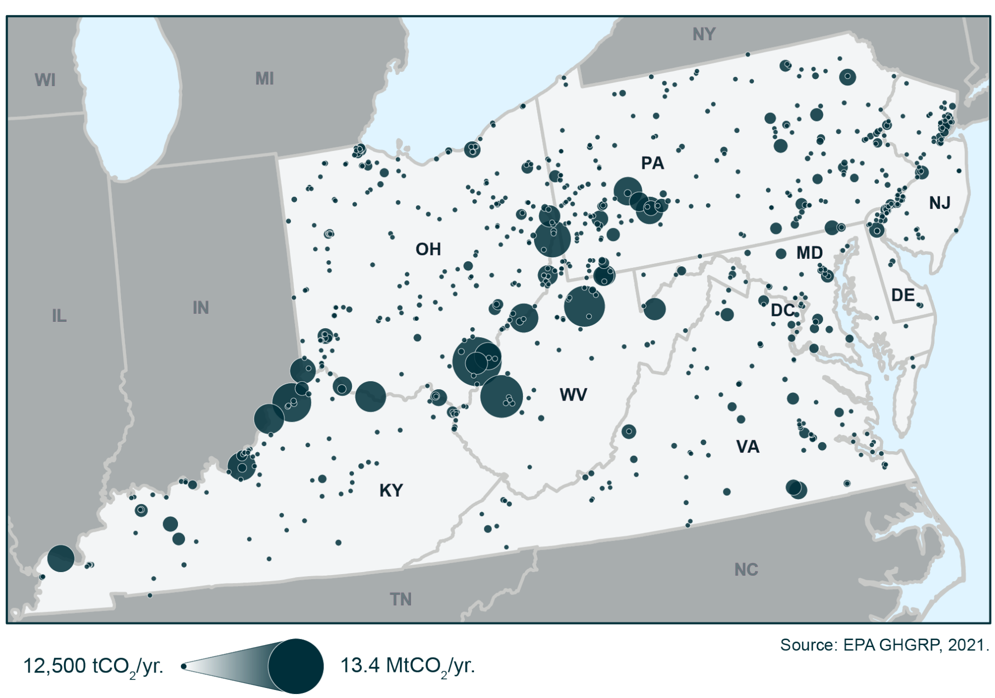
Source: EPA GHGRP, 2021.

Opportunities for carbon capture retrofit

SECTION 45Q TAX CREDIT ELIGIBILITY

The largest federal incentive for carbon capture, utilization, and storage is Section 45Q of the US tax code. First enacted in 2008, Section 45Q is a performance-based tax credit for eligible carbon management projects that securely store CO_2 in geologic formations or beneficially use captured carbon oxides for industrial purposes. The current version of the credit was established under the Inflation Reduction Act of 2022, which reduced the minimum CO_2 emissions thresholds to 18,750 tCO_2/yr. for electricity generating facilities and 12,500 tCO_2/yr. for industrial facilities. The Inflation Reduction Act also increased the value of the credit for point-source capture to \$85 per tCO_2 when stored in a saline geologic formation and \$50 per tCO_2 when stored as part of an enhanced oil recovery operation.[7] This analysis identified 789 facilities within the Mid-Atlantic region that are eligible for the Section 45Q tax credit (figure 3).

Figure 3. Mid-Atlantic facilities eligible for the 45Q tax credit.



Source: EPA GHGRP, 2021.

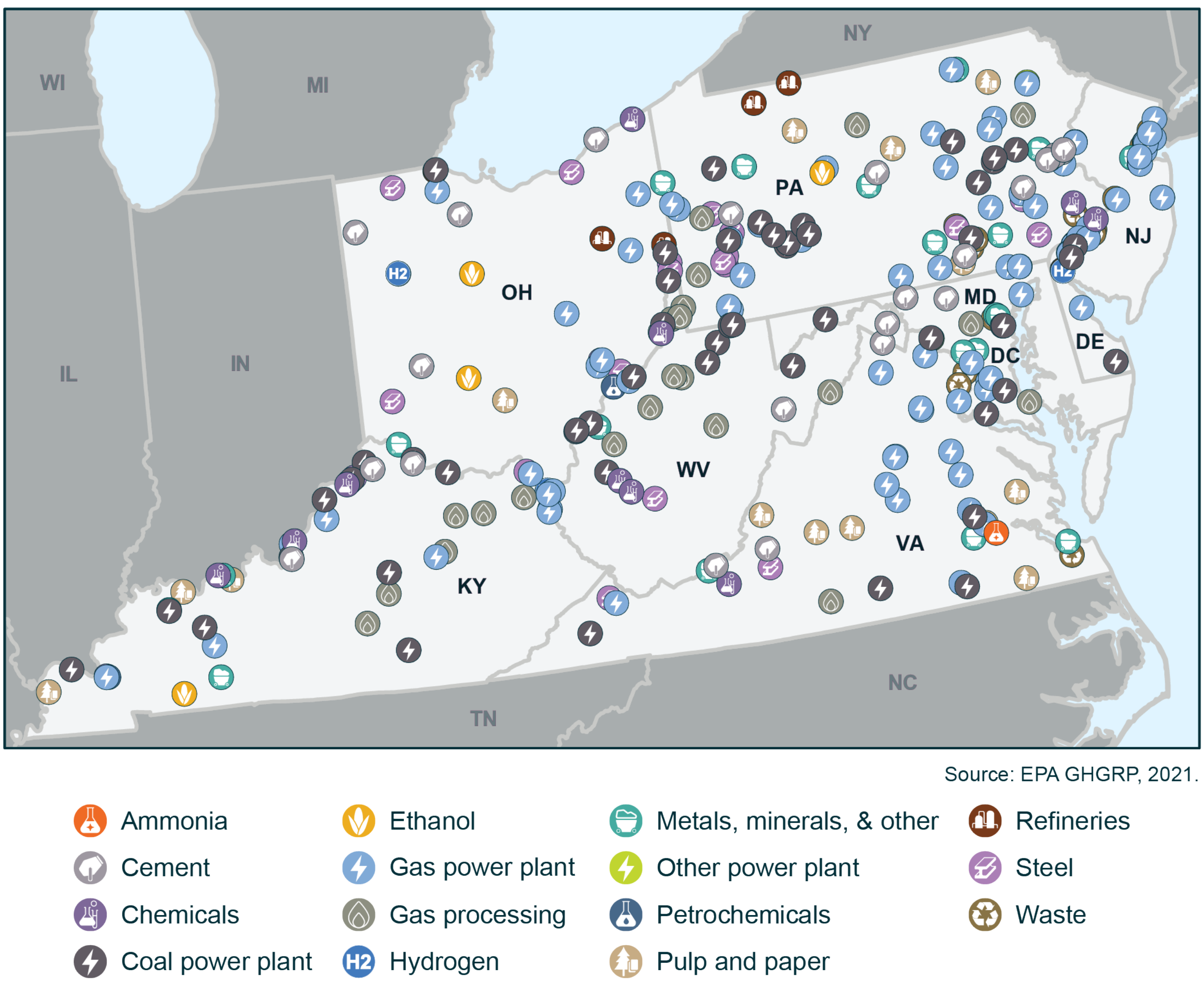
7 26 USC 45Q: Credit for carbon oxide sequestration.

FACILITY ASSESSMENT CONSIDERATIONS

Although many facilities qualify for the 45Q tax credit, larger facilities may be more economical to retrofit, as the cost to capture CO_2 decreases as the quantity of captured CO_2 increases. For this reason, this analysis focused on facilities with emissions greater than 100,000 tCO_2/yr. and industrial sectors where the return on investment for capture retrofit is short (15 years). This subset of facilities includes 286 facilities from all sectors and total emissions of 370.0 $MtCO_2$/yr. (figure 4). Facility emissions are not homogenous, even among facilities in the same sector using similar fuel mixtures. These variations can arise from engineering factors or the presence (or absence) of pollution controls, which can impact the feasibility of carbon capture for a facility. The feasibility of carbon capture is affected by the technical ability to remove CO_2 from a flue gas and the economic conditions for deploying the technology.

Further examination of industrial equipment units with emissions reported to GHGRP is required to determine the quantity of capturable emissions at each facility.[8] Total capturable emissions are adjusted to account for various emissions sources and technological limitations of carbon capture at each facility type to determine the "capturable fraction" of CO_2 emissions for each facility. The capturable fraction of CO_2 emissions is varied for each industry considered in this analysis.

Figure 4. Power plants and industrial facilities in the Mid-Atlantic with CO_2 emissions greater than 100,000 tCO_2/yr.



8 US Environmental Protection Agency Office of Atmospheric Protection, "Greenhouse Gas Reporting Program (GHGRP)."

Power sector

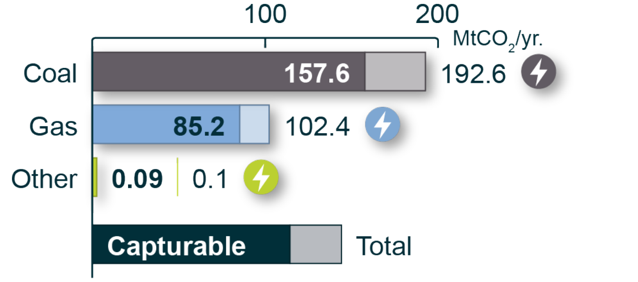
Power generators comprise nearly half of facilities with emissions greater than 100,000 tCO_2/yr. in the region (82 gas-fired, 53 coal-fired, and 1 biomass-fired) and contribute 80 percent of the region's emissions (295.0 $MtCO_2$/yr., figure 5). All emissions from electricity generation are targets for carbon capture and are considered for this study regardless of the fuel type used by the facility.

Industrial sector

Refineries, cement, steel, and pulp and paper have the largest contributions among industrial sectors, while the remaining industrial sectors contribute fewer than 10.0 $MtCO_2$/yr. per sector (figure 6).

Each industrial sector has unique criteria for carbon capture retrofit compatibility and feasibility. Some sectors' exhaust streams allow for the entire facility's emissions to be included in the capture system, while others have only select equipment suitable for capture. The best candidates for near-term retrofit will likely have large volumes of high-purity CO_2 from relatively few sources at the facility, which can reduce the cost of capture and retrofit at a facility. In the long term, all gas-fired units and CO_2-dilute flue gases are feasible for capture, especially with enhanced incentives from the Inflation Reduction Act. The following subsections detail potential capture streams within each sector, including streams from on-site combustion and process emissions particular to the sector described.

Figure 5. Total and capturable emissions from power plants with facility emissions greater than 100,000 tCO_2/yr.

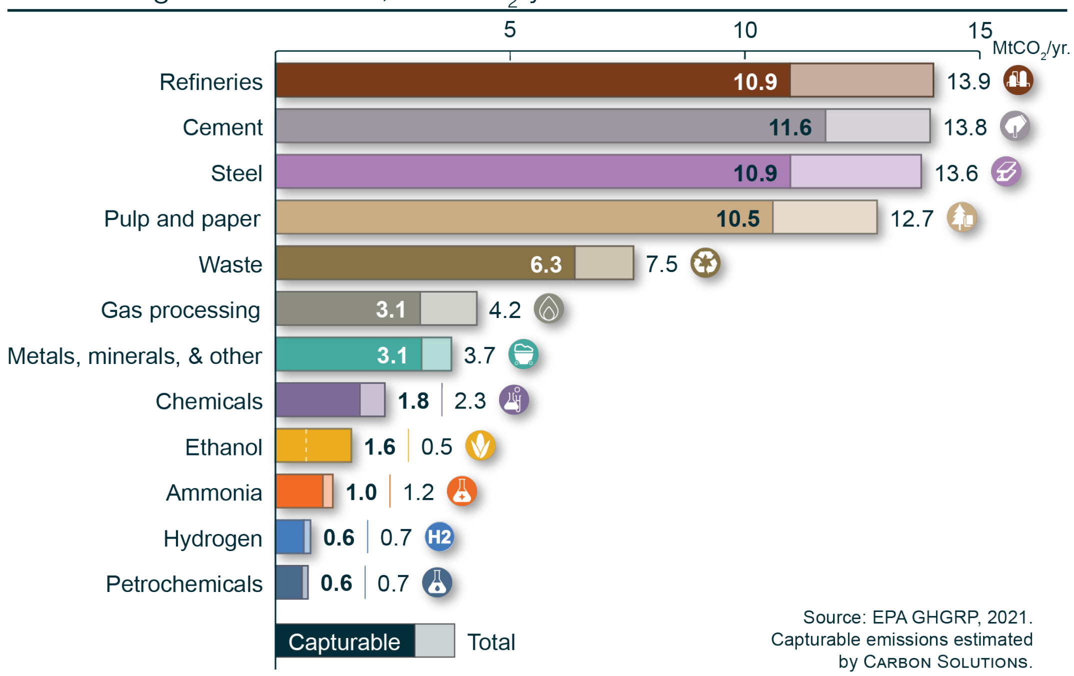


Source: EPA GHGRP, 2021.
Capturable emissions estimated
by Carbon Solutions.

Ammonia

The Mid-Atlantic contains one ammonia facility with facility emissions greater than 100,000 tCO_2/yr., which emits 1.2 $MtCO_2$/yr. The most economical flue gases for capture at ammonia production facilities are from the hydrogen production units. The total capturable quantity of CO_2 from these units is dependent on the placement of the capture unit or units within the facility. For the near term, we assumed retrofit included two capture units within the configuration, raising the capturable fraction to 90 percent. In the long term, all facility CO_2 emissions are viable for capture.

Figure 6. Total and capturable emissions from industrial plants with facility emissions greater than 100,000 tCO_2/yr.



Note: Capturable emissions are greater than total emissions for ethanol as the total emissions here refers to the total emissions reported to GHGRP, which does not include the fermentation process, a capturable stream at ethanol facilities.

Source: EPA GHGRP, 2021.
Capturable emissions estimated
by Carbon Solutions.

Cement

The Mid-Atlantic contains 22 cement facilities with facility emissions greater than 100,000 tCO_2/yr., with total sector emissions of 13.8 $MtCO_2$/yr. Nearly all emissions from cement facilities are suitable for capture. This is due to the large contribution of emissions from relatively few units. In the long term, all process heat units can be targeted for retrofit regardless of fuel type.

Chemicals

The Mid-Atlantic contains 11 chemical facilities with facility emissions greater than 100,000 tCO_2/yr., with total sector emissions of 2.4 $MtCO_2$/yr. The unit configurations and flue gas composition of chemical manufacturing facilities vary widely. Generally, most emissions are produced from gas-fired process heaters, but an in-depth unit and chemical engineering analysis must be conducted for each facility to identify exhaust streams with the purest CO_2. Due to data variability and aggregational reporting practices, this analysis considered all stationary combustion for long-term capture and assumed a uniform capturable fraction of 78 percent.

Ethanol

The Mid-Atlantic contains four ethanol facilities with facility emissions greater than 100,000 tCO_2/yr., with total emissions reported to GHGRP of 0.54 $MtCO_2$/yr. Including CO_2 emissions from the fermentation process, which is not reported to GHGRP, the total capturable emissions for ethanol facilities is 1.6 $MtCO_2$/yr. Capturable emissions from ethanol are dependent on the quantity of ethanol produced at the facility. Fermentation produces nearly pure $CO_{2,}$ which can be easily and cheaply captured. The current ethanol production capacity of each facility was used to estimate capturable emissions from each facility for the near-term scenario. The midcentury scenario also includes emissions from process heat units as capturable emissions.

Gas processing

The Mid-Atlantic contains 24 gas processing facilities with facility emissions greater than 100,000 tCO_2/yr., with total sector emissions of 4.2 $MtCO_2$/yr. Gas processing facilities include all upstream natural gas facilities that transport gas (such as compressor stations) or alter the raw gas (such as processing plants). Units within this sector may have very pure flue gases, allowing capture costs and retrofit infrastructure to be minimized. These units are generally gas-fired, and the flue gases are treated similarly to electrical generators. Natural gas pipeline compressor stations are of particular interest because they are sources of waste heat that can greatly reduce the capture cost. The waste heat can be used during the carbon capture process and lower the need for additional heat input.

Hydrogen

The Mid-Atlantic contains three hydrogen production facilities with facility emissions greater than 100,000 tCO_2/yr., with total sector emissions of 0.6 $MtCO_2$/yr. Hydrogen manufacturers are treated similarly to ammonia producers and must be analyzed at the unit level. In the near term, midstream capture from reforming reactors will be the most favorable for capture, followed by process heat. Most facility emissions at hydrogen production facilities were targeted for capture in the midcentury scenario.

Metals, minerals, and other

The Mid-Atlantic contains 20 metals, minerals, and other facilities with facility emissions greater than 100,000 tCO_2/yr., with total sector emissions of 3.7 $MtCO_2$/yr. Metals, minerals, and other is the broadest category of industrial facilities, including all sub-sectors from universities to agriculture to most manufacturing types and mineral extraction. Capture quantities vary widely between facilities, but most reflect CO_2 emissions from natural gas-fired units.

Petrochemicals

Petrochemical facilities require unit-level analyses to calculate the capturable emissions at each facility. Specific streams were selected manually to ensure all emissions are capturable. In the long term, most CO_2 emissions from these facilities are viable for CO_2 capture. The Mid-Atlantic contains two petrochemical facilities with facility emissions greater than 100,000 tCO_2/yr., with total sector emissions of 0.4 $MtCO_2$/yr.

Pulp and paper

Emissions and fuel use from pulp and paper manufacturers have large contributions from biogenic fuels. Biogenic emissions are combined with all process CO_2 emissions to estimate the quantity of capturable emissions for the near-term scenario. In the long term, all CO_2 emissions from process heat can also be included in this total. The Mid-Atlantic contains 15 pulp and paper facilities with facility sector emissions greater than 100,000 tCO_2/yr., with total emissions of 12.7 $MtCO_2$/yr.

Refineries

The Mid-Atlantic contains 11 refineries with facility emissions greater than 100,000 tCO_2/yr., with total sector emissions of 13.9 $MtCO_2$/yr. There are many different emitting units within petroleum refineries, but the most economical targets for carbon capture are fluid catalytic cracking units. These units produce a large volume of high-purity CO_2 in the flue gases and are the only units considered for capture in most refineries in the near term. For the midcentury scenario, all CO_2 emissions from process heaters can be included in the total capturable quantities.

Steel

The Mid-Atlantic contains 22 steel facilities with emissions greater than 100,000 tCO_2/yr., with total sector emissions of 13.6 $MtCO_2$/yr. There are few unit types at steel manufacturing facilities with emissions that have near-term economic viability for carbon capture. The near-term scenario considered emissions from carbon monoxide (CO) boilers, blast furnaces, and basic oxygen process furnaces. For the midcentury scenario, all CO_2 emissions from process heaters were included in the total capturable quantities.

Waste

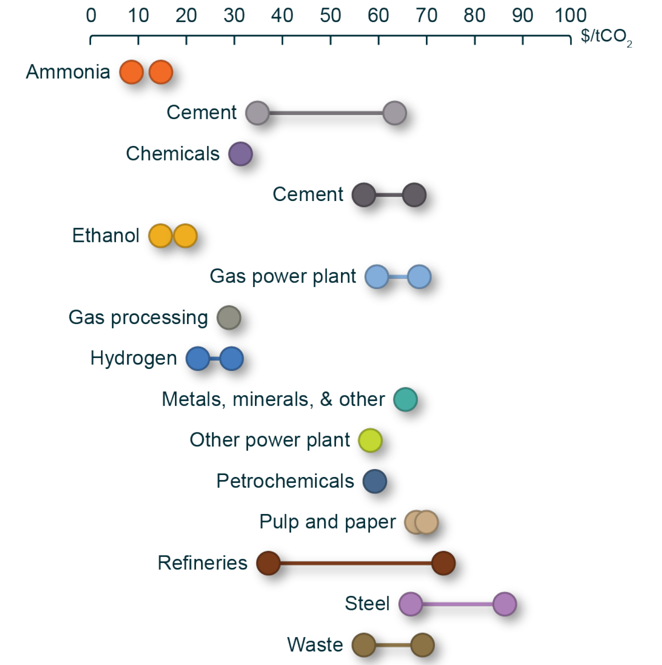
The Mid-Atlantic contains 15 facilities with facility emissions greater than 100,000 tCO_2/yr., with total sector emissions of 7.5 $MtCO_2$/yr. Some waste facilities employ incinerators to dispose of refuse. These facilities may use this combustion to power electricity generation and, thus, are treated similarly to electrical generators for carbon capture retrofit. Waste facilities of this type generally use a mixture of municipal waste and fossil fuels in their combustion units, which allows all emissions from electrical generating units to be considered for the midcentury scenario. The near-term scenario considered the two largest waste-to-power facilities within the region.

Capture cost considerations

The cost to capture CO_2 from a given flue gas stream varies widely depending on several factors, most of which are the same as those used to consider near-term capture opportunities. The molar concentration of CO_2 in the flue gas, the volume of CO_2 emitted, and the presence of pollution control devices are the primary drivers of the overall capture costs at a facility. Generally, high-volume flue gas streams with high molar concentrations of CO_2 and low pollutant concentrations have lower capture costs when compared to flue gas streams with lower concentrations of CO_2 and higher concentrations of pollutants.

This analysis used cost estimates from the Great Plains Institute's 2020 Transport Infrastructure for Carbon Capture and Storage whitepaper.[9] These cost estimates were derived from a literature review and meta-study of published capture costs for a range of industries and equipment configurations. These estimates are in 2020 US dollars and have not been updated to account for inflation, changes in material and labor costs, or advancements in capture technologies. The range of capture costs by sector used in the near-term and midcentury scenarios is shown in figure 7.

Figure 7. Range of capture costs used in the near-term and midcentury modeling scenarios.



Note: The bar between circles indicates additional facilities used a capture cost between the two circle values.

9 Abramson, McFarlane, and Brown, "Transport Infrastructure for Carbon Capture and Storage."

Storage opportunity identification

This analysis used the *SCO_2T^{PRO}* model from Carbon Solutions to assess geologic CO_2 storage opportunities in the Mid-Atlantic region. *SCO_2T^{PRO}* is a CO_2 storage site evaluation tool that uses geologic storage estimates and machine learning algorithms to calculate the cost of a Class VI injection well, given flow rates, market factors, ease of storage, and subsurface dispersion plumes.[10]

Modeling storage via *SCO_2T^{PRO}* requires input data for a variety of geologic reservoir properties, including depth, thickness, porosity, permeability, pressure, and temperature. These properties will vary in prospective geologic storage reservoirs, precipitating the need for input datasets that reflect this geospatial variability to create meaningful regional assessments. Unfortunately, there is no single publicly available dataset of saline storage formations suitable for modeling CO_2 storage properties and storage costs across the study area. Existing publicly available datasets lack sufficient coverage (geographic, stratigraphic, missing requisite data types, etc.) and/or spatial variability.

To produce a cohesive, region-wide storage estimate and to inform the *SCO_2T^{PRO}* model, Carbon Solutions created a geologic database covering more than 20 saline storage formations across the Mid-Atlantic by validating and integrating data from a range of sources into a combined database. Sources for onshore reservoir data include but are not limited to the NETL National Carbon Sequestration Database and Georgaphic Information System (NATCARB), US Department of Energy (DOE) Regional Carbon Sequestration Partnerships, United States Geological Survey, state geological surveys, and new data generated by Carbon Solutions.[11] Geologic storage reservoir data for the offshore Atlantic region is sourced from the Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment Project, a 2015 DOE-funded study assessing offshore geologic storage potential.[12]

The capacity of a storage reservoir depends on a range of factors. The interplay between these factors can be complex, and the impact of different reservoir properties can be situational and non-intuitive.[13] Generally, the reservoirs with the greatest potential for CO_2 storage will be relatively thick formations with high porosity and permeability. They must also have temperatures and pressures sufficient for storing CO_2 as a supercritical fluid and an overlying caprock with low permeability capable of preventing vertical CO_2 migration. Thicker reservoirs with higher porosity will have higher overall storage capacities and densities. Similarly, thick reservoirs with high permeability will support higher injection rates and require fewer wells, leading to reduced storage costs.

10 Middleton et al., “Great SCO_2T! Rapid Tool for Carbon Sequestration Science, Engineering, and Economics.”

11 Bauer et al., “NATCARB.”

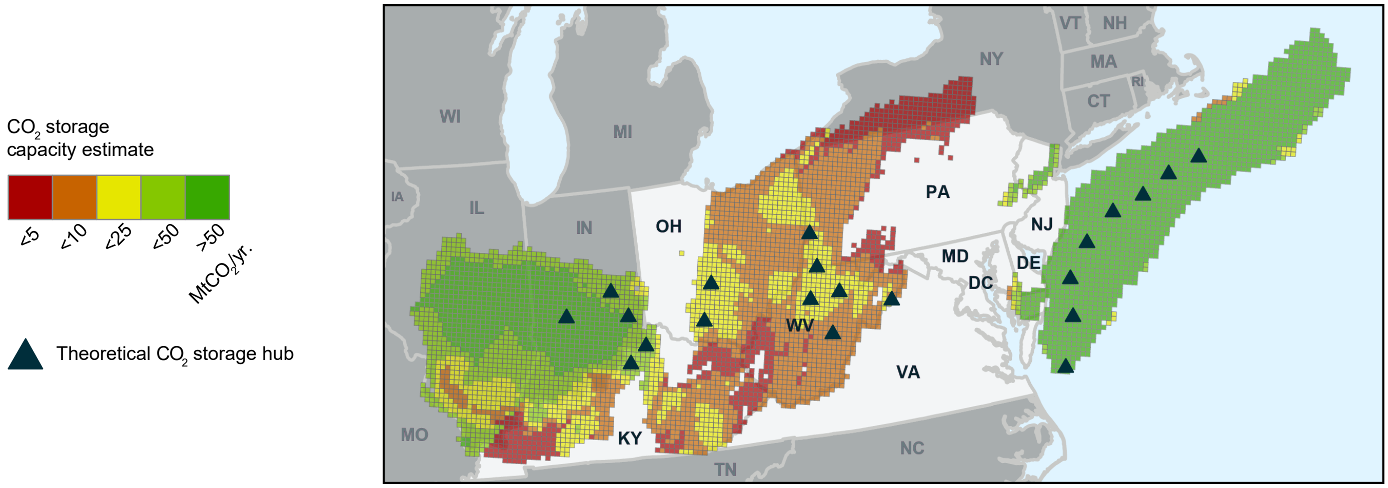
12 Gupta, “Mid-Atlantic US Offshore Carbon Storage Resource Assessment Project (Final Technical Report).”

13 Middleton et al., “Identifying Geologic Characteristics and Operational Decisions to Meet Global Carbon Sequestration Goals.”

The Mid-Atlantic has many carbon storage opportunities in both onshore and offshore saline geologic formations (figure 8). Additional saline geologic storage potential was also considered in the Illinois Basin, found in Illinois and Indiana, to provide the near-term and midcentury *SimCCS[PRO]* scenarios more choices for developing the optimal deployment scenario for the Mid-Atlantic capture facilities. The three offshore units extend from the mouth of the Chesapeake Bay to the southern Gulf of Maine. Though oil and gas reservoirs that may be suitable for CO_2-enhanced oil recovery exist in the region, this study only considers storage in saline formations.

In addition to the overall capacity for storing injected CO_2, ideal locations for CO_2 storage must consider the cost of a Class VI well for the permanent storage of CO_2 in a saline reservoir (figure 9). A Class VI well injects CO_2 deep into the subsurface for the purpose of permanent storage, according to federal rules enforced by the EPA. States, tribes, or territories may apply for primary enforcement authority over Class VI well permitting if their program meets or exceeds the federal requirements.[14] As with storage capacity estimates, the cost of a well varies based on the geologic characteristics and geographic conditions of a specific well location.

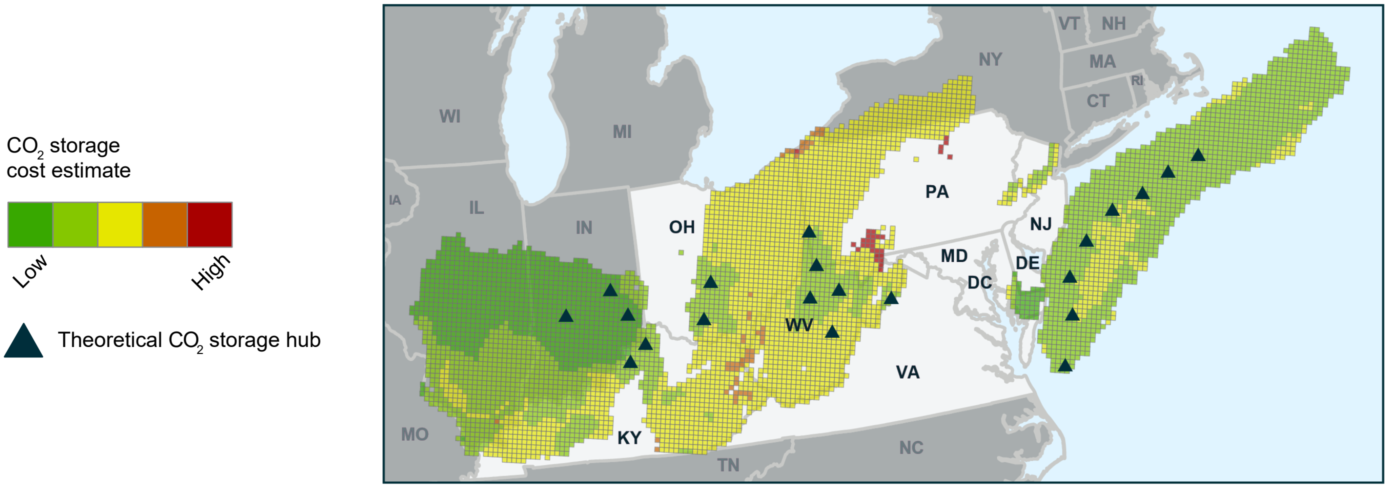
Figure 8. Estimated saline geologic storage capacity in the Mid-Atlantic and surrounding regions.



Based on CARBON SOLUTIONS SCO_2T^{Pro} 2022.

Note: Blue triangles indicate theoretical storage locations that are included in the near-term and midcentury scenarios.

Figure 9. Estimated saline geologic storage cost in the Mid-Atlantic and surrounding regions.



Based on CARBON SOLUTIONS SCO_2T^{Pro} 2022.

Note: Blue triangles indicate theoretical storage locations that are included in the near-term and midcentury scenarios.

14 US Environmental Protection Agency, "Class VI - Wells Used for Geologic Sequestration of Carbon Dioxide."

While excellent storage candidates with ample capacity, offshore geologic units can be more costly than onshore opportunities due to logistical and surficial factors. Developing offshore storage facilities requires specialized construction equipment, increased labor costs due to high demand for specialized tasks, logistical constraints, and other challenges unique to offshore operations, all of which increase the cost of installation. These additional considerations for offshore well development can lead to increased costs of up to ten times that of comparable onshore wells.

Further, offshore pipeline infrastructure requires additional hardening (e.g., increased pipeline wall thickness, weatherized platforms, etc.) to withstand the conditions and hazards of the marine environment. Logistics and infrastructure considerations can also lead to significant cost increases for pipeline development, with a cost multiplier of up to fourteen times compared to onshore pipeline construction.[15] This analysis uses a cost multiplier of four for offshore pipelines, which is then increased for sensitive or protected marine areas.

This analysis selected 21 locations for theoretical storage hubs within the highest-quality geologic units of the region, as displayed in figures 8 and 9. Each theoretical storage hub may include multiple injection wells, depending on the geology of the location. The Great Plains Institute's Transport Infrastructure for Carbon Capture and Storage whitepaper found that aggregating CO_2 from multiple sites optimizes economies of scale and maximizes carbon reduction. These hubs are meant to be representative locations and do not consider land use, mineral rights, and other factors vital for specific storage hub siting. The hubs are also geographically distributed to provide storage locations throughout the region. Since the Mid-Atlantic contains significant storage potential, not all theoretical hubs are utilized for storing captured CO_2 emissions from the region.

Mid-Atlantic deployment scenarios

While storing captured CO_2 on-site may be utilized at some facilities in actual deployment, this study assesses economywide deployment of carbon capture through an optimized transport network that connects the sources and storage facilities described. To build these deployment scenarios, this analysis utilized the *CostMAP^PRO^* and *SimCCS^PRO^* models developed by Carbon Solutions.[16]

*SimCCS^PRO^* attempts to minimize the overall social impact, environmental impact, and cost of CO_2 transport routes based on numerous layers of geographic information and land use factors, such as urban areas, land ownership, geographic features, indigenous lands, natural resources, and existing infrastructure. The weights used by *CostMAP^PRO^* were determined using a combination of literature and expert opinion, and the output consists of the cost weight network and the routing weight network files, which are then used by *SimCCS^PRO^* to build the lowest-cost CO_2 pipeline network.

This analysis developed two primary CO_2 capture, storage, and transport infrastructure scenarios in the region. The near-term scenario develops an optimized network using facilities with the techno-economic potential to deploy carbon capture in the next 15 years, while the midcentury scenario models a transport network that could develop into the midcentury for all major facilities and capture streams described above in the Mid-Atlantic. In each of the near-term and midcentury scenarios, all capturable emissions from all sources described in the respective scenario are captured, transported, and permanently stored in saline geologic formations. While all capture facilities from each scenario are included in the respective result, the number of theoretical storage hubs included in a scenario is based on how many are required to store all captured CO_2 at the lowest cost.

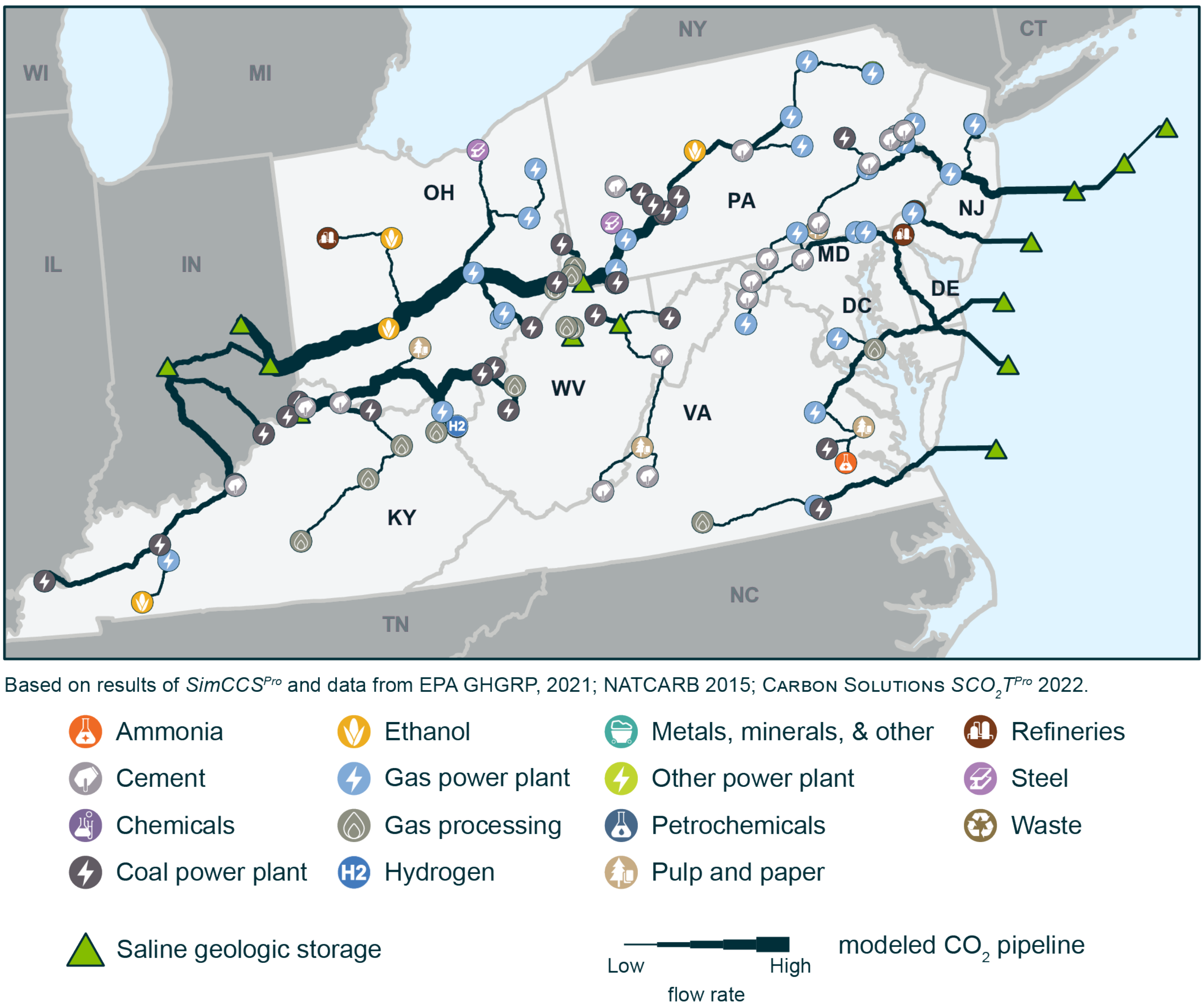
15 Vidas et al., "Analysis of the Costs and Benefits of CO_2 Sequestration on the US Outer Continental Shelf.

16 Middleton et al., "SimCCS"; Hoover, Yaw, and Middleton, "CostMAP: An Open-Source Software Package for Developing Cost Surfaces Using a Multi-Scale Search Kernel."

NEAR-TERM SCENARIO

This analysis identified a subset of emitting facilities within the Mid-Atlantic that not only meet eligibility thresholds for the 45Q tax credit but also possess other key characteristics that make the economics of capture favorable for near-term investment in the next 15 years. These facilities generally have flue gas streams with a high volume of concentrated, high-purity CO_2, which lowers the cost of capture on a per ton basis. Other criteria include the expected longevity of operations and the availability of capture technology appropriate for the emission type. These facilities present an initial framework for near-term investment in carbon capture deployment. The near-term scenario connects 102 capture facilities to 14 saline geologic storage hubs through 4,655 miles of pipeline infrastructure, capturing and permanently storing a total of 220.5 $MtCO_2$/yr. (figure 10).

Figure 10. Near-term scenario for carbon capture and storage deployment in the Mid-Atlantic.



Based on results of *SimCCS^Pro* and data from EPA GHGRP, 2021; NATCARB 2015; Carbon Solutions *SCO_2T^{Pro}* 2022.

The largest emissions contributions from near-term opportunities are from power generation (figure 11). Coal and gas power plants (26 and 27 plants, respectively) in the near-term scenario capture 193.5 $MtCO_2$/yr., and the biomass-fired plant captures an additional 0.09 $MtCO_2$/yr.

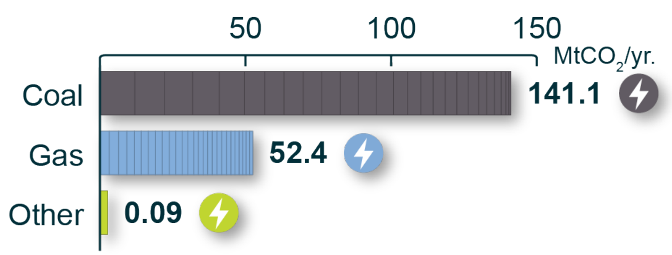
There are also many near-term carbon capture deployment opportunities in the industrial sector, primarily from cement, pulp and paper, petroleum refineries, and steel facilities (figure 12). In the near-term scenario, 48 industrial facilities capture a total of 26.9 $MtCO_2$/yr.

The near-term scenario utilizes both onshore and offshore storage opportunities, resulting in the general development of two pipeline networks. The division between these two categories of facilities falls roughly along the Appalachian Mountains; facilities that connect to offshore storage are generally east of the Appalachian Mountains, while facilities connected to onshore storage are generally west of the Appalachian Mountains.

The offshore transport network is characterized by five discrete pipeline networks connecting onshore capture facilities with offshore storage hubs. A total of 35 capture facilities transport 42.3 $MtCO_2$/yr. to seven offshore storage hubs through 1,764 miles of CO_2 pipeline infrastructure.

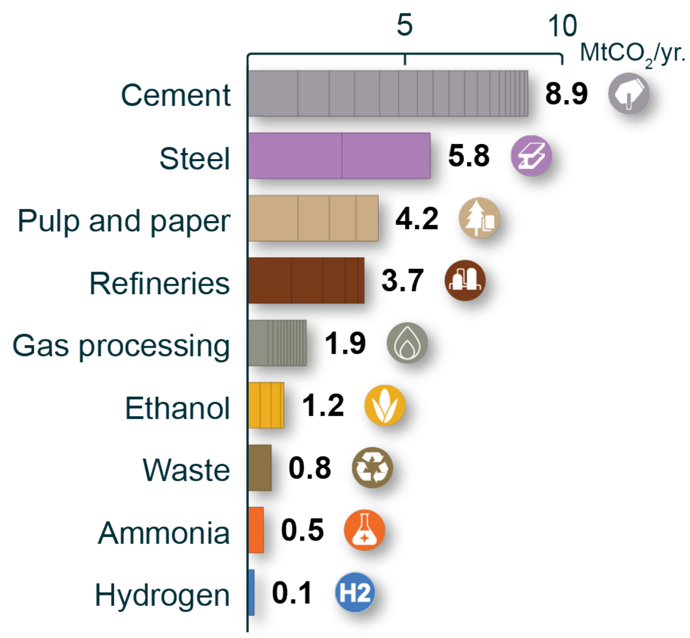
There are 67 capture facilities connecting to onshore storage hubs, capturing 178.3 $MtCO_2$/yr. These capture facilities connect to seven onshore saline storage hubs throughout Appalachia and the Ohio River Valley, connected by 2,891 miles of CO_2 pipeline.

Figure 11. Captured emissions at power plants in the near-term scenario.



Note: Each subsection within each bar represents a separate facility.

Figure 12. Captured emissions at industrial facilities in the near-term scenario.



Note: Each subsection within each bar represents a separate facility.

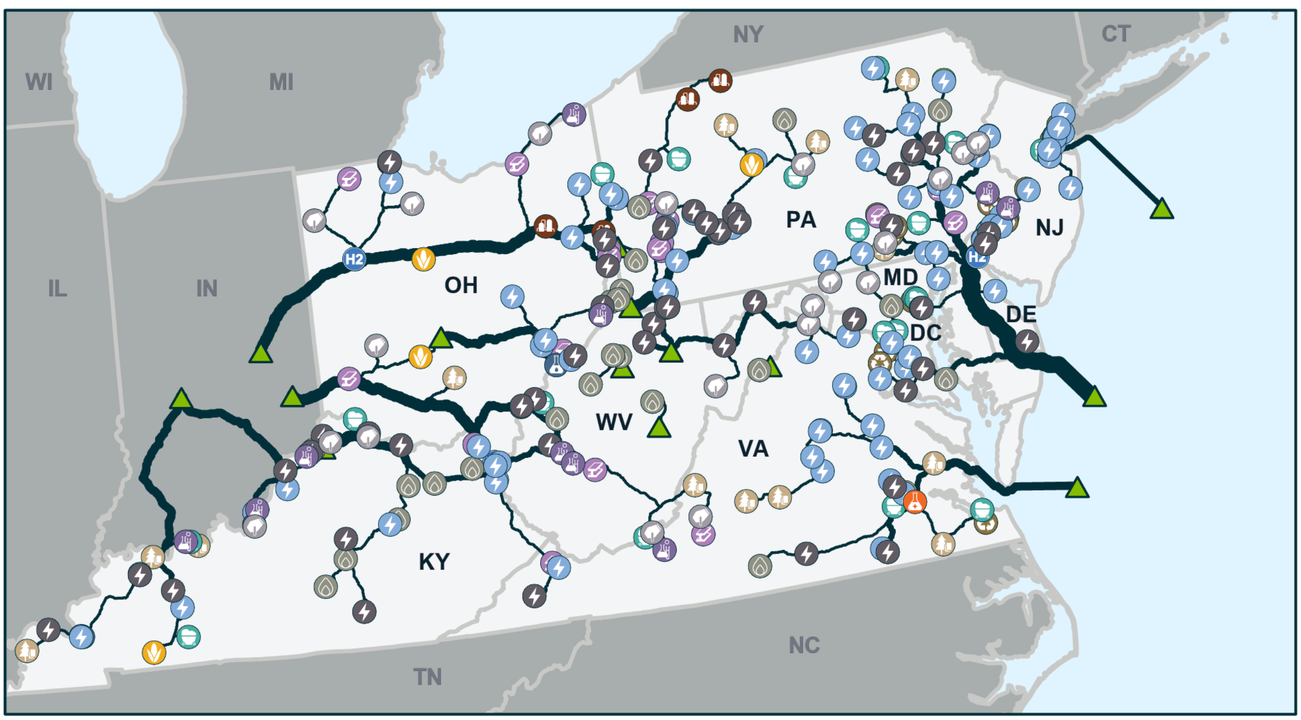
MIDCENTURY SCENARIO

The midcentury scenario includes capture at all industrial and power facilities with facility emissions greater than 100,000 tCO_2/yr. in the region, as shown in figures 5 and 6. The midcentury deployment scenario resulted in 304.7 $MtCO_2$/yr. captured at 286 facilities, which was transported to 14 saline storage hubs through 6,719 miles of CO_2 transport pipeline infrastructure (figure 13).

The primary capture opportunities in the midcentury scenario continue to be power plants, primarily coal and gas plants (figure 14). The portion of captured CO_2 from industrial sources increases to 20.3 percent of total captured CO_2 in the midcentury scenario, from 12.2 percent in the near-term scenario. Additionally, capture facilities from metals, minerals, and other, chemicals, and petrochemicals are now included in the midcentury scenario (figure 15).

Like the near-term scenario, the resulting infrastructure is divided into networks that connect capture facilities to onshore storage and networks that connect capture facilities to offshore storage. A few of the onshore networks are smaller networks within the interior of Appalachia, where connecting to larger regional trunk lines may be prohibitively expensive for relatively few total emissions due to the rugged terrain and high density of protected areas. Offshore storage locations are linked by three discrete networks roughly defined as the New York City metropolitan area, eastern Pennsylvania and the Washington, DC-Baltimore urban corridor, and southern and central Virginia. These networks each consolidate captured emissions to one trunk line before linking to offshore storage hubs.

Figure 13. Midcentury scenario for carbon capture and storage deployment in the Mid-Atlantic.



Based on results of *SimCCS*[Pro] and data from EPA GHGRP, 2021; NATCARB 2015; Carbon Solutions SCO_2T[Pro] 2022.

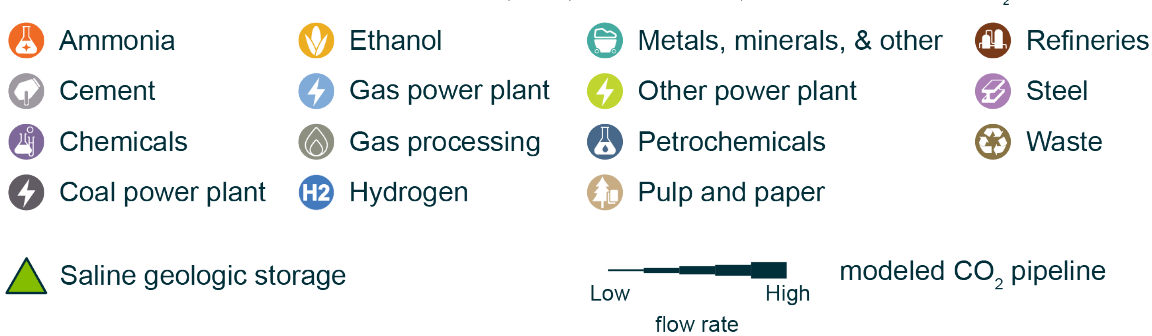
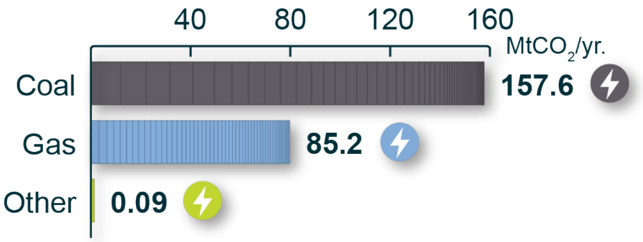
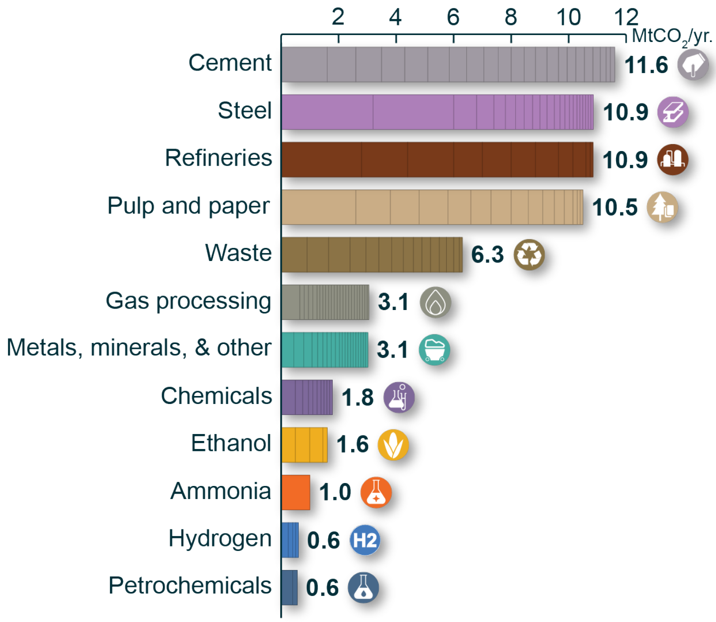


Figure 14. Captured emissions at power plants in the midcentury scenario.



Note: Each subsection within each bar represents a separate facility.

Figure 15. Captured emissions at industrial facilities in the midcentury scenario.



Note: Each subsection within each bar represents a separate facility.

NATIONAL CARBON MANAGEMENT INFRASTRUCTURE OPPORTUNITIES

While this study focuses on carbon capture and storage deployment opportunities within the Mid-Atlantic, the results demonstrate the region's potential to participate in a national network for carbon capture and storage deployment. As noted above, a primary finding of the Great Plains Institute's 2020 Transport Infrastructure for Carbon Capture and Storage whitepaper was that a long-term, regional-to-national approach to planning CO_2 transport infrastructure can achieve beneficial economies of scale, reduce overall transport and investment costs, and minimize the land use impact of necessary infrastructure.[17]

Conclusion

Economywide deployment of carbon capture technology is necessary to achieve midcentury carbon emissions reduction goals and is the only option to fully decarbonize some industrial sectors. While the primary sources of CO_2 emissions in the Mid-Atlantic are power plants, the region does contain many opportunities for emissions reductions at industrial facilities using carbon capture. The Mid-Atlantic region also contains many opportunities for CO_2 storage in saline geologic formations, with onshore opportunities in the Appalachian Basin, Ohio River Valley, and nearby in the Illinois Basin, as well as offshore opportunities on the shallow Atlantic continental shelf and parts of the slope.

The Mid-Atlantic has significant potential to reduce its carbon emissions through carbon capture and storage, both in the near term and into the midcentury. The near-term scenario proposed in this study captures 220.5 $MtCO_2$/yr. at 102 facilities, which are stored at 14 theoretical storage hubs connected by 4,655 miles of CO_2 pipelines. The midcentury modeling scenario sees a build-out of 6,721 miles of CO_2 pipeline to transport 304.7 $MtCO_2$/yr. captured at 286 facilities to 14 theoretical storage hubs.

Planning a coordinated build-out of CO_2 transport infrastructure connecting sources to a regional network of storage sites can reduce costs and logistical hurdles for individual facilities while maximizing CO_2 storage and the cost-efficiency of the entire network. Additionally, planning for midcentury levels of CO_2 transport may be more economically efficient in the long term than only considering the near-term opportunities or individual point-to-point projects.

17 Abramson, McFarlane, and Brown, "Transport Infrastructure for Carbon Capture and Storage."

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