TEAM PENNSYLVANIA

Successful Deployment of Carbon Management and Hydrogen Economies in the Commonwealth of Pennsylvania

ROAD MAP ON CARBON MANAGEMENT AND HYDROGEN DEVELOPMENT IN PENNSYLVANIA

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GREAT PLAINS INSTITUTE

This report is dedicated to Steven Carpenter on behalf of the Pennsylvania Energy Horizons Cross-Sector Collaborative. May his memory be for an eternal blessing.

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Executive Summary

Pennsylvania is well-positioned to use carbon management, the suite of technologies needed to reduce carbon emissions from industrial and power facilities, and hydrogen technologies to support the decarbonization of its power and industrial sectors, while protecting and creating well-paying jobs that boost the state's economy. To effectively use these technologies, the state needs to identify and address barriers to project development and provide support to project developers.

Carbon Management and Hydrogen as Climate Mitigation Tools

Carbon management and hydrogen technologies can play a critical role in mitigating Pennsylvania's carbon dioxide (CO_2) emissions. For key carbon-intensive industries such as steel and cement, carbon capture, utilization, and storage (CCUS) can reduce significant CO_2 and carbon monoxide (CO) emissions resulting from production processes. In the commonwealth's power sector, CCUS can significantly reduce the carbon footprint from natural gas use. Thus, carbon capture is an essential emissions reductions tool for major industrial sectors in the state that are otherwise difficult to decarbonize. The same facilities, infrastructure, and storage resources needed for CCUS in the commonwealth can also be used for hydrogen production for further decarbonization efforts (GPI, 2022a).

Hydrogen can be an important emissions reductions tool for the commonwealth because it does not generate direct emissions of pollutants or greenhouse gases at its point of use. Large, difficult-to-abate sectors important to Pennsylvania's economy, such as trucking, steel and chemicals manufacturing, and industrial and municipal heating, can eliminate their direct emissions using hydrogen as a feedstock. Conversion of natural gas, an abundant resource in Pennsylvania, into hydrogen generates relatively pure CO_2 to be captured and stored while maintaining a high-heat energy source for the state's various industries.

Pennsylvania's Path Forward

Pennsylvania's position in the market and potential for the commercial deployment of (CCUS) and the storage of CO_2 generated from hydrogen production depends on the commonwealth's geologic CO_2 storage potential and ability to address several challenges to commercial deployment. Pennsylvania has a large potential capacity for CO_2 storage that is estimated at 97.6 billion short tons (tons) or 88.5 billion metric tons ($GtCO_2$), which, according to some estimates, is roughly 300 years of Pennsylvania's CO_2 emissions. (PDCNR, 2009). Although the commonwealth has great storage potential, it has many challenges to commercial deployment. These challenges are primarily non-technical and include developing a set of laws, policies, and regulatory support. The commonwealth needs to develop a forward-looking understanding of markets, a set of incentives, citizenry support, and industry support for carbon management and hydrogen.

The commonwealth can look to other states that have made progress on commercial deployment for insight on how to address these challenges. The strategies used to address these non-technical issues have varied from state to state and can result in different outcomes regarding project development. Louisiana is one state that has prioritized the advancement of CCUS by addressing many of these non-technical issues and has received interest from developers. The state has worked to provide regulatory certainty to potential developers through their Geologic Sequestration of Carbon Dioxide Act and Carbon Dioxide Trust Fund and impending Underground Injection Control (UIC) Class VI primacy for CO_2 injection wells. (USEA, 2021).

Addressing these non-technical issues will not guarantee that CCUS and hydrogen developers will come. Wyoming has addressed these non-technical issues and is still waiting for developers to arrive for other reasons, such as economic viability of capture technologies for the sectors present in the state. This result should not be viewed as a reason to delay addressing non-technical issues. If a state has not addressed these non-technical issues and there is no supportive regulatory and statutory environment for projects, it significantly increases the likelihood that project developers will find opportunities in states that are more favorable to their project.

To date, Pennsylvania has not addressed these non-technical issues, creating roadblocks for CCUS developers in the commonwealth. The two most significant issues facing Pennsylvania with respect to carbon management are the lack of pore space certainty—the ownership, unitization, and long-term stewardship of carbon storage sites—and certainty regarding management of the UIC Class VI program— determining whether the commonwealth intends to independently manage CO_2 storage well permitting. Substantial efforts will be required in the commonwealth to motivate and educate the legislative and executive branches to address these two issues.

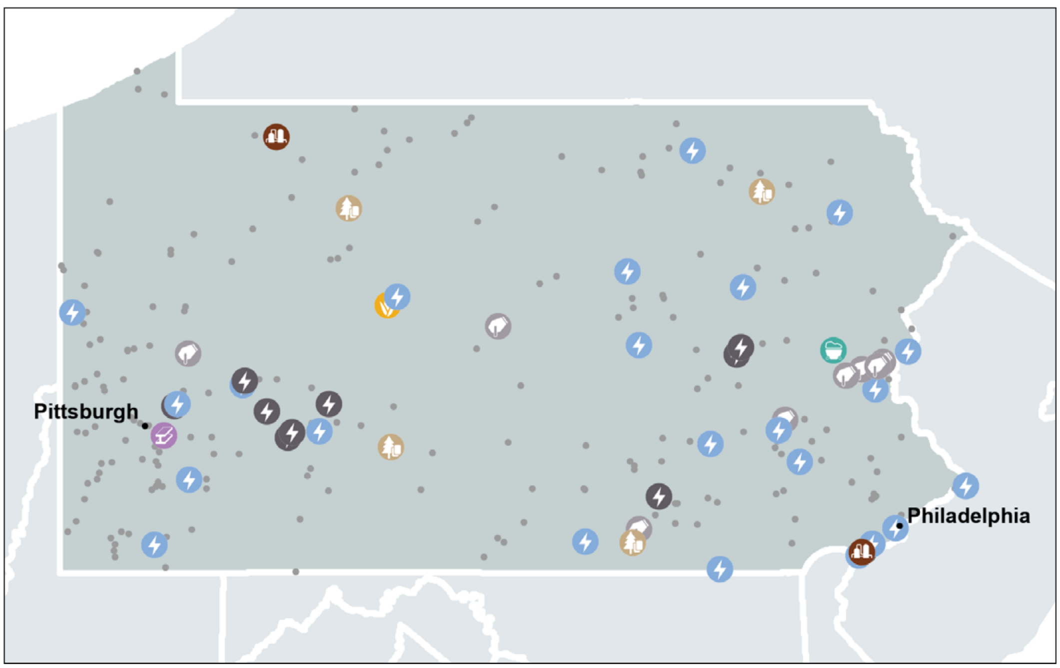
This Road Map provides an approach for the commonwealth to address these issues as it looks to advance carbon management and hydrogen project development to help meet midcentury climate goals outlined by the Pennsylvania Climate Action Plan. Pennsylvania is a leader of industry, manufacturing, and energy production. (PDGS, 2017). To grow opportunities for its citizens and maintain its role in the nation's industrial and energy sectors while meeting anticipated climate and decarbonization goals, the commonwealth must consider how best to support and deploy the full suite of carbon management (capture, transport, storage, and utilization) and hydrogen infrastructure, and hydrogen production and storage opportunities.

Carbon Management and Hydrogen Development Potential

Since 2008, and further updated in 2018, the US federal government has provided a financial incentive for the capture and long-term storage of carbon dioxide via Section 45Q of the US Tax Code (IRS, 2018). This incentive, often referred to as the 45Q tax credit, can aid the economic viability of CCUS project development in the commonwealth. It should be noted that the modeling developed for this Road Map was conducted prior to the signing of the Inflation Reduction Act, which provides several changes to the 45Q tax credit, including lower capture thresholds for industrial and power facilities and increased credit values for storage in saline and enhanced oil recovery formations.

The analyses conducted in this Road Map are expected to remain valid and useful, though additional facilities may now be considered viable. Fifty facilities in Pennsylvania are eligible for the 45Q tax credit (Figure 1). The state's 45Q-eligible facilities have collective CO2 emissions of 81.8 million metric tons per annum (MMTPA), of which 62.4 MMTPA are suitable for capture. The suitability of emissions for capture depends on originating facility type and the purity of CO_2 in the exhaust gases. The state's 45Q-eligible facilities account for 89 percent of all emissions from stationary combustion sources in Pennsylvania. This analysis identified 22 facilities among the state's 45Q-eligible facilities as near-term capture opportunities, which indicates that the facilities have flue gas streams with high volumes of concentrated, high-purity CO_2, allowing for efficient capture and enhanced economic conditions for positive return on investment (ROI) over the next 10 to 15 years. These near-term opportunities emit a total of 45.4 MMTPA CO_2, of which 34.7 MMTPA are capturable CO_2.

Figure 1: 45Q-eligible facilities in Pennsylvania

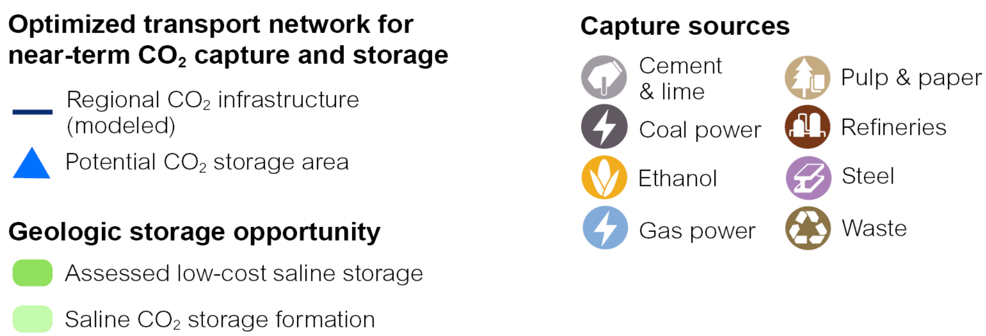


Source: Figure authored by Elizabeth Abramson, 2022. Based on data from EPA GHGRP, 2020.

Near-term and midcentury scenarios were constructed using the SimCCS model to analyze carbon capture opportunities and the resulting need for CO_2 transport infrastructure. The model simulates optimized CO_2 transport infrastructure by linking cost-effective sources of CO_2 with areas of economic demand for utilization or long-term geologic storage (Middleton et al., 2022). The near-term capture opportunities described above resulted in 933 miles of CO_2 transport infrastructure corridors connecting capture facilities to potential permanent storage locations (Figure 2).

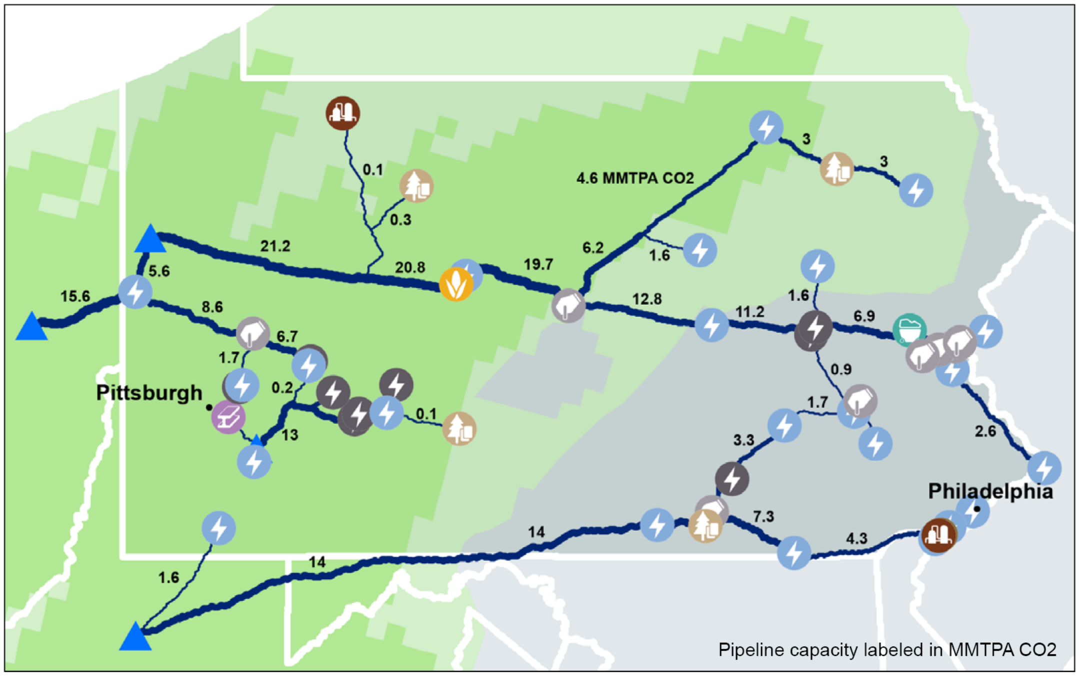
Figure 2. Near-term carbon capture opportunities infrastructure scenario

Source: Figure authored by Elizabeth Abramson, 2022. Based on results of the SimCCS model and data from EPA GHGRP, 2020; NATCARB, 2015; SCO_2T, 2020.

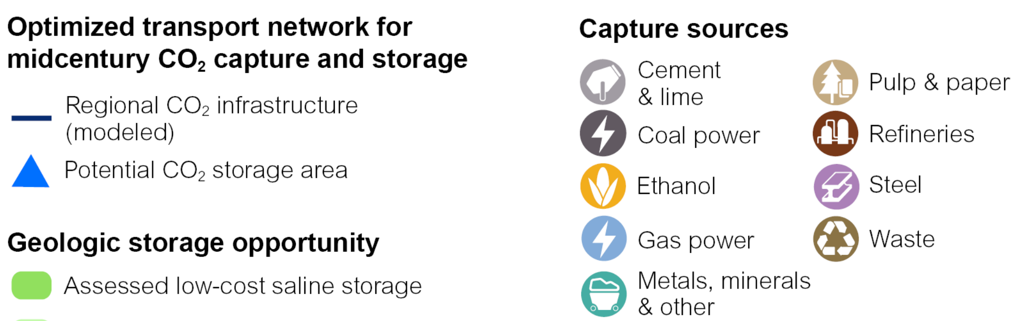


Under the midcentury scenario, these facilities were connected by a modeled infrastructure network of approximately 1,433 miles of CO_2 transport corridors (Figure 3). The National Energy Technology Laboratory (NETL) CO_2 Transport Cost Model was used to determine the physical and capital requirements of the transport network in each scenario (Dubois, McFarlane, and Bidgoli; 2017). The SCO2TPro geologic storage model was used to calculate the potential total storage capacity of geologic reservoirs in Pennsylvania, Ohio, and West Virginia, and to identify low-cost areas in this region as proposed storage hubs for captured emissions (Middleton et al., 2020). These proposed hubs have an estimated geologic storage potential of 27.1 billion metric tons of CO2 in multiple geologic formations.

Figure 3. Midcentury carbon capture opportunities infrastructure scenario



Source: Figure authored by Elizabeth Abramson, 2022. Based on results of the SimCCS model and data from EPA GHGRP, 2020; NATCARB, 2015; SCO_2T, 2020.



Technical, Policy and Regulatory Needs to Implement the Road Map

The commonwealth has opportunities across a wide variety of venues to advance commercial scale deployment of CCUS and hydrogen production (GPI, 2022b). To successfully use these opportunities, the commonwealth must identify access to and ownership of usable pore space for permanent carbon storage and develop a framework to unitize or amalgamate pore space. This Road Map suggests evaluating risk issues such as orphan wells and uncertainty of plugging and abandonment, conversion of Class II wells to Class VI wells, Class VI primacy, and long-term post-closure stewardship. Environmental, energy, and social justice (EESJ) is a significant requirement for all federal projects moving forward, including those qualifying for funds associated with the Bipartisan Infrastructure Law (BIL).

Suggested Next Steps

The Road Map recommends several next steps that are detailed in this report and are summarized below. The steps are presented based on temporal priority, with issues requiring a longer time for implementation presented first. All steps should address environmental justice (EJ) concerns during their respective processes, with environmental justice considerations outlined at the end of this section.

1. **Statutory Framework**: The commonwealth must establish a statutory framework that attracts project developers and investors. Without this foundational requirement, Pennsylvania will struggle to attract the projects and infrastructure needed to decarbonize while maintaining a robust economy and workforce.

> **Suggested Action:** The commonwealth should immediately commission a study to address the statutory issues identified by the Road Map that concern their legislative and executive branch operational issues to determine the timing and mechanisms to move legislation through the legislature.

2. **Underground Injection Control (UIC) Class VI Primacy**: Class VI primacy is one of the two most significant issues hindering Pennsylvania's advancement of commercial CCUS.

> **Suggested Action:** The commonwealth must decide if it is able to process applications more quickly than the EPA and identify if it has the resources and technical expertise to take on primacy and can afford to maintain this expertise should it acquire it.

3. **Consider Regional Approaches (intra- and inter-state collaboration)**: Pennsylvania has a great opportunity to participate in a network connecting northeastern US emission sources with low-cost, high-capacity geologic storage in the Ohio River Valley.

> **Suggested Action:** Pennsylvania must quickly determine what inter-state opportunities it will pursue. Many of these collaborative efforts, including the upcoming BIL hydrogen hub Funding Opportunity Announcement (FOA), will require predetermined discussions, decisions, and execution of agreements defining these inter-state relationships.

4. **Department of Energy (DOE) Hydrogen Hubs**: The commonwealth does not currently have the necessary agreements and structures to be an applicant compliant with the expected FOA. It is unknown if the commonwealth has the necessary data, participants,

> **Suggested Action:** The commonwealth should immediately identify any teaming partners, likely neighboring states, and prepare the necessary agreements, memorandum of understandings (MOUs), and structures to allow the state to engage as a prime partner for the hydrogen hubs FOA.

and stakeholder engagement to understand the hydrogen production options—how much, by whom, and where—to address the suspected requirements for the hydrogen hubs FOA.

5. **Bipartisan Infrastructure Law (BIL) Funding**: There is significant funding under the BIL set aside specifically to address many of the issues and tasks necessary for the full-scale commercial deployment of carbon management projects and hydrogen production with carbon capture. The commonwealth should consider as many funding mechanisms as possible to advance Pennsylvania-centric deployments, such as those in the BIL technical assistance guide.

> **Suggested Action:** The federal government has provided significant access to funding through the Bipartisan Infrastructure Law in many of the areas discussed in this Road Map. The commonwealth should identify lead agencies and process the required applications and paperwork to gain access to funding.

6. **Future Studies**: Many of the suggestions in the Road Map cannot be addressed until further information, details, structure, statutes, and funding exist. To that end, the commonwealth should commission several further studies that would augment, support, and advance much of the work detailed by the Road Map.

> **Suggested Action:** The commonwealth should consider commissioning the following studies that can assist in providing guidance, certainty, data, and analysis that are likely needed and will be requested by stakeholders as the Road Map is implemented:
>
> CO2 Capture and Storage Opportunities analysis to identify the commonwealth's potential projects
>
> Stakeholder engagement and outreach effort to identify, understand, and address stakeholder (e.g., possible project developers) concerns.
>
> Jobs and economic analysis to assess the impact of CCUS commercial deployment on the commonwealth.
>
> Hydrogen production study to serve as the basis for a DOE FOA 2664 Hydrogen Hub submittal
>
> Hydrogen color-blind study to help address EESJ, stakeholder engagement, social license to operate, and outreach.

7. **Digital Transformation:** Digitizing the commonwealth's subsurface data will allow for consistency in curation and updates. Digitization will allow developers looking for the latest screening data for pore space decisions to save time and will invite commercial developers because it will reduce project screening and decision time.

> **Suggested Action:** The commonwealth should initiate the digitization of its subsurface data immediately. Advancing the development of an enhanced Exploration and Development Well Information Network (EDWIN) customer-facing portal is a near-term, cost-effective next step.

8. **Comment and Engage Where Possible:** There are several proposed regulatory changes and possible public policy opportunities for the commonwealth to engage that provide opportunities to be seen as an active player by stakeholders. This engagement can be seen as positive and risk-reducing for projects and can incentivize and encourage project developers to invest in Pennsylvania.

> **Suggested Action:** Pennsylvania is behind other states with respect to the regulatory, statutory, and infrastructure required to advance commercial scale carbon management deployment. The commonwealth should consider engaging in public discourse and providing thoughtful responses to public inquiries to dispel some negative stakeholder perceptions.

9. **Use/Acceptance of Standards and Best Practices:** Standards and best practices offer an independent and pre-approved method to accomplish many aspects or tasks within the carbon management value chain. These standards and best practices can be cited by statute which can translate to economic efficiencies that provide needed de-risking and may be the difference between securing financial close or financial failure.

> **Suggested Action:** Standards and best practices are generally easy solutions when attempting to provide clarity and consistency. The commonwealth should consider citing them in statute to lessen project risks for developers. Any state agency (e.g., Pennsylvania Department of Environmental Protection (PDEP) or Pennsylvania Department of General Services (PDGS)) can cite, refer to, or require using a standard or best practice when processing permit applications or permits to operate.

10. **Environmental, Energy, and Social Justice (EESJ)**: Environmental, energy, and social justice considerations will need to be incorporated into the commonwealth's carbon management and hydrogen actions. The commonwealth can rely on the Environmental Protection Agency (EPA) and DOE website and dashboards for data and screening to be used for project decisions that will use federal funding and develop its own tools to address Pennsylvania-specific EESJ considerations.

> **Suggested Action:** EESJ requirements are a requirement of all BIL funding and will likely be part of any future federal funding, at least during the remainder of the Biden Administration. The commonwealth should consider adopting the use of the EPA's Environmental Justice (EJ) Screening Tool across all state and federally funded projects and continue developing and advancing PDEP's Environmental Justice Areas Viewer.

Acronym Guide

45Q – Section 45Q federal tax credit for carbon oxide sequestration
BGS – Pennsylvania Bureau of Geological Survey
BIL – Bipartisan Infrastructure Law
CCUS – Carbon capture, utilization, and storage
CCS – Carbon capture and storage
CO_2 – Carbon dioxide
CURC – Carbon Utilization Research Council
DAC – Direct air capture
DOE – US Department of Energy
EDX – National Energy Technology Laboratory's Energy Data eXchange
EESJ – Environmental, Energy, and Social Justice
EOR – Enhanced oil recovery
EPA – US Environmental Protection Agency
EJ – Environmental Justice
EDWIN – Exploration and Development Well Information Network
FLIGHT – EPA's Facility Level Information on Greenhouse Gases Tool
FOA – Funding Opportunity Announcement
GHG – Greenhouse gas
GHGRP – EPA's Greenhouse Gas Reporting Program
GPI – Great Plains Institute
MOU – Memorandum of Understanding
MTPA – metric tons per annum
MMTPA – million metric tons per annum
MRCSP – Midwest Regional Carbon Sequestration Partnership
NATCARB – National Carbon Sequestration Database and Geographic Information System
NOI – Notice of Intent
NETL – National Energy Technology Laboratory
PDCNR – Pennsylvania Department of Conservation and Natural Resources
PDEP – Pennsylvania Department of Environmental Protection
PDGS – Pennsylvania Department of General Services
ROI – Return on investment
RFI – Request for Information
UIC – Underground Injection Control
USEA – United States Energy Association

Pennsylvania Emissions Profile Data

Pennsylvania is the fourth largest CO_2 emitting state nationally with a range of sectors contributing to these emissions. (EIA, 2019). Each industrial sector in the state varies in terms of emissions and fuel profiles and has unique considerations to accomplish sector-wide decarbonization. Pennsylvania's Climate Action Plan aims for an 80 percent reduction in statewide emissions by 2050 compared to 2005 levels (PDEP, 2021). This analysis assesses potential carbon capture retrofit opportunities, and the infrastructure and geology considerations necessary for transporting and storing captured CO_2 emissions.[i]

Facilities and Emissions by Sector

Two hundred seventy-nine facilities in Pennsylvania reported emissions to Environmental Protection Agency's (EPA) Greenhouse Gas Reporting Program (GHGRP) in 2020.. Generally, these facilities can be divided into two groups: electricity generation and industrial facilities. The largest contributions to the state's total CO_2 budget are from electricity generators. Coal and gas power plants combined to produce 71.8 MMTPA CO_2 in 2020. Metals, minerals, and wastes are the most numerous facilities but have relatively modest contributions to overall CO_2 emissions. Steel, cement, and pulp and paper manufacturers are also important sources within the industrial sector and have significant opportunities to incorporate carbon capture technologies. Table 1 below describes the number of facilities and total emissions for each sector.

The feasibility for carbon capture in the facilities in the commonwealth varies widely and depends on a few factors. Facility emissions are not homogenous, even between facilities in the same sector using similar fuel mixtures. These variations can arise from engineering factors or the presence (or absence) of pollution controls and can impact the feasibility of capture for a facility. Close examination of industrial equipment units using the EPA Facility Level Information on Greenhouse Gases Tool (FLIGHT) is required to determine the quantity of capturable emissions at each facility (EPA FLIGHT, 2021). Emissions are reported under the EPA Code of Federal Regulations Part 98, which categorizes industrial process emissions into sector subparts including power and industrial sectors.

GPI's Carbon Capture Utilization and Storage (CCUS) Report, published in 2022, may contain fewer 45Q eligible facilities than FLIGHT for Pennsylvania because of additional screening conducted as part of the methodological considerations regarding individual process streams and the kind of greenhouse gases (GHGs) emitted by each facility. This analysis only considered process emissions (e.g., not stationary combustion emissions) for industrial facilities and not just those that reported 100,000 MMTPA CO_2 of stationary combustion. Generally, stationary combustion emissions at industrial facilities are not as high purity as individual process streams, which typically leads to a higher cost of capture. Thus, they are not considered except when they have significant volumes. Another methodological consideration

[i] Most of the material in this section is derived from the Carbon Capture Opportunities and Storage Opportunities in Pennsylvania, Technical Report prepared by Carbon Solutions, LLC for the Great Plains Institute (GPI) in 2022.

for excluding a facility is when facilities have large contributions from non-CO_2 GHGs such as some aluminum manufacturers and coal mines. Although these considerations narrowed the list of facilities that are considered economically feasible for capture, Pennsylvania has substantial opportunity at the remaining facilities to support capture projects.

Table 1. Pennsylvania industrial and power sector emissions

Sector	Number of facilities	CO_2 emissions MMTPA CO_2
Cement	8	3.7
Chemicals	15	0.6
Coal power plants	15	24.5
Ethanol	1	0.2
Gas power plants	48	47.3
Gas processing	44	2.0
Metals, minerals & other	50	2.9
Other power plants	2	0.04
Petrochemicals	2	0.2
Pulp & paper	10	3.1
Refineries	6	2.1
Steel	27	5.9
Waste	51	2.8
Total	**279**	**95.3**

Source: EPA GHGRP 2020.

45Q Tax Credit Eligibility

The largest financial incentive for CCUS projects across the US and in Pennsylvania is Section 45Q of the US Tax Code. 45Q is a performance-based tax credit for eligible CCUS projects that securely store CO_2 in geologic formations for permanent storage or beneficially use captured carbon oxides for industrial purposes. Industrial and power facilities are eligible for Section 45Q based on a minimum CO_2 emissions capture threshold of 100,000 metric tons per annum (MTPA) for industrial facilities and 500,000 MTPA for power facilities. These thresholds were lowered in the Inflation Reduction Act, which was signed after this analysis was conducted. The changes in 45Q in the Inflation Reduction Act are expected to increase the viability of CCS at the facilities included in this study and may increase the number of viable facilities beyond those in this study.

This analysis identifies 50 facilities in Pennsylvania that are eligible for the Section 45Q tax credit and offers favorable economics in the near-term and midcentury modeling. Emissions from these facilities total 81.8 MMTPA and power generators eligible under 45Q compose most of the facilities—23 gas-fired and 9 coal-fired plants, totaling 32 of the 50 facilities—and emissions, at 68.8 MMTPA. Table 2 presents the 45Q-eligible facilities by sector, emissions, and potential capture quantities.

Table 2. 45Q-eligible facilities in Pennsylvania

Sector	Number of facilities	CO_2 emissions MMTPA CO_2	Potential capture quantity MMTPA CO_2
Cement	8	3.9	3.3
Coal power plants	9	24.4	20.8
Ethanol	1	0.2	0.4
Gas power plants	23	44.4	34.7
Metals, minerals & other	1	0.9	0.1
Pulp & paper	4	2.7	1.0
Refineries	2	1.8	0.4
Steel	1	3.5	1.0
Waste	1	0.9	0.8
Total	**50**	**81.8**	**62.4**

Source: EPA GHGRP 2020.

Near-term Capture Opportunities

This analysis identified 22 out of Pennsylvania's 50 emitting facilities that meet eligibility thresholds for the 45Q tax credit and possess other key characteristics that make the economics of capture appear particularly favorable for near-term investment. These facilities have flue gas streams with a high volume of concentrated, high-purity CO2, which lowers the capture cost. Other criteria include the economic health of the emitting facility and availability of capture technology appropriate for the emission type. The methodology for this study identified near-term capture opportunities which would have a positive return on investment (ROI) in 10-15 years. While most aging coal power plants are not viable and would retire before positive ROI is achieved, it was expected that several large coal plants would remain online through the first portion of the energy transition to account for the baseload power demand. The coal power plants selected for this cohort are the largest plants in that sector that are most likely to continue operations at least until ROI is achieved.

The largest contributions from the near-term opportunities are from power generation. Coal and gas power plants—14 plants in total—produce 36.6 MMTPA CO2 with 30.1 MMTPA CO2 likely able to be captured. Emissions from natural gas combined cycle have a higher abatement cost than other units; however, the large volume of CO_2 emitted, and consistent operations, make them technically good targets because these units have clean flue gas streams and generally require minimal pre-treatment prior to the utilization of an amine capture unit. Table 3 details the near-term facility opportunities by sector, facilities, emissions, and potential captured quantities. The near-term and midcentury storage scenarios are shown in figures 2 and 3.

Table 3. Near-term capture opportunities in Pennsylvania

Sector	Number of facilities	CO_2 emissions MMTPA CO_2	Potential capture quantity MMTPA CO_2
Cement	3	2.0	1.7
Coal power plants	5	18.5	15.9
Ethanol	1	0.2	0.4
Gas power plants	9	18.1	14.2
Pulp & paper	1	1.0	0.6
Refineries	1	1.1	0.3
Steel	1	3.5	1.0
Waste	1	0.9	0.8
Total	**22**	**45.4**	**34.7**

Source: EPA GHGRP 2020.

Storage Opportunities

Pennsylvania has significant long-term storage opportunities. Carbon Solutions, LLC's SCO_2T^{Pro} model and the US Department of Energy's (DOE) National Carbon Sequestration Database and Geographic Information System (NATCARB) were used to model and assess the geologic CO_2 storage opportunities (Nelson & Carr, 2009). 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 well given flow rates, market factors, ease of storage, and the subsurface CO_2 plume resulting from injection.

Pennsylvania, the Ohio River Valley, and Appalachia all have significant long-term geologic storage opportunities. The analysis identified seven formations in Ohio, Pennsylvania, and West Virginia with CO2 storage potential capacity between 60 million metric tons and 10.8 billion metric tons (table 4). Preparing for site-specific injection (including a Class VI UIC permit) will require additional reservoir characterization and modeling to verify the suitability for injection in specific formation(s).

Table 4. Total identified CO_2 storage capacity in Pennsylvania, West Virginia, and Ohio*

Formation	Storage capacity Billion metric tons	Depth Meters	Average gross thickness Meters
Lockport	10.2	316 - 3,093	76
Mt. Simon	3.1	1,486 -2,351	31
Oriskany	1.7	424 - 2,805	15
Potsdam	0.3	2,052 - 2,838	41
Rome Trough	0.1	3,169 - 5,864	38
Rose Run	10.8	1,129 - 6,361	62
Sandusky	0.9	1,098 - 4,531	44

Source: SCO_2T^{PRO}, 2022.

*NOTE: The Rome Trough is classified as a "Formation" under the NATCARB/MRCSP naming conventions, which is the source for this data. Pursuant to MRCSP reports, the lithographic unit "Basal Sands-Rome Trough" is considered distinct from the Rome Formation and this report and methodology followed the MRCSP convention and keep the two units distinct.

CO_2 Transport Infrastructure Scenarios

The analysis developed two primary CO_2 capture, storage, and transport infrastructure scenarios: near-term opportunities in the next 10 to 15 years and longer-term midcentury scenarios envisioned over the next 30 years. The analysis utilized the SimCCS model to optimize potential CO_2 transport infrastructure networks. The SimCCS model conducts cost optimization by building transport infrastructure out to the lowest cost sources if given either an overall capture and storage quantity goal, or through economic equilibrium if run under a competitive economic scenario. These inputs include consumer/purchaser willingness-to-pay, capture source required rate of return, and breakeven price.

In this analysis for Pennsylvania, cost considerations were used in the facility retrofit feasibility assessment, and capture scenarios were constructed with an overall capture and storage goal determined by the state's total capture and storage capacity. SimCCS was used to develop an optimized statewide transport network that would deliver the maximum amount of potential capture to storage locations, rather than using individual facility cost estimates to pit companies against each other in a competitive economic equilibrium scenario (where cost savings are prioritized over carbon reduction). The near-term opportunity scenario identified 22 facilities linked by 933 miles of new infrastructure and would transport 34.7 million metric tons of CO2 per year to storage hubs (figure 4).

Figure 4. Near-term capture opportunities infrastructure scenarios

Source: Figure authored by Elizabeth Abramson, 2022. Based on results of the SimCCS model and data from EPA GHGRP, 2020; NATCARB, 2015; SCO_2T, 2020.

Optimized transport network for near-term CO_2 capture and storage

- Regional CO_2 infrastructure (modeled)
- Potential CO_2 storage area

Geologic storage opportunity

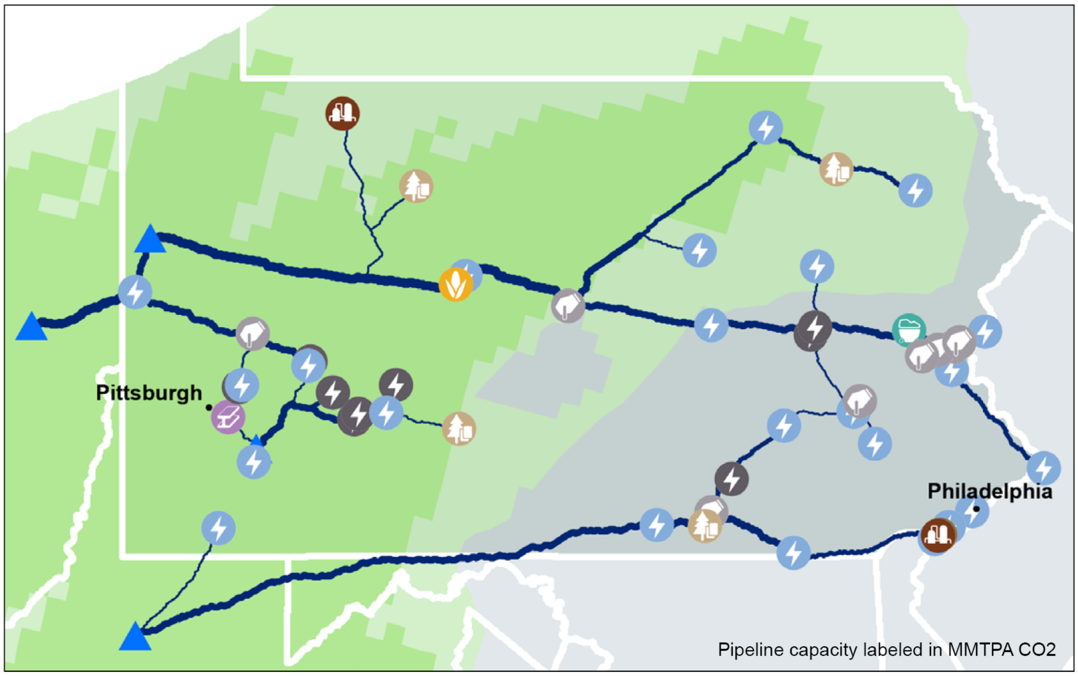
- Assessed low-cost saline storage
- Saline CO_2 storage formation

Capture sources

- Cement & lime
- Coal power
- Ethanol
- Gas power
- Pulp & paper
- Refineries
- Steel
- Waste

The midcentury scenario includes all 50 45Q-eligible industrial or power facilities, capturing 62.4 MMTPA CO_2 emissions using 1,433 miles of infrastructure to transport 41.6 MMTPA CO_2 per year to long-term storage hubs, with the remaining CO_2 stored at the respective capture facilities. The midcentury transport network could utilize the right-of-way established by existing pipelines in Pennsylvania, reducing the need to establish new land use corridors and taking advantage of the 12,118 miles of fossil fuel pipelines in the commonwealth. The captured emissions in this scenario would be transported to the four theoretical storage hubs. These hubs would distribute the CO_2 to possible storage locations (figure 5).

Figure 5. Midcentury capture opportunities infrastructure scenarios



Source: Figure authored by Elizabeth Abramson, 2022. Based on results of the SimCCS model and data from EPA GHGRP, 2020; NATCARB, 2015; SCO_2T, 2020.

Optimized transport network for midcentury CO_2 capture and storage

- Regional CO_2 infrastructure (modeled)
- Potential CO_2 storage area

Geologic storage opportunity

- Assessed low-cost saline storage
- Saline CO_2 storage formation

Capture sources

- Cement & lime
- Coal power
- Ethanol
- Gas power
- Metals, minerals & other
- Pulp & paper
- Refineries
- Steel
- Waste

Reuse or repurpose of these established rights-of-way and easements could reduce the initial cost of constructing new CO_2 transport infrastructure. There is likely little to no value in the reuse or repurposing of oil and gas pipelines to CO_2 use and certainly no use for repurposing for hydrogen use, as noted by the DOE's discussion with industry, but both DOE and industry concur on the significant value of the rights-of-way (USEA, 2022).

Inter- and Intra-state Carbon Management Infrastructure Opportunities

Considering decarbonization goals for the broader region, Pennsylvania has a great opportunity to participate in a network connecting northeastern US emissions sources with low-cost, high-capacity geologic storage in the Ohio River Valley. A regional-scale approach to planning CO_2 transport infrastructure can achieve beneficial economies of scale and reduce overall transport and investment costs, while also minimizing the land use impact of necessary infrastructure (GPI, 2020). This strategy can also position the commonwealth as a key player and participant in the overall strategy that can capture, transport, and store emissions as needed from outside the commonwealth while also taking advantage of reciprocal agreements to utilize additional resources outside of Pennsylvania.

Hydrogen as a Decarbonization Solution

Hydrogen is an important emissions reductions tool because it does not generate direct emissions of pollutants or greenhouse gases at its point of use. Large, difficult-to-abate sectors important to Pennsylvania's economy, such as trucking, steel and chemicals manufacturing, and industrial and municipal heating, can eliminate their direct emissions using hydrogen.

Conversion of natural gas, an abundant resource in Pennsylvania, into hydrogen generates relatively pure CO_2. The analysis and data collected for carbon emissions, capture, transport, and storage can be applied to consider hydrogen production, which provides additional opportunities to use the same facilities, infrastructure, and storage potential (GPI, 2022a). As such, the same data and analysis used for carbon management can determine the amounts of CO_2 emitted, which can be used to plan for the transportation and storage of the CO_2 generated from the centralized production of hydrogen from natural gas.

Analysis of Data

This section analyzes data and evaluates opportunities to advance the commercial scale and deployment of CCUS and hydrogen production and infrastructure in the commonwealth. In general, the analysis covers technical, non-technical, financial, and policy-related barriers and opportunities.

Pre-screening to Identify Pore Space for Carbon Storage

Addressing the challenges in screening for pore space for carbon storage can help the commonwealth attract project developers. Lack of data is the primary challenge for screening pore space. When industry and the public can access high-quality and consistently curated data they can quickly, and with some level of scrutiny, identify usable pore space. Although public funding and research has created large amounts of data, there are no efficient tools to connect and access that data to aid in the screening process in the commonwealth. A state that provides ways to cross reference existing wells and subsurface data, such as through providing access to related data sets, will be well-positioned to attract project developers. Offering this data to project developers in the commonwealth will give them a relatively quick mechanism to do high level screening and allow them to focus their efforts on locating appropriate storage locations, thus expediting project development.

There are a host of options, sources, and data that can adequately identify the pore space volumes, permeability, and injectivity of the subsurface in the commonwealth. The most significant is DOE's National Energy Technology Laboratory's (NETL) Energy Data eXchange (EDX) (DOE, 2022). Developed in 2011, EDX offers a means for better preservation of DOE's research for future access and reuse and provides efficient and easily discoverable access to authoritative, relevant, external data resources. These data repositories provide significant first-level screening for potential developers and allow economic development agencies at the state or local level to encourage developers' consideration of certain pore spaces. Increasing the presence and quality of necessary data will allow project developers to efficiently utilize these tools and rapidly identify economic opportunities in the commonwealth.

Commonwealth acceptance, encouragement, or mandated use of accepted standards and best practices can help also drive commercial deployment. This use of standards and best practices is especially helpful when considering how a project developer identifies and plans the access and use of the pore space. There are several standards and best practices designed to address the pore space and detailed reservoir characteristics necessary to implement a carbon storage project.

Orphan Wells and Uncertainty of Plugging and Abandonment

Identifying orphaned, abandoned, unidentified or subsequently discovered wells, followed by plugging and abandonment is necessary to manage risk in carbon storage projects.

It is important to identify and address reservoir penetration risk from storage projects. The identification, cataloging, assessment, and plugging and abandonment of wellbores has progressed substantially, with focus on orphaned, unknown, or newly discovered wellbore penetrations through the caprock seal of the storage reservoir. These identification and risk assessment processes should include Class II wells—wells used to inject fluids associated with oil and natural gas production—considered for carbon storage projects. This inclusion ensures that former hydrocarbon wellbores are as de-risked as possible and compliant with current standards and best practices to be considered for carbon storage.

Depending on the jurisdiction and application, these standards and best practices are housed in various places. They exist in the public domain but can be referenced or cited by statutes and rules, such as the way the Internal Revenue Service refers to the industry standard, CSA/ANSI ISO 27916:19 in the 45Q tax law. State statutes can incorporate full narratives, cite, or refer by reference many standards and best practices. This flexibility provides the commonwealth options as it considers if, where, and how to extract the salient parts of desired standards and best practices and integrates them with specific commonwealth requirements.

All federal carbon management programs require a risk assessment as part of the application process, including addressing risks associated with orphan wells in the project area, and the commonwealth must consider them in their carbon management program as well. The commonwealth can also consider using federal funding opportunities to advance the orphan well plugging and abandonment programs. There are significant funding opportunities included in the Bipartisan Infrastructure Law (BIL) and Section 349 of the Energy Policy Act of 2005 (42 U.S.C. 15907) to identify, plug, remediate and reclaim abandoned or orphaned wells.

The DOE has invested some federal funding related to this work. Through its Systematic Assessment of Wellbore Integrity for Carbon Storage Projects Using Regulatory and Industry Information, DE-FE0009367, the DOE identified existing, plugged, and abandoned wellbores as one of the greatest risks for CO_2 migration pathways. Much of this work has been incorporated into current best practices both within the DOE's carbon management program and by outside organizations that include the ISO standard for geologic storage and CO_2 storage using enhanced oil recovery (CO_2-EOR). All of DOE's Regional Carbon Sequestration Partnerships, as well as the CarbonSAFE programs, must address abandoned and orphaned wells. It should also be noted that the Midwest Regional Carbon Sequestration Partnership (MRCSP)—one of DOE's Regional Carbon Sequestration Partnerships—included legacy well identification for southwestern Pennsylvania as part of the MRCSP Phase III effort. All appropriate historical documentation and location data were added to Pennsylvania's Exploration and Development Network (EDWIN), which is Pennsylvania's oil and gas well database. EDWIN continues to evaluate legacy data as it becomes available.

Conversion of Class II Wells to Class VI Wells

There is potential in the commonwealth to repurpose Class II wells to Class VI wells for carbon storage, however, the static nature of rules and regulations for geologic reservoirs can make this repurposing difficult. The regulations for permitting Class VI wells are more specific and contain more comprehensive requirements than those for permitting Class II wells. Class II well owners or operators who inject CO_2 primarily for long-term storage must often obtain a Class VI permit from either the EPA or primacy-holding state if there is increased risk to underground sources of drinking water.

Addressing this difficulty in converting well types is key to encouraging the use of the thousands of Class II wells in operation across the country to be repurposed and reused for carbon storage. There are approximately 140,000 operating Class II EOR wells in the US, injecting approximately 70 million metric tons of CO_2 per year (Godec, 2021) against the two currently permitted Class VI wells that inject slightly more than 1 million metric tons per year of CO_2. The sheer volume of Class II wells has led to the EPA considering converting suitable Class II wells to Class VI wells. The DOE conducted interviews of Class II well operators to understand the issues that may exist in converting this vast resource of Class II wells to geological storage only. Through the United States Energy Association's (USEA) Consensus Program with DOE, more than 70 participants engaged in an interactive roundtable discussion entitled *"Roundtable on Carbon Storage Research & Development Priorities for Existing Wells"* via Zoom on February 23, 2022. This roundtable showed that industry overwhelmingly believes they have the technical capability to repurpose wells, but it is unclear if they have the authority or clear guidance to accomplish the transition. Industry also agreed that repurposing Class II wells for monitoring CO_2 plumes created from injecting CO_2 may be more appropriate than conversion to Class VI injection wells. Monitoring wells are required for all Class VI wells, so converting Class II wells for plume monitoring could still lead to major cost savings for an injection project.

Unitization or Amalgamation of Pore Space

Unitization or amalgamation of pore space can reduce regulatory risks and uncertainty for project deployment. As of 2020, and reported in the *Study on States' Policies and Regulations per CO_2-EOR-Storage Conventional, residual oil zone, and EOR in Shale: Permitting, Infrastructure, Incentives, Royalty Owners, Eminent Domain, Mineral-Pore Space, and Storage Lease Issues* (USEA, 2020), the Executive Summary provided a valuable overview of the commonwealth's status of subsurface regulatory status:

> *"Minimal CO_2-EOR activities occur in the state. Regulatory risks and uncertainty regarding the cost and extent of regulation pose a significant hurdle to expansion of CO_2-EOR or to geologic storage activities in the state. No CO_2 distribution network exists, and current state laws appear to specifically exclude CO_2 from eminent domain statutes. Ownership of pore space is unclear. Pennsylvania has no statutory regime for carbon dioxide sequestration."*

The USEA report provides a detailed evaluation of current statutory and legislative issues. A second USEA report expands on pore space ownership, acquisition, eminent domain, unitization, and liability, and evaluates more states. Collectively, the two works summarize much of the US's mineral producing states (USEA, 2020; USEA, 2021). These reports collectively cover the states of Alabama, California, Colorado, Illinois, Indiana, Kansas, Kentucky, Louisiana, Michigan, Mississippi, Montana, Nebraska, New Mexico, North Dakota, Ohio, Oklahoma, Pennsylvania, Tennessee, Utah, West Virginia, and Wyoming. This report is a good reference for consideration by the commonwealth as a comparison to what other states have done and examples are provided for possible consideration and adoption.

Long-term Post-closure Stewardship

While geologic storage is considered safe, effective, and permanent, long-term stewardship—what entity assumes liability for permanently stored CO_2—can be a significant issue that creates a challenge to full-scale deployment of carbon management technologies. Unless the government expressly assumes stewardship of the stored CO_2, the injector or operator will remain responsible for the post-injection liabilities and, therefore, may choose not to initiate the project (DeFigueiredo, 2007).

The main solution to this issue is for either the state or federal government to assume the long-term stewardship of stored CO_2. This strategy provides a reliable assurance to investors that potential impacts will be addressed by assuming that the state and federal government will be in existence for a long period of time. Several states have enacted legislation that conveys long-term stewardship of permanently stored CO_2 to the state to provide added certainty to project investors and further convey their support of carbon management projects. Some states categorize the storage of CO_2 as a public good—government mandated climate change mitigation—and that the liability for the stored CO_2 should ultimately fall to the government.

The federal land management agencies could provide similar support for long-term stewardship by issuing guidance and rulemaking specific to the processes, terms, and conditions for obtaining rights to use federal land for geologic storage. The National Petroleum Council suggested another solution in *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage* (DOE, 2019). The Roadmap suggested an approach that applies layers of risk management obligations across all phases of geologic sequestration—operation, post-injection site care, and post-closure.

Environmental, Energy, and Social Justice (EESJ)

EESJ will play a role in any federally funded carbon management or hydrogen projects. President Biden issued Executive Order 14008 on January 27, 2022, which mandated that the federal government integrate environmental justice (EJ) across all federal agencies. The Executive Order created the Justice40 program that requires all federal programs that provide project funding must ensure that 40 percent of the project funding or 40 percent of the project benefits or 40 percent of the project remediation goes directly to communities that have been disproportionally affected by environmental injustice and inequity.

According to DOE's current Environmental Justice Fellow, Catherine Clark, American Association for the Advancement of Science & Technology Policy Fellow at the DOE Office of Fossil Energy & Carbon Management, as presented on June 21, 2022, at USEA's Carbon Conversion Procurement Grants- Virtual Workshop for Manufacturers for Fuels, Chemical, And Bioproducts:

“Environmental justice is the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. This goal will be achieved when everyone enjoys: The same degree of protection from environmental and health hazards, and Equal access to the decision-making process to have a healthy environment in which to live, learn, and work.”

At the same event, the DOE provided a description of Energy Justice:

“Seeks equity in the social and economic participation in the energy system while remediating social, economic, and health burdens on ‘frontline communities’ explicitly centering their concerns, [and] aims to make energy more accessible, affordable, clean, and democratically managed for all communities.”

While the Executive Order and DOE have provided direction, there is a lack of guidance on implementation. The Carbon Utilization Research Council, in a letter to Energy Secretary Granholm, points out that the Biden Administration has not been clear on what they expect relative to EJ (CURC, 2022). Specifically, they ask the Administration to provide clear guidance in its funding opportunity announcements and to define how EJ will be evaluated into award selections and by what criteria and metrics will the Administration make judgments.

As they await clearer guidance, states can comply with the requirements of the Justice40 program and develop screening tools that assist in identifying these frontline communities. States can also use state-specific data to start making project decisions about when and how to engage with these stakeholders. The DOE has provided some early notions of what their guidance may look like, and states can take advantage as early movers to increase their awareness and develop or enhance decision-making tools. The DOE’s stated priorities for Justice40 include:

1. Decrease energy burden in disadvantaged communities.
2. Decrease environmental exposure and burdens for disadvantaged communities.
3. Increase parity in clean energy technology access and adoption in disadvantaged communities.
4. Increase access to low-cost capital in disadvantaged communities.
5. Increase clean energy enterprise creation (Minority or disadvantaged business enterprises) in disadvantaged communities.
6. Increase the clean energy job pipeline and job training for individuals from disadvantaged communities.
7. Increase energy resiliency in disadvantaged communities.
8. Increase energy democracy in disadvantaged communities.

Class VI Primacy Considerations

The commonwealth's decision to acquire or not acquire Class VI primacy will likely greatly affect the length of time it takes to permit Class VI wells in the state. The Safe Drinking Water Act, Underground Sources of Drinking Water, Underground Injection Control (UIC), Class VI Carbon Dioxide Injection Well program significantly impacts decisions and implementation of carbon management and hydrogen projects. The commonwealth should consider whether it is most advantageous to secure primacy, request a joint work agreement with EPA, in Pennsylvania's case Region 3, or remain under the purview of the federal UIC program.

The primary enforcement authority, often called primacy, refers to state, territory, or tribal responsibilities associated with implementing EPA-approved UIC programs. A state, territory, or tribe with UIC primacy oversees the UIC program in that state, territory, or tribe. When this occurs, the EPA provides authorization and delegation to the jurisdiction to implement the program and therefore has "primacy". States seeking UIC primacy must demonstrate that the state has:

1. Authority over underground injection;
2. Regulations that meet or exceed federal requirements; and
3. All the necessary administrative, civil, and criminal enforcement penalty remedies.

Primacy applications contain six core elements, including:

1. **Governor's letter:** The governor of a state must write a letter requesting approval for UIC program primacy. The governor's letter must specify that approval is sought under section 1422 or section 1425 of the Safe Drinking Water Act.
2. **Program description:** The program description is a document describing, in narrative form, the scope, structure, coverage, and processes of the state program.
3. **Attorney general's statement**: The Attorney General's statement is a certification by a qualified representative of the state asserting that the state's statutes, regulations, and judicial decisions demonstrate adequate authority to administer the UIC program.
4. **Memorandum of agreement between the state and the EPA regional administrator:** The memorandum of agreement is the central agreement setting out the provisions and arrangements between the state and EPA. The memorandum of agreement describes the administration, implementation, and enforcement of the state's UIC program.
5. **Copy of the state's UIC statutes and regulations:** States seeking primacy under Section 1422 may incorporate the federal regulations by reference, adopt the federal language verbatim, or draft provisions that are as stringent as the federal requirements.
6. **Documents demonstrating the state's public participation process:** The state must provide documentation of the public participation process the state used to notify the public of its intent to apply for primacy.

The process to primacy has four (4) distinct phases, which include:

- Phase I: pre-application activities
- Phase II: completeness review and determination
- Phase III: application evaluation
- Phase IV: rulemaking and codification

As the commonwealth evaluates whether UIC primacy is appropriate, there are several considerations that can assist in evaluating the value of holding primacy.

- **Legislative crosswalk:** Compare the current state of the UIC program and statutes against the EPA UIC program to identify gaps to be closed by the legislature. This effort is typically the most significant and the most time consuming. This exercise provides a list of what will be required to meet or exceed the federal program requirements. The commonwealth also needs to determine who will administer the program on behalf of the state. Additionally, the issue of pore space ownership and liability must be addressed. Often these two issues deter a state's willingness to invest the time and effort to secure primacy.
- **Consider interagency (EPA) and Pennsylvania labor sharing agreements:** This strategy helps ensure appropriate permit application resources are available during the immediate future and the time in which a state may achieve UIC Class VI primacy. These agreements will help to identify and ensure that applications are received, managed, and processed in a timely fashion and balances the available EPA resources and the demands and expectations of Pennsylvania's applicants. In some cases, and the current situation within EPA with respect to EPA's staff and capacity, labor sharing agreements are used even when a state decides not to pursue primacy. This mechanism provides the state and the EPA with augmentation of staff and resources to ensure the timely review and processing of permit applications.
- **Regulation Crosswalk:** The UIC primacy application requires a side-by-side comparison of the EPA UIC Class VI rules and the state's rules. This comparison is done to ensure that the primacy application and subsequent program at the state level are equal to or more stringent than the federal program. This will identify any gaps, overlaps, or issues that may need to be addressed.

Another topic for consideration under the umbrella of UIC primacy is whether a state has a desire to consider UIC Class VI permitting as a service and to offer said services for a fee to the public. Recently, the state of Wyoming, through the Wyoming Energy Authority, initiated Carbon Sequestration as a Service. The Wyoming Energy Authority's initiative to establish Carbon Sequestration as a Service would involve building commercial sequestration sites with wells for injecting CO_2. Louisiana and Oklahoma have discussed this topic and are considering how this may influence future commercial deployment of carbon management projects within their state. Pennsylvania, with its extensive infrastructure, experienced workforce, and favorable business environment, could put itself at a competitive advantage if it considered Class VI permitting as a service.

Hydrogen

Pennsylvania's natural gas industry produced 7.1 trillion cubic feet of natural gas in 2020, making the commonwealth the second largest natural gas producer in the US, following Texas. Pennsylvania operators have proven reserves of nearly 100 trillion cubic feet, a significant resource that can continue to provide investment, employment, and revenue opportunities for the commonwealth far into the future. Hydrogen production facilities equipped with CO_2 capture can help Pennsylvania realize the benefits of this extensive resource in an increasingly carbon-constrained world and provide an important energy feedstock to help efficiently abate emissions in other industrial sectors important to Pennsylvania's overall economy.

Hydrogen production, the associated storage of CO_2, and the infrastructure required to dispense hydrogen offers many opportunities for the commonwealth to engage. DOE has set aside some $8 billion to form several hydrogen hubs. A plan for success will likely include the expected requirements of the forthcoming Funding Opportunity Announcement (FOA) as indicated in the recent Notice of Intent (NOI) by DOE that included the following details:

- 6-10 hydrogen hubs ranging from $400M to $1.25B
- A 50 percent Matching Cost Share is required
- Minimum proposed production of 50 to 100 metric tons per day of clean H_2
- Preference will be given to hubs that produce larger quantities of clean hydrogen
- Hubs must be increasingly interconnected to other energy systems
- Significant focus on Justice40 Initiative
- Significant focus on substantial community outreach and engagement
- Significant focus on Community Benefit Agreements

While hydrogen is a colorless gas, the hydrogen industry has developed a naming convention that uses colors to identify the fuel or feedstock used to generate or produce hydrogen. Today we see the following:

- **Green hydrogen** is produced through water electrolysis with renewable electricity.
- **Blue hydrogen** is sourced from fossil fuels with carbon capture applied to the process. Efforts to convert Pennsylvania's natural gas resources into hydrogen can fit this definition, if developed with carbon capture capabilities.
- **Gray hydrogen** is produced from fossil fuels, usually through steam methane reforming where the CO_2 is released to the atmosphere.
- **Black and brown hydrogen** is produced from coal and the CO_2 is released to the atmosphere.
- **Turquoise hydrogen** is extracted by using the thermal splitting of methane via methane pyrolysis. As a result, the carbon is removed as a solid.
- **Purple hydrogen** is made though using nuclear power and heat through combined chemo thermal electrolysis splitting of water.
- **Pink hydrogen** is generated through electrolysis of water by using electricity specifically from a nuclear power plant.
- **Red hydrogen** is produced through the high-temperature catalytic splitting of water using nuclear power thermal as an energy source.
- **White hydrogen** refers to naturally occurring hydrogen, such as a gas field.

A study to baseline and standardize how hydrogen production is discussed, how it is shared with the public and stakeholders, and how it is understood to make EESJ considerations has great value and does not currently exist in the marketplace.

Statutory Framework

Pennsylvania currently lacks a sufficient statutory framework to allow for large scale deployment of carbon management projects. Without laws and policies that provide a supportive environment for project developers and investors, the commonwealth is essentially “not open for carbon management business”.

To remedy this deficiency, the Pennsylvania General Assembly should aggressively pursue legislation and require the appropriate agencies to enact rulemaking that fully address the following:

- **Define pore space ownership**: An example of a statute that provides a template is Wyoming Statute § 34-1-152.
- **Define CO_2 ownership, from cradle to grave, or capture to post-closure**: An example of a statute that provides a template includes Wyoming Statute § 30-5-501, which clarifies that vis-à-vis storage rights, production rights are dominant but cannot interfere with storage.
- **Establish or confirm mineral rights primacy, define how subsurface activities will be coordinated, and establish unitization or amalgamation rules/thresholds for CO_2 storage reservoirs**: Examples of statutes that provide a template include Wyoming Statute § 35-11-315, which provides a mechanism for unitization of storage interests, and Wyoming Statute § 34-1-513, which specifies the injector, not the owner of pore space, is generally liable.
- **Establish CO_2 stewardship requirements for each stage of a carbon storage project**: Examples of statutes that provide examples include Wyoming Statute § 30-5-502, which provides a certification procedure for CO_2 incidentally stored during EOR, and Wyoming Statute § 35-11-313 establishes permitting procedures and requirements for CCS/CCUS sites.
- **Establish an organization within state government to administer and enforce CO_2 storage activities and provide the organization funding**: The mechanism for this effort, specifically with respect to EPA UIC Class II and VI wells, is via state primacy.
- **Establish a stewardship fund to administer CO_2 storage projects and provide for long-term stewardship needs post-closure**: An example of statutes that provide an example include Wyoming Statute § 35-11-318 that provides a mechanism for post-closure monitoring, reporting, and verification via a trust fund approach.

An additional method for assuming the long-term liability for CCUS projects includes a larger federal government effort similar to the Price-Anderson Act, which was created for the nuclear power generation industry as it considered the same two CCUS long-term liability issues—is the industry big enough to handle a large catastrophic event and will the entities be in existence to settle their liabilities decades later? The Act provides indemnification for operators against public liability for a nuclear incident, established quality and safety requirements, and provided authority to DOE for enforcement. The commonwealth and the federal government could create a similar environment for CCUS if they so choose.

Louisiana has an established Geologic Sequestration of Carbon Dioxide Act and Carbon Dioxide Trust Fund which is perceived by many as the most complete in the country. Coupled with their impending UIC Class VI primacy for CO_2 injection wells. Louisiana provides regulatory certainty to potential CCUS project developers (USEA, 2021).

National Petroleum Council's report, "Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage" (DOE, 2019), provides another perspective on this issue of long-term risk, liability, and indemnification. The Council's report suggested a layered approach that applies layers of risk management obligations across all phases of geologic sequestration (operation, post-injection site care, and post-closure). During the early stages of CCUS deployment, it is difficult for mature industry risk management approaches to be applied, and both developers and government will need incentives to expand the CCUS industry to full commercial scale, where normal industrial risk processes apply.

The upcoming DOE FOA for establishing hydrogen hubs requires that the submitting entity is a registered corporation, quasi-governmental entity, or otherwise situated to be able to enact the technical, economic, and development activities likely required by the FOA. The Request for Information (RFI) specifically indicates that an academic entity cannot be the lead, as the funding is not aimed toward traditional research. The expectation is that any entity, especially a state, be prepared to enter into agreements with other states, authorized by their respective Governors, or otherwise create or authorize entities, authorities, or agencies to act as the lead entity for the response to the hydrogen hub FOA. Pennsylvania currently has not created nor identified such an entity to conduct business on its behalf in response to the expected FOA.

Suggested Next Steps

The commonwealth can take several steps to transition and thrive in carbon management and hydrogen decarbonization commercial deployment scenarios. Due to Pennsylvania's lagging position compared to other states, the state should act on these efforts immediately and simultaneously. Some of these tasks will have a long lead time, such as legislative changes, while others will be much easier to complete. For Pennsylvania to compete for the federal and private/commercial dollars at stake, the state must consider and act upon these next steps. The suggested next steps are listed in order of temporal priority.

1. Statutory Framework

Pennsylvania needs to establish the necessary framework for decarbonization to benefit both the environment and the Pennsylvania economy. It is essential that the commonwealth establish a statutory framework that attracts project developers and investors. Without this basic, foundational requirement, Pennsylvania will struggle to attract the projects and infrastructure needed to decarbonize while maintaining a robust economy and workforce.

As discussed earlier, the two most significant aspects not addressed by Pennsylvania law include pore space and primacy. Currently the commonwealth does not possess the statutory authority and, therefore, has not promulgated the rules to address a myriad of pore space issues, liability issues, and the control of the permitting process to ensure commercial entities experience certainty and timely responses.

Suggested Action: The commonwealth should immediately commission a study to address the statutory and regulatory issues addressed by the Road Map. This study should address the commonwealth's legislative and executive branch operational issues to determine the timing and mechanisms to move legislation through Harrisburg. With an understanding of the timing and political players (e.g., Governor's office, House and Senate leadership, etc.), the study should focus on the legislation details regarding the following topics:

Pore space ownership: Define CO_2 ownership from capture to post closure. Establish or confirm mineral rights primacy, define how subsurface activities will be coordinated, and establish unitization or amalgamation of rules/thresholds for CO_2 storage reservoirs. Establish CO2 stewardship requirements for each stage of a carbon storage project.

Liability: Possible exclusion to any operator post-closure liability relief, e.g., commonwealth assumption of liability in instances where an operator failed to comply with applicable standards or otherwise provided deficient or fraudulent information to secure approval of site closure.

Administration: Establish an organization within state government to administer and provide the statute and regulations to enforce CO_2 storage activities and regulate the projects. Ensure sufficient long-term resource and capacity needs for efficient project review and agency oversight.

2. UIC Class VI Primacy

The commonwealth should determine its interest in controlling the timing of the review of Class VI permits, obtaining the human and technical resources needed to review Class VI permits, and willingness to make legislative and statutory changes necessary to apply for Primacy of the UIC Class VI program.

As part of this decision matrix, it is recommended that Pennsylvania utilize the available funding through the Bipartisan Infrastructure Law (BIL), which sets aside $50MM for states to access to augment current human and project capital, to action a road map to determine the necessary changes required for primacy application, as well as to provide internal state human resource and technical support.

Specific topics identified by the BIL include:

- **Program startup**: There may be unavoidable delays between the approval of permits and actual operation of permitted wells such that the EPA funding will be necessary and should be provided to bridge that gap and allow approved state primacy programs to establish a sound Class VI program foundation.
- **Training**: States will also need additional support for the hiring and training of state Class VI personnel, and the state program funding programs likely do not address these costs. EPA is developing a training program for Class VI permit application reviewers, a program that will be available to state agency personnel as well. EPA should provide hiring and training funding through its BIL appropriations to allow state agency personnel to participate in the EPA training. The Ground Water Protection Council is developing a complementary and more intensive training curriculum designed specifically for state agencies and personnel to prepare them to implement the Class VI program and review permit applications. EPA funding should also support the participation of state UIC program personnel in this training program.
- **Data management**: States will have initial and ongoing costs for computers and programs to manage routine data elements associated with Class VI injection. These costs include an IT infrastructure to manage a program (hardware), management of the data generated by the program (custom software), annual maintenance of infrastructure, replacement plans for aging technology, estimated future costs for growth of the program in the IT budget, and planning for additional costs of customizations and upgrades of software. States will need funding to establish these systems before they have funding available from permitting and operating fees. This data management can and should be considered part of any data collection and curation plan should the commonwealth consider a digitization transformation.

The EPA has suggested a request letter to better understand which states are interested and a template is provided in Appendix A: EPA Class VI Support template.

Suggested Action: Class VI primacy is one of the most significant issues hindering Pennsylvania's advancement of commercial CCUS. Under the current constraint, the EPA will likely take years to process Class VI applications. The commonwealth must decide if it can process applications more quickly than the EPA and identify if it has the resources and technical expertise to take on primacy and can afford to maintain this expertise should it acquire it.

If the commonwealth chooses not to pursue Class VI primacy, it should consider entering into a work share agreement (e.g., memorandum of understanding (MOU)) with the EPA to allow Pennsylvania regulatory "assistance" and "engagement" with the EPA for Pennsylvania-submitted permits.

The BIL contains $50 million set aside for states to assist in this process of "deciding", "scoping", and "writing new regulations," based on whether a state pursues primacy or a work share relationship. Not pursuing the BIL primacy funding should not be an option.

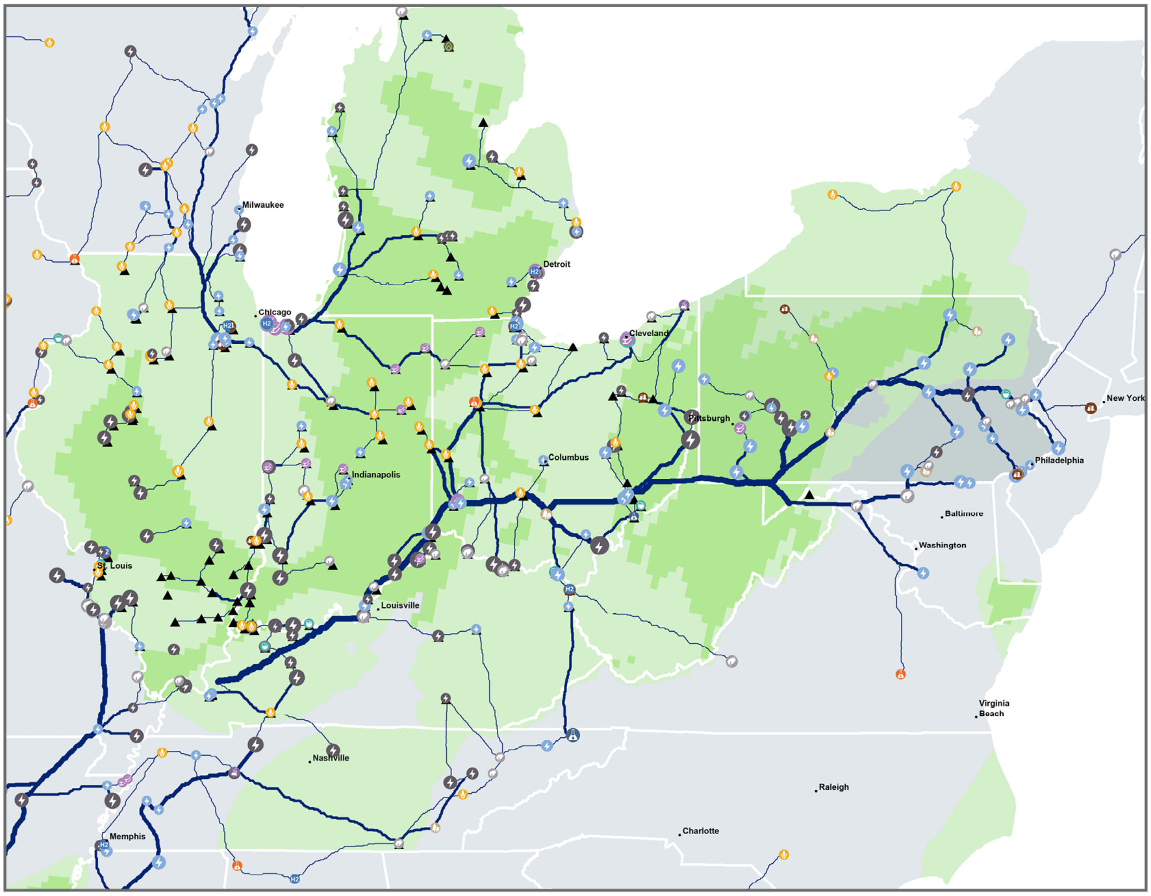
3. Consider Regional Approaches (intra- and inter- state opportunities)

Pennsylvania has a great opportunity to participate in a network connecting northeastern US emission sources with low-cost, high-capacity geologic storage in the Ohio River Valley. This notion of inter- and intra-state opportunities is the only mechanism allowing states to partner and cross borders. The Team Pennsylvania Foundation is well suited to lead these efforts and should consider which opportunities best suit the program and policy goals of the commonwealth. Many of these regional efforts are described in GPI's recent CCUS report (GPI, 2022), presented in figure 6 below and the recent Hydrogen Atlas (GPI, 2022) Western Pennsylvania hydrogen opportunities, located in Appendix B.

Suggested Action: Pennsylvania must quickly determine what inter-state opportunities it will pursue. Many of these collaborative efforts, including the upcoming BIL hydrogen hub FOA, will require predetermined discussions, decisions, and execution of agreements defining these inter-state relationships. Pursuant to the RFI and NOI released by DOE, it is expected that the entity submitting a response to the hydrogen hub must be a corporation or agency capable of actioning the tasks required by the FOA.

Many states have engaged in partnerships and signed MOUs. Some have created or planned to use quasi-state-like entities to lead the efforts, e.g., New York State Energy Research and Development Authority and Wyoming Energy Authority. This requirement puts Pennsylvania in a reactive position instead of a proactive position and it is recommended that, with all due haste, the commonwealth determine if, when, and how it intends to engage with any inter-state partners and to engage both the executive and legislative branches as soon as possible to address this issue.

Figure 6: Regional-scale opportunities for CO_2 transport corridors



Source: Figure authored by Elizabeth Abramson, 2022. Based on results of the SimCCS model and data from EPA GHGRP, 2020; NATCARB, 2015; SCO_2T, 2020.

Optimized transport network for midcentury CO_2 capture and storage

- Regional CO_2 infrastructure (modeled)
- Potential CO_2 storage area

Geologic storage opportunity

- Assessed low-cost saline storage
- Saline CO_2 storage formation

Capture sources

- Ammonia
- Cement & lime
- Chemicals
- Coal power
- Ethanol
- Gas power
- Gas processing
- Metals, minerals & other
- Petrochemicals
- Pulp & paper
- Refineries
- Steel
- Waste

4. Department of Energy Hydrogen Hubs

The commonwealth does not currently have the necessary agreements and structures to be an applicant compliant with the expected FOA. It is unknown if the commonwealth has the necessary data, participants, and stakeholder engagement to understand the hydrogen production options—how much, by whom, and where—to address the suspected requirements for the hydrogen hubs FOA.

Suggested Action: The commonwealth should immediately identify any teaming partners, likely neighboring states, and prepare the necessary agreements, MOUs, and structures to allow the state to engage as a prime partner for the hydrogen hubs FOA. The RFI can be found in the Federal Register.

5. Bipartisan Infrastructure Law (BIL) Funding

There is significant funding under the BIL set aside specifically to address many of the issues and tasks necessary for the full-scale commercial deployment of carbon management projects and hydrogen production as a means to decarbonize. The commonwealth should consider as many funding mechanisms as possible to advance Pennsylvania-centric deployments, such as those in the BIL technical assistance guide.

These considerations may include:

- UIC Class VI Primacy support - $50MM
- Abandoned or Orphaned Well Program - $25MM for each State
- Abandoned or Orphaned Well Program regulatory improvements - $20MM for each State
- Abandoned or Orphaned Well Matching Grants to plug, remediate, reclaim, and mitigate - $30MM for each State
- Abandoned or Orphaned Well Funding to plug, remediate, reclaim, and mitigate on Federal Lands - $30MM from DOE, Interstate Oil and Gas Compact Commission, Bureau of Land Management, and States
- Hydrogen Hubs - $8 billion

Suggested Action: BIL funding is readily available and should be pursued by the commonwealth. The federal government has provided significant access to funding in many of the areas discussed in this Road Map. The commonwealth should identify lead agencies to process the required application and paperwork to gain access to funding. This task is also a low-cost, immediate opportunity to assist Pennsylvania in advancing its “open for business” stance.

6. Future Studies

Many of the suggestions in this Road Map cannot be addressed until further information, details, structure, statutes, and funding exist. To that end, the commonwealth should commission several further studies that would augment, support, and advance much of the work detailed by the Road Map.

Suggested Action: The commonwealth should consider commissioning the following studies that can assist in providing guidance, certainty, data, and analysis that are likely needed and will be requested by stakeholders as the Road Map is implemented. These studies include:

Appendix C: GPI Pennsylvania CO_2 Capture & Storage Opportunities Fact Sheet 2022 provides a first look at the deployment potential of CCUS projects within the state. If the commonwealth actions the suggested tasks in the Road Map, there will be significant removal of barriers (e.g., regulatory uncertainty, etc.) that can have a positive impact on the commercial-scale deployment of CCUS. This suggested study should address "potential" projects, not just the projects that have been announced. Understanding what project developers are thinking, planning, and willing to speak about will only occur if the commonwealth engages with them.

Stakeholder engagement and outreach effort to identify, understand, and address stakeholder (e.g., project developers) concerns and issues. Currently, many of these barriers are unknown and make it difficult for the commonwealth to prepare for commercial-scale projects. This effort will have synergies with the next suggested effort, which is an economic impact—jobs and tax revenue—of commercial-scale CCUS deployment.

Jobs and economic analysis of the impact of CCUS commercial deployment on the commonwealth. This work should advance existing work that includes Appendix D: Rhodium Group Jobs Report and Appendix E: Jobs and Economic Impact of Carbon Capture Deployment: Midcontinent Region. Once completed, this work will allow the state to better understand and forecast the job creation and financial impact (e.g., tax revenue) of the commercial aspects of CCUS.

Hydrogen production study that will serve as the basis for DOE FOA 2664 Hydrogen Hub submittal. The upcoming FOA will require the commonwealth to address hydrogen production from a variety of feedstocks, discuss and implement a plan for the distribution of the produced hydrogen, and discuss the economic and greenhouse gas emission reduction of hydrogen use. These topics are not yet defined by the state and are a critical part of the proposal. It would be incumbent on the state to be able to answer these topics and have supporting data.

Hydrogen color-blind study could address several topics that include EESJ, stakeholder engagement, social license to operate, and outreach. The commonwealth should complete the suggested hydrogen color-blind study that evaluates the fuel feedstock used by the process to produce the hydrogen and the carbon intensity of the production process. Similar to the two most important issues identified by this Road Map—pore space and primacy—a color-blind hydrogen study will have great value in addressing much of the misinformation surrounding hydrogen and provide data for stakeholder engagement, EESJ, and the larger overarching social license to operate that has become key to much of the energy space under the Biden Administration. The current EESJ requirements and social/community engagement are fraught with issues using color-coded descriptions of hydrogen production. A first mover to eliminate the color-coding and provide a level-basis, common language to talk about the feedstock and carbon intensity or carbon footprint of the process will have a significant advantage in the social license and stakeholder engagement process.

7. Digital Transformation

Digitizing the commonwealth's subsurface data will allow for consistency in curation and updates. Digitization will allow developers looking for the latest screening data for pore space decisions to save time and will invite commercial developers because it will reduce project screening and decision time. This data is applicable to carbon management projects for Class VI considerations as well as hydrogen storage options. The commonwealth should invest in server/data infrastructure that combines current data accessible to the commonwealth, e.g., Department of Natural Resources-State Geological Survey, Department of Environmental Protection-Oil and Gas Management, publicly available data from EDX, NATCARB, the US Geological Survey, and others, and private data available from industry. Academia should be included in this digital transformation as there are potential value-added options that they bring to the table.

A suggested place to start compiling data is with Pennsylvania's EDWIN database, which is maintained and served by the Pennsylvania Department of Conservation and Natural Resources (PDCNR) Bureau of Geological Survey (BGS) and includes the most comprehensive archive and searchable database of Pennsylvania's oil and gas well data and subsurface geological data/geophysical logs/sample studies. In addition, the PDCNR BGS has been involved in all the mapping/data creation for EDWIN that is associated with EDX, NATCARB, and the US Geological Survey. With the proper financial support, the existing EDWIN system can be expanded to include additional digital datasets and combined with proper funding and development of Pennsylvania Department of Environmental Protection's (PDEP) existing online tools, both agencies will be aptly prepared to provide a significant data resources that would allow project developers to focus on pore space opportunities, the state's regulatory requirements, and permit tracking.

Suggested Action: The commonwealth should initiate the digitization of its subsurface data immediately. Advancing the development of an enhanced Exploration and Development Well Information Network (EDWIN) customer-facing portal is a near-term, cost-effective next step.

8. Comment and Engage Where Possible

There are currently several proposed regulatory changes and possible public policy opportunities for the commonwealth to engage on through commenting and other actions. This engagement can be seen as positive and risk-reducing and can incentivize and encourage project developers to invest in Pennsylvania. Additionally, commenting on these issues provides the commonwealth with "standing" in the event they would like to further challenge proposed regulatory changes, etc.

Current options for such engagement include:

- EPA GHG Report Tool Subpart PP, to include Direct Air Capture (DAC), as part of 45Q
- EPA GHG Report Tool Subpart VV, to allow EPA to post 45Q applications using CSA/ANSI ISO 27916:19 Carbon dioxide capture, transportation, and geological storage — Carbon dioxide storage using EOR to be shared publicly

- 45Q Direct Pay Conversations on direct pay and credit transferability in conjunction with the Carbon Capture Coalition (116th Congress, renewable-specific)
- SEC Release Nos. 33-11042; 34-94478, The Enhancement and Standardization of Climate-Related Disclosures for Investors Registrants with Exchange Act reporting obligations pursuant to Exchange Act Section 13(a) or Section 15(d)

Suggested Action: Pennsylvania is behind other states with respect to the regulatory, statutory, and infrastructure required to advance commercial-scale carbon management deployment. Engaging in public discourse and providing thoughtful responses to public inquiries allows Pennsylvania to dispel some negative stakeholder perceptions, and allows Pennsylvania to engage with industry and commonwealth stakeholders in the other opportunities in this Road Map.

It is also suggested that the state begin a state-wide and value-chain-wide stakeholder engagement. Pennsylvania is not considered “in the game,” and that perception must change, beginning with industry engagement. Ask industry stakeholders what they need and ask them to define, from their perspective, why they haven’t engaged with the commonwealth. With the information from this Road Map, coupled with industry-specific data and suggestions, it should be easier and clearer to address what Pennsylvania is lacking for commercial deployment of CCUS.

9. Use/Acceptance of Standards and Best Practices

Standards and best practices offer an independent and pre-approved method to accomplish many aspects or tasks within the carbon management value chain. These standards and best practices can offer regulatory certainty if cited by statute, which can translate to economic efficiencies that provide needed de-risking and may be the difference between securing financial close or financial failure. Many standards are internationally created, reviewed by certifying bodies, and accepted by the US. Other best practices have been developed by DOE over years of research and may assist the commonwealth in attracting, driving, and sustaining carbon management at full-scale commercial deployment. Standards and best practices to consider are listed in Appendix F.

Suggested Action: Standards and best practices are generally easy solutions when attempting to provide clarity and consistency for project development and implementation. Specifically, the DOE Best Practices Manuals are free. Most Standards, while having a cost of several hundred dollars, don’t need to be purchased by the state, only that the standards are enforced. The latter takes political will, which may not come easily or quickly. Any state agency (e.g., Pennsylvania Department of Environmental Protection (PDEP) or Pennsylvania Department of General Services (PDGS)) can cite, refer to, or require using a standard or best practice when processing permit applications or permits to operate. If chosen, this can be an immediate and low-cost method to provide consistency and certainty to industry.

10. Environmental, Energy, and Social Justice (EESJ)

States can rely on EPA and DOE websites and dashboards for data and screening to be used for project decisions that will use federal funding. The commonwealth can position itself to be efficient with good state-specific data and to provide the federal government an advanced tool in Pennsylvania that builds on and advances the early beta versions put forth by the federal government. There are several options that can position Pennsylvania better on EESJ, including a digital transformation to collect and curate the necessary data for any EESJ considerations. The data can and should help advance DOE and the whole of government to better understand and implement projects that:

1. Establish standards and metrics to ensure tangible reductions in greenhouse gas emissions.
2. Decrease energy burden in disadvantaged communities.
3. Decrease environmental exposure and burdens for disadvantaged communities.
4. Increase parity in clean energy technology access and adoption in disadvantaged communities.
5. Increase access to low-cost capital in disadvantaged communities.
6. Increase clean energy enterprise creation (minority or disadvantaged business enterprises) in disadvantaged communities.
7. Increase the clean energy job pipeline and job training for individuals from disadvantaged communities.
8. Increase energy resiliency in disadvantaged communities.
9. Increase energy democracy in disadvantaged communities.

Suggested Action: EESJ requirements are a requirement of all BIL funding and will be part of any federal funding, at least during the remainder of the Biden Administration. The commonwealth should consider two immediate action items to advance the EESJ requirements.

Implement the EPA's Environmental Justice (EJ) Screening Tool across all state and federally-funded projects. The EJ screening tool allows projects to meet responsibilities related to the protection of public health and the environment. The tool is based on nationally consistent data and an approach that combines environmental and demographic indicators in maps and reports.

Continue to develop and advance PDEP's Environmental Justice Areas Viewer. This Pennsylvania-specific EJ screening and mapping tool is an outgrowth of the digitalization effort discussed earlier and can allow a more detailed methodology to be put in place by the commonwealth. It also allows the commonwealth to incorporate significant state-level data that is missing from the EPA's EJ tool. Environmental justice issues vary throughout the country and the continued development of a Pennsylvania-specific EJ screening tool allows project developers to efficiently address EJ concerns in the commonwealth.

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Appendix A: EPA Class VI Support Request Letter Template

<<date>>

Mr. Michael S. Regan, Administrator
Environmental Protection Agency
Mail Code 1101A
1200 Pennsylvania Avenue, N.W.
Washington, DC 20460

Via email at: Regan.Michael@epa.gov; Brenda.Mallory@ceq.eop.gov;

RE: Infrastructure Investment and Jobs Act (IIJA) (H.R. 3684), Secure Geologic Storage Permitting (Sec. 40306) for EPA's Class VI UIC well permit grant program for states seeking Class VI primacy

Dear Administrator Regan,

Pursuant to the Infrastructure Investment and Jobs Act (IIJA), Section 40306, the Commonwealth of Pennsylvania intends to request grant funds to the maximum extent possible under the program to develop, implement, and action a request for primacy of the EPA's Underground Injection Control (UIC) Class VI Well Program.

It is our understanding that the details of these awards under this Section of the IIJA have not yet been finalized. The intent of this letter is to provide notice to EPA of Pennsylvania's intent to request funds and a request that EPA provide information about the primacy grant award program, as soon as it is available.

If you have any questions or if we can provide any additional information, please do not hesitate to reach out at your earliest.

Respectfully,

Commonwealth of Pennsylvania

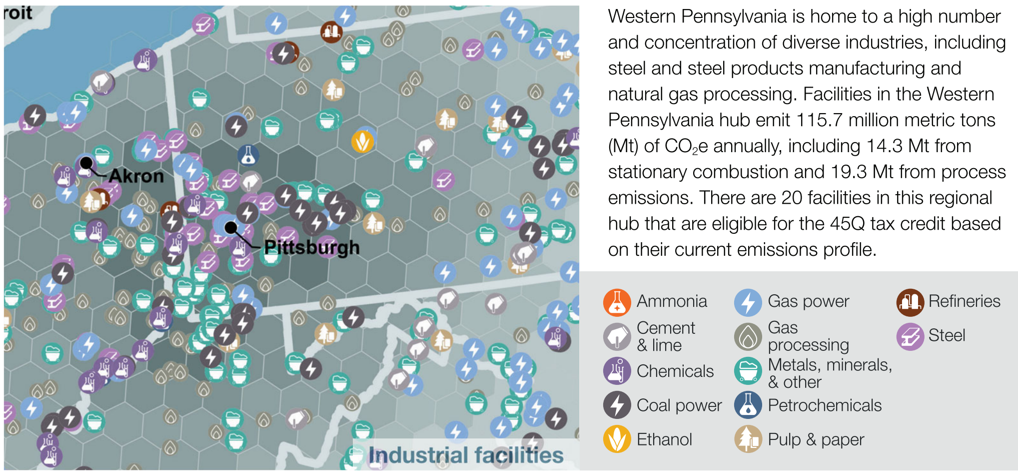
pc: Brenda Mallory, Chair, White House Center on Environmental Quality
Adam Ortiz, Regional Administrator, EPA Region 3

Appendix B: GPI US Carbon & Hydrogen Hubs Atlas - Western Pennsylvania

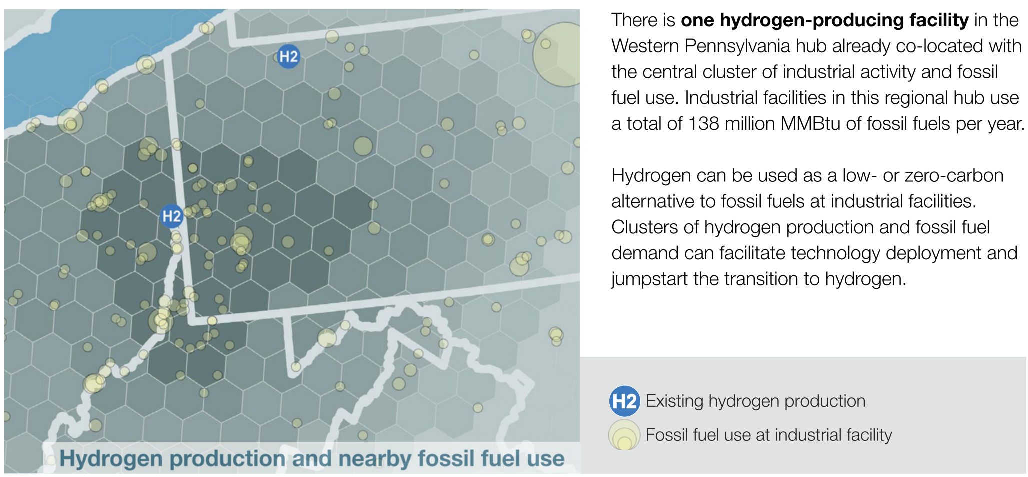
Western Pennsylvania Hub

The existing landscape of industrial production, commodity transport infrastructure, and geologic carbon storage capacity make Western Pennsylvania a natural launching point for investment in carbon capture and low-carbon hydrogen deployment.

Industrial Emissions and Fossil Fuel Use



Western Pennsylvania is home to a high number and concentration of diverse industries, including steel and steel products manufacturing and natural gas processing. Facilities in the Western Pennsylvania hub emit 115.7 million metric tons (Mt) of CO_2e annually, including 14.3 Mt from stationary combustion and 19.3 Mt from process emissions. There are 20 facilities in this regional hub that are eligible for the 45Q tax credit based on their current emissions profile.



There is **one hydrogen-producing facility** in the Western Pennsylvania hub already co-located with the central cluster of industrial activity and fossil fuel use. Industrial facilities in this regional hub use a total of 138 million MMBtu of fossil fuels per year.

Hydrogen can be used as a low- or zero-carbon alternative to fossil fuels at industrial facilities. Clusters of hydrogen production and fossil fuel demand can facilitate technology deployment and jumpstart the transition to hydrogen.

Industrial facility emissions

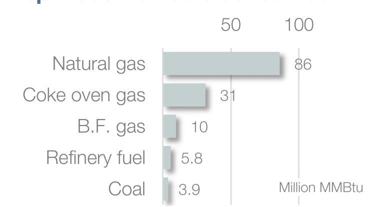
Sector	Total # of Facilities	Total Emissions	Stationary Combustion Emissions	Process Emissions
Cement	1	0.2	< 0.1	0.2
Chemicals	5	0.8	0.8	-
Coal power plants	18	75.8	2.5	-
Gas power plants	13	9.0	0.2	-
Gas processing	44	2.9	2.6	0.3
Metals, minerals & other	37	18.5	0.9	17.6
Petrochemicals	2	0.1	0.1	-
Pulp & paper	2	0.1	0.1	-
Refineries	2	0.8	0.6	0.2
Steel & steel products	28	7.5	6.5	1.0
Total	**152**	**115.7**	**14.3**	**19.3**

All emissions are in million metric tons CO_2e.

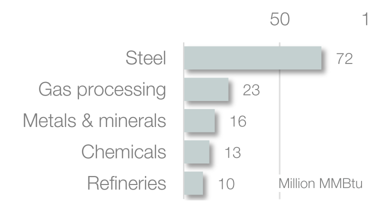
The top industrial fuels consumed in the Western Pennsylvania hub include natural gas at 86 million MMBtu per year and coke oven gas at 31 million MMBtu per year. Steel and gas processing plants are the largest consumers of fossil fuels in this regional hub, consuming 72 million MMBtu and 23 million MMBtu of fossil fuels, respectively.

Using hydrogen as a medium- and high-intensity energy source to displace conventional fossil fuels can reduce combustion emissions alongside other solutions like electrification and renewable energy. Process emissions from product manufacture are another major source of GHGs at industrial facilities. These production processes may not involve fuel combustion and would require other solutions such as carbon capture to fully decarbonize.

Top industrial fuels consumed



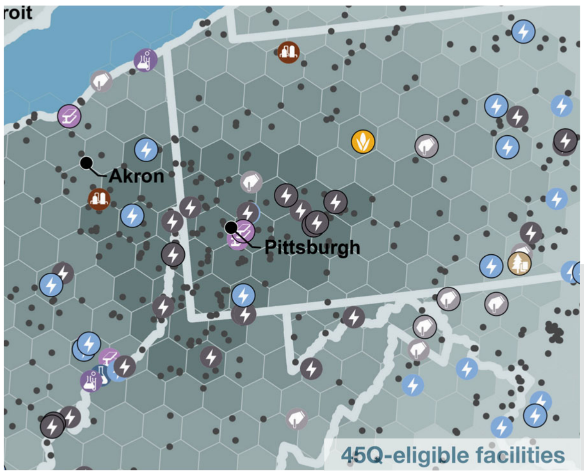
Largest fuel-consuming industries



Western Pennsylvania Hub

Carbon capture and storage is an essential tool for achieving midcentury climate goals, maintaining the competitiveness of US industry, and protecting and creating high-wage jobs. Carbon capture is crucial in decarbonizing key carbon-intensive industries where CO_2 emissions are inherent to the chemistry of production processes and cannot be eliminated solely by switching to low-carbon electricity. The US has capacity to safely and permanently store thousands of years of carbon emissions in geologic saline formations.

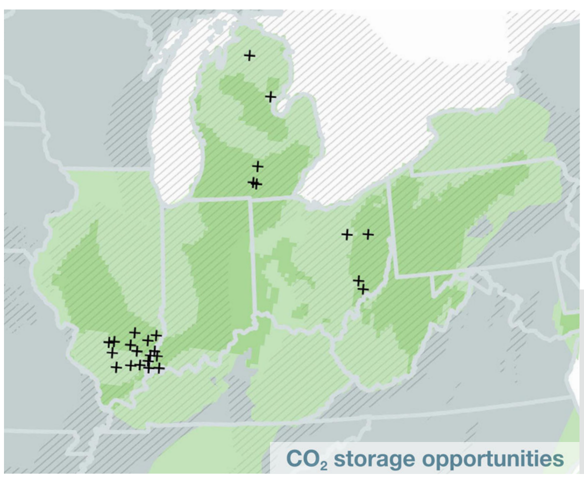
Carbon Capture and Storage



The Section 45Q tax credit lowers cost barriers to carbon capture and storage. Among the 20 industrial and power facilities in the Western Pennsylvania hub that meet emissions thresholds for Section 45Q eligibility, nine have been identified as near- to medium-term candidates for capture retrofit over the next 10 to 15 years.

45Q-eligible facilities by industry

- Cement & lime
- Steel
- Coal power
- Near- to medium-term
- Gas power
- Additional emitting facility
- Refineries

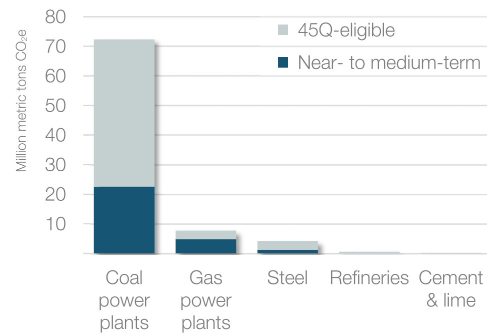


Western Pennsylvania has potential to act as a major carbon storage destination for capture facilities and carbon removal. The state of Pennsylvania has potential to store 18 billion metric tons of CO_2 in secure geologic saline formations, and also has extensive capacity for carbon storage in geologic fossil basins.

Geologic storage opportunity

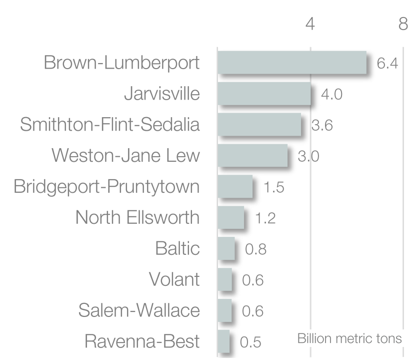
- Assessed low-cost saline storage
- Saline CO_2 storage formation
- Fossil CO_2 storage formation
- + Existing petroleum production site

Carbon capture opportunities

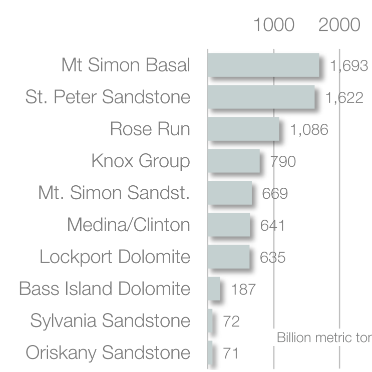


- Industrial and power facilities emit **115.7 Mt CO_2e per year**
- **45Q-eligible** facilities emit **85.5 Mt CO_2e per year**
- **28.6 Mt CO_2 per year** are **capturable** in the **near- to medium-term**

Fossil storage formations
by CO_2 storage capacity



Saline storage formations
by CO_2 storage capacity

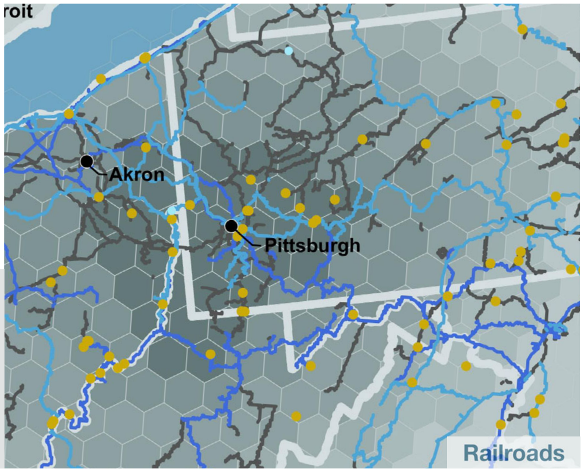


Western Pennsylvania Hub

Industrial hubs can offer existing transportation infrastructure, delivery routes, and distribution networks needed for the efficient supply of feedstocks and delivery of products. Hydrogen may be blended into existing natural gas pipelines for co-firing, and both carbon and hydrogen could be transported by rail, freight trucking, or barge. Existing pipeline rights-of-way may be crucial for efficient and equitable routing of new CO_2 pipelines for utilization and permanent storage.

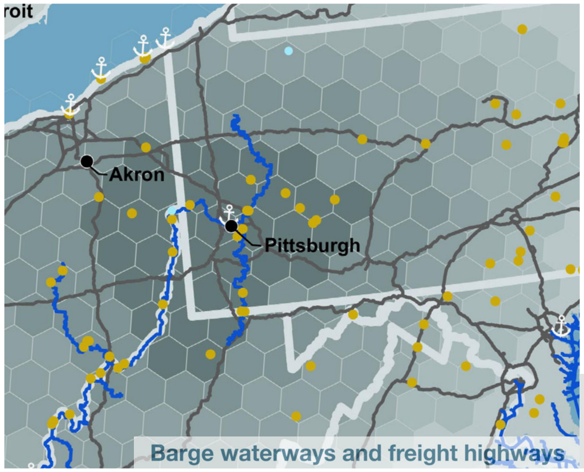
Transport Infrastructure

Many industrial facilities are located along rail lines and often use rail transport to import and export goods. Railroads can also play a role in transporting captured carbon and hydrogen. Many of the facilities in the Western Pennsylvania hub are located along major rail lines, facilitating connection to markets across the US.



Railroad networks
- Union Pacific Railroad
- BNSF Railway
- CSX Transportation
- Norfolk Southern Railway
- All others

Freight trucks and barges can each play a role in the development of carbon and hydrogen transport networks. Both transport options are flexible, enabling routes to evolve over time and the frequency of transport to adapt in line with the volume of material being transported. With several major ports on Lake Erie and access to shipping channels along the Ohio river, Western Pennsylvania is well-positioned to access global and international markets for carbon and hydrogen.

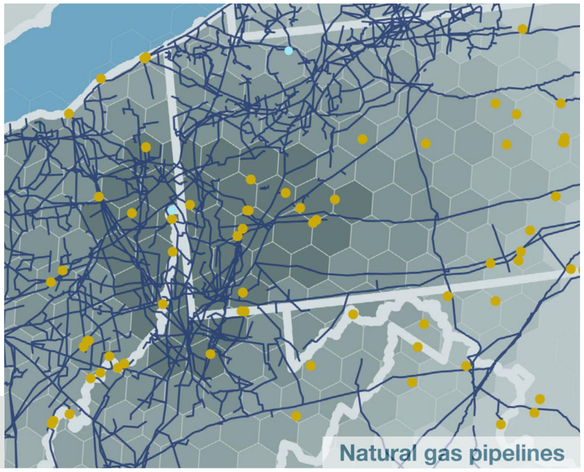


- Interstate highway
- Navigable waterway
- Major port

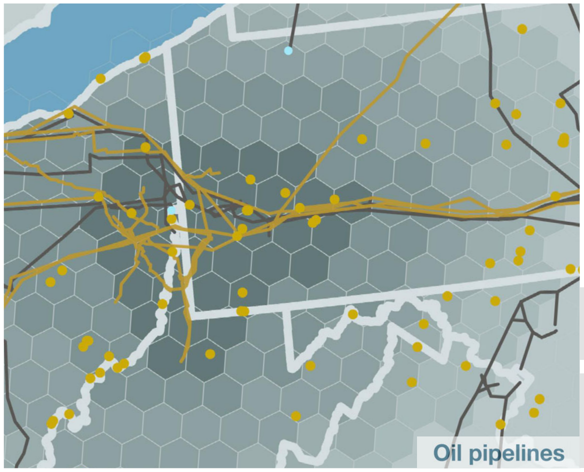
Logistical challenges to carbon and hydrogen pipeline deployment can be reduced by following existing right-of-way of natural gas lines. The Western Pennsylvania hub currently has 5,323 miles of natural gas pipelines.

Infrastructure	Miles
Natural gas pipelines	5,323
Oil pipelines	1,406

- Existing CO_2 pipelines
- Natural gas pipelines



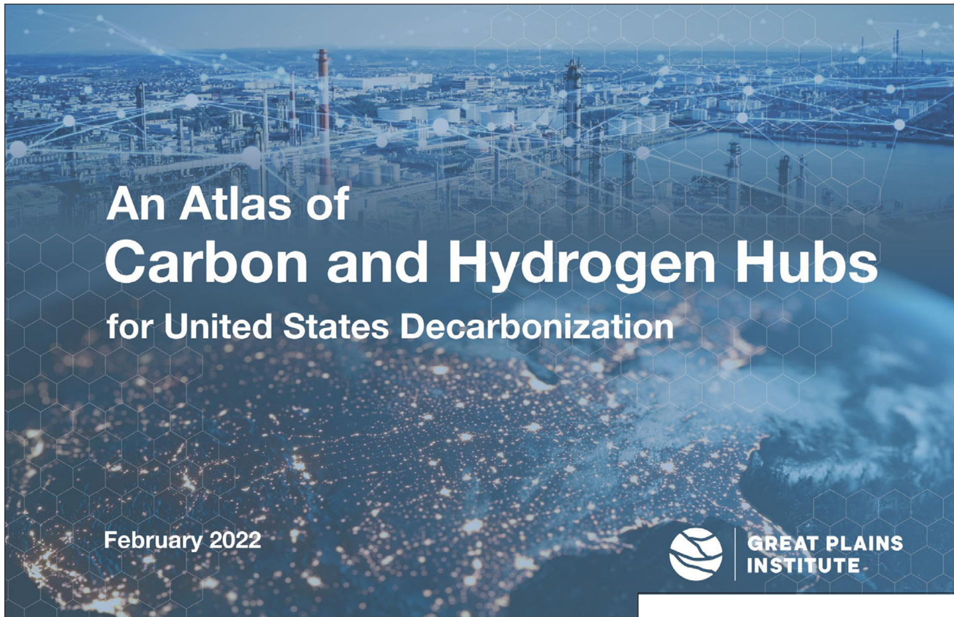
Collocating new CO_2 and hydrogen pipelines along existing pipeline routes can maximize efficiency and reduce surface impacts. New CO_2 and hydrogen pipelines could follow existing right-of-way established along the Western Pennsylvania hub's 1,406 miles of oil pipelines to achieve efficient buildout.



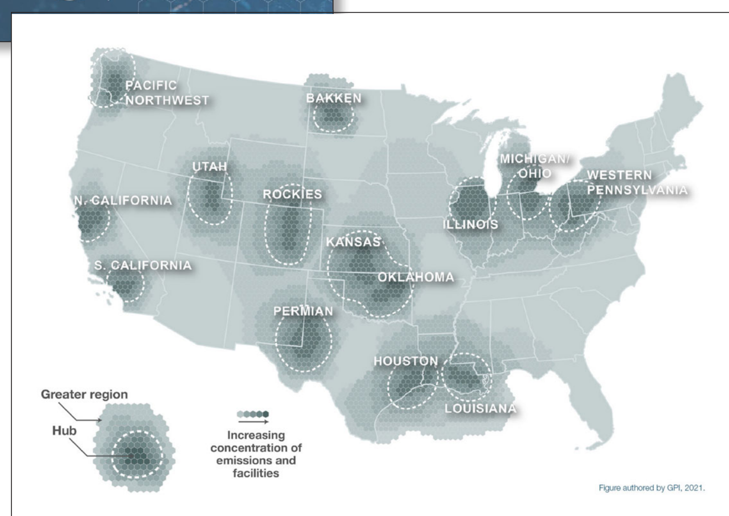
- 45Q-eligible facility
- Existing hydrogen production

- Existing CO_2 pipelines
- Hydrocarbon gas liquids pipelines
- Petroleum pipelines

GPI's Atlas of Carbon and Hydrogen Hubs



Download the report at carboncaptureready.org



About the Great Plains Institute

A nonpartisan, nonprofit organization, the Great Plains Institute (GPI) is transforming the energy system to benefit the economy and 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.

Learn more: www.betterenergy.org

GREAT PLAINS INSTITUTE

February 1, 2022

Appendix C: GPI Pennsylvania CO_2 Capture & Storage Opportunities Fact Sheet

Pennsylvania CO_2 Capture and Storage Opportunities

Pennsylvania is the fourth largest emitting state nationally and has large contributions from a range of sectors.[1] Each sector varies in emissions and fuel profiles, presenting unique considerations to accomplish sector-wide decarbonization.

Analysis by the Great Plains Institute and Carbon Solutions, LLC assessed the potential for carbon capture retrofit at industrial and power facilities in Pennsylvania. This analysis created a number of scenarios for carbon capture, transport, and storage in Pennsylvania and the surrounding region.

[1] US Energy Information Administration, 2019.

Pennsylvania 45Q-eligible facilities, by sector

Sector	# Eligible facilities	CO_2 emissions	Capture estimate
Cement	8	3.9	3.3
Coal power plants	9	24.4	20.8
Ethanol	1	0.2	0.4
Gas power plants	23	44.4	34.7
Metals & minerals	1	0.9	0.1
Pulp & paper	4	2.7	1.0
Refineries	2	1.8	0.4
Steel	1	3.5	1.0
Waste	1	0.9	0.8
Total	**50**	**81.8**	**62.4**

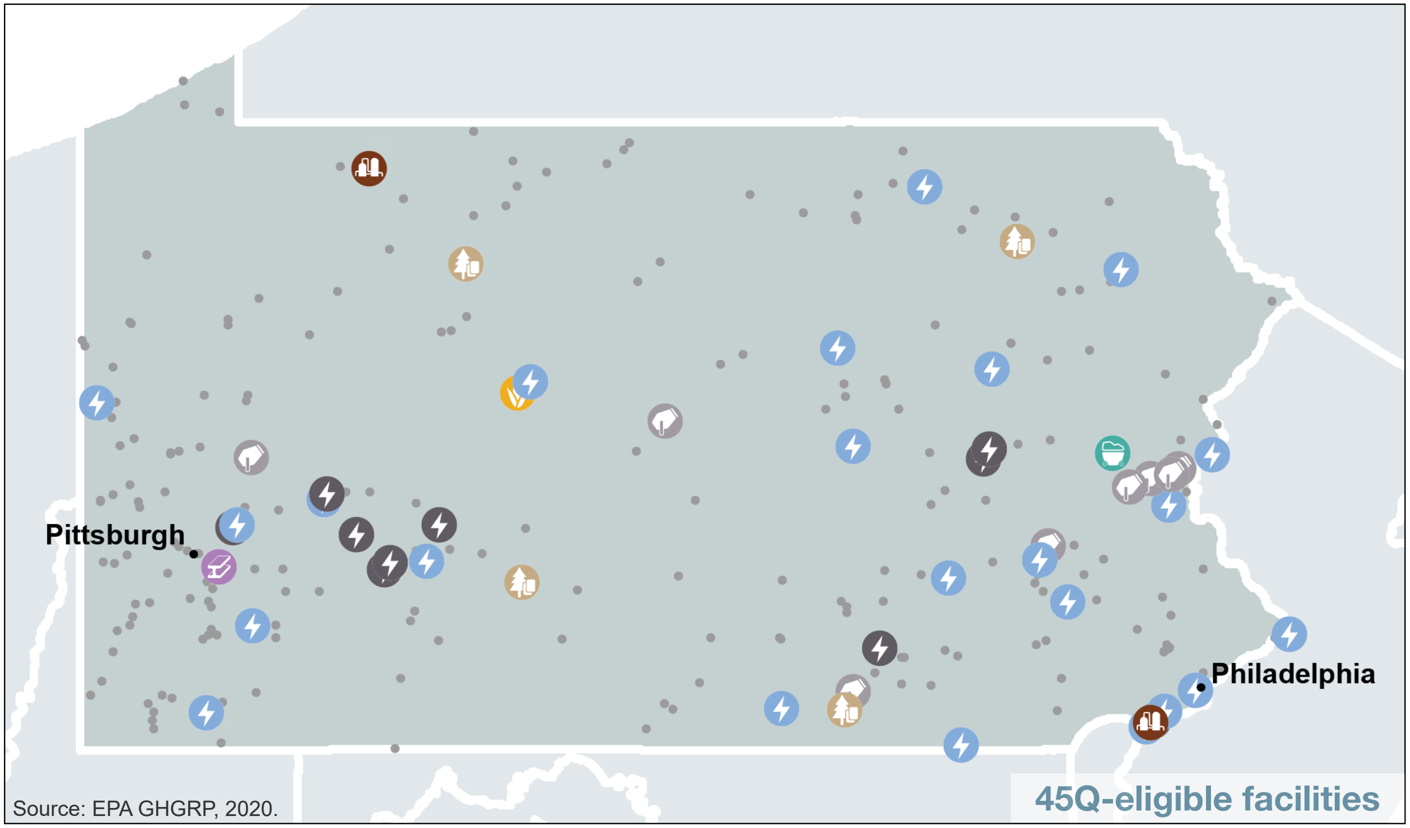
Source: EPA GHGRP, 2020. Emissions in million metric tons CO_2 per year

CO_2 capture opportunities

There are 50 facilities in Pennsylvania that are eligible for the Section 45Q tax credit. These facilities emit a total of 81.8 million metric tons per year, of which it is estimated that 62.4 million metric tons would be suitable for capture annually. The state's 45Q-eligible facilities account for 89% of all emissions from stationary combustion sources in the state.

45Q-eligible facilities

- Cement & lime
- Coal power
- Ethanol
- Gas power
- Metals & minerals
- Pulp & paper
- Refineries
- Steel
- Waste
- Additional emitting facilities



Pennsylvania CO_2 Capture and Storage Opportunities

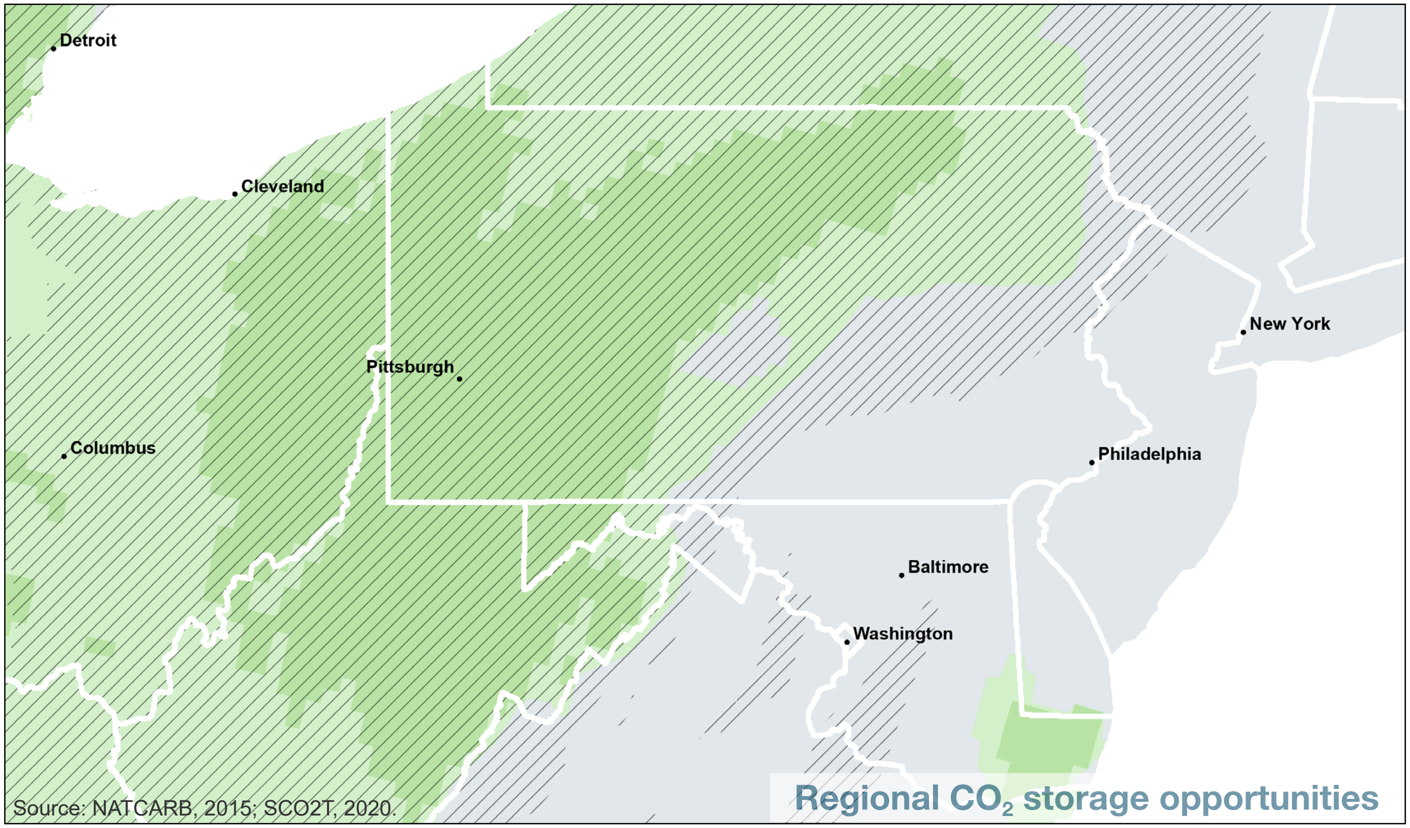
Regional geologic CO_2 storage opportunities

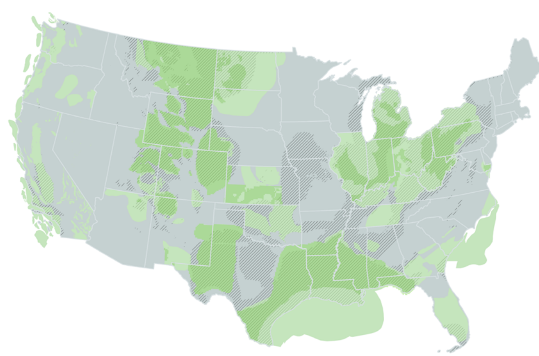
Pennsylvania, the Ohio River Valley, and Appalachia have a multitude of geologic formations for long-term storage opportunities. Storage capacity varies between formations, with the Rose Run and Lockport formations each providing over 10 billion metric tons of technical CO_2 storage capacity within Pennsylvania, Ohio, and West Virginia alone.

Data on geologic CO_2 storage potential is provided by the Department of Energy's National Carbon Sequestration Database and Geographic Information System (NATCARB) and Carbon Solutions LLC's, SCO_2T^{PRO} model.

Geologic formation	Regional CO_2 storage capacity Billion metric tons
Rose Run	10.8
Lockport	10.2
Mt. Simon	3.1
Oriskany	1.7
Sandusky	0.9
Potsdam	0.3
Rome Trough	0.1

Source: $SCO_2T^{PRO.}$ 2022.





Geologic storage opportunity

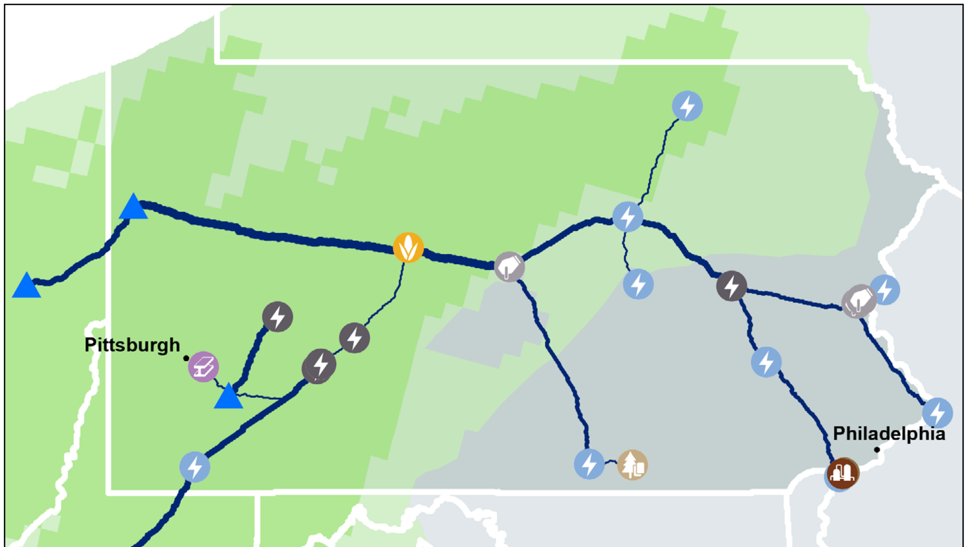
- Assessed low-cost saline storage
- Saline CO_2 storage formation
- Fossil CO_2 storage formation

Pennsylvania CO_2 Capture and Storage Opportunities

CO_2 transport infrastructure scenarios

Near-term opportunities

A near-term opportunity scenario incorporated facilities identified as candidates with a potential positive return on investment in carbon capture retrofit in the near-term (10-15 years). The 22 facilities in this cohort include a range of industrial and power facility types. This scenario is linked by 933 miles of new infrastructure and would transport 34.7 million metric tons of CO_2 to storage hubs per year.



Near-term CO_2 capture and transport opportunities

Long-term planning

A midcentury scenario included capture at all 50 of Pennsylvania's 45Q-eligible industrial and power facilities. This scenario uses 1,433 miles of infrastructure and would transport 41.6 million metric tons of CO_2 to long-term storage hubs annually. The Great Plains Institute's 2020 *Transport Infrastructure for Carbon Capture and Storage* found beneficial economies of scale and cost savings when planning CO_2 transport networks for the long term.

Midcentury CO_2 capture and transport opportunities

Optimized transport network for CO_2 capture and storage

- Regional CO_2 infrastructure (modeled)
- Potential CO_2 storage area

Geologic storage opportunity

- Assessed low-cost saline storage
- Saline CO_2 storage formation

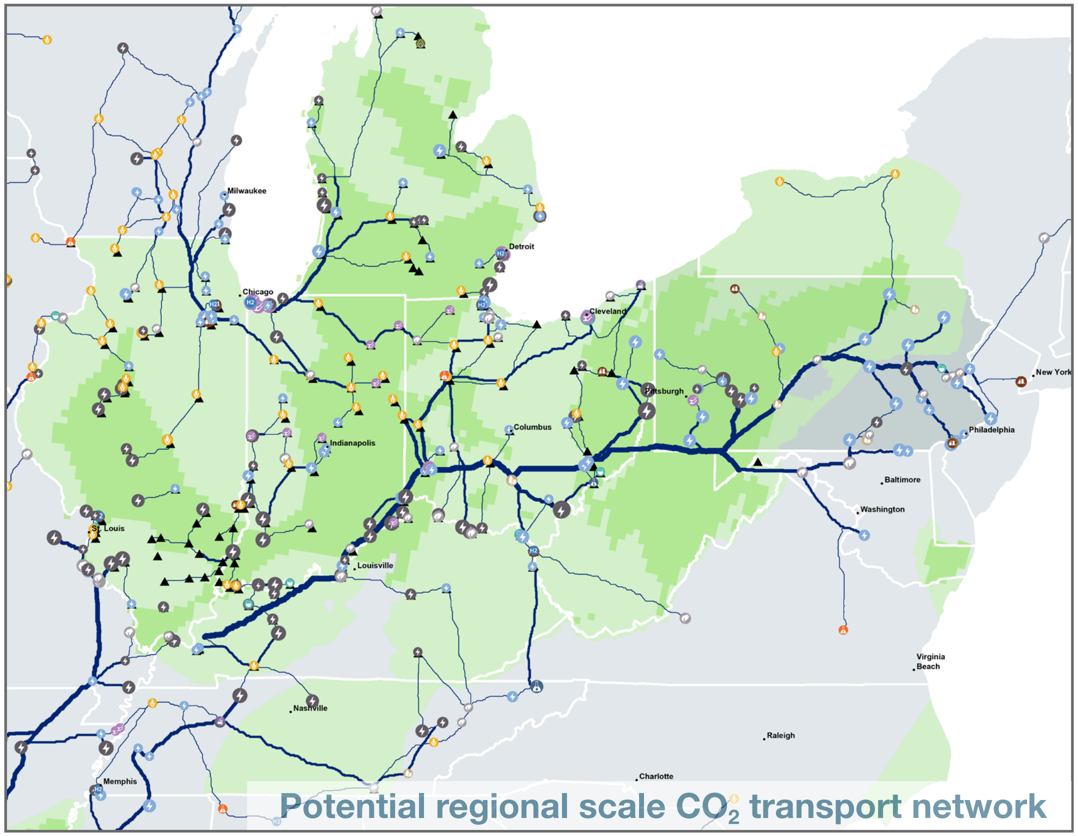
Capture sources

- Cement & lime
- Coal power
- Ethanol
- Gas power
- Metals & minerals
- Pulp & paper
- Refineries
- Steel
- Waste

Source: Regional Carbon Capture Deployment Initiative, 2020; Carbon Solutions LLC, 2022.

Pennsylvania CO_2 Capture and Storage Opportunities

Regional CO_2 transport infrastructure scenario



Optimized transport network for CO_2 capture and storage

- Regional CO_2 infrastructure (modeled)
- Potential CO_2 storage area

Geologic storage opportunity

- Assessed low-cost saline storage
- Saline CO_2 storage formation

Capture sources

- Ammonia
- Cement & lime
- Chemicals
- Coal power
- Ethanol
- Gas power
- Gas processing
- Metals & minerals
- Petrochemicals
- Pulp & paper
- Refineries
- Steel
- Waste

Source: Regional Carbon Capture Deployment Initiative, 2020; Carbon Solutions LLC, 2022.

A long-term approach to planning CO_2 transport infrastructure can enable overall cost savings and increase efficiencies in the network. A long-term regional planning scenario conducted as a part of this analysis shows Pennsylvania as part of a central CO_2 transport corridor aggregating emissions from sources throughout Pennsylvania and the Northeast down through Ohio and Indiana into Kentucky. An integrated regional network could reduce per-ton transport costs and minimize materials and land use required while achieving greater levels of emissions reduction and carbon storage.

When considering broader regional opportunities, Pennsylvania has great opportunity to participate in a network that would connect northeastern US emission sources with low-cost and high capacity geologic storage in the Ohio River Valley.

For complete analysis results and methodology, download the full report at carboncaptureready.org

GREAT PLAINS INSTITUTE

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Appendix D: Rhodium Group Jobs Report

Carbon Capture Jobs and Project Development Status

CARBON CAPTURE PROJECT DEVELOPMENT AT RISK DUE TO COVID-19

Absent Congress enacting recommendations by the Carbon Capture Coalition, the emerging domestic carbon capture industry is at significant risk from the immediate market crisis and long-term economic uncertainty created by the coronavirus (COVID-19). The International Energy Agency (IEA) reports that due to the COVID-19 crisis, global investments in energy technologies are set to fall a staggering 20 percent in 2020.

Carbon capture projects are at risk of delay or cancellation as project developers face profound near-term financial challenges and as tax equity markets shrink and can no longer provide project investment on favorable terms, if at all. Ensuring that current projects proceed on pace, as well as increasing the number of carbon capture projects in the near-term development pipeline, will reduce carbon emissions cost-effectively, spur economic activity, create and preserve jobs, and support domestic energy and industrial production and supply chains. At the same time, there is tremendous potential to dramatically increase the pace of carbon capture project deployment, if market certainty can be provided.

CARBON CAPTURE COALITION

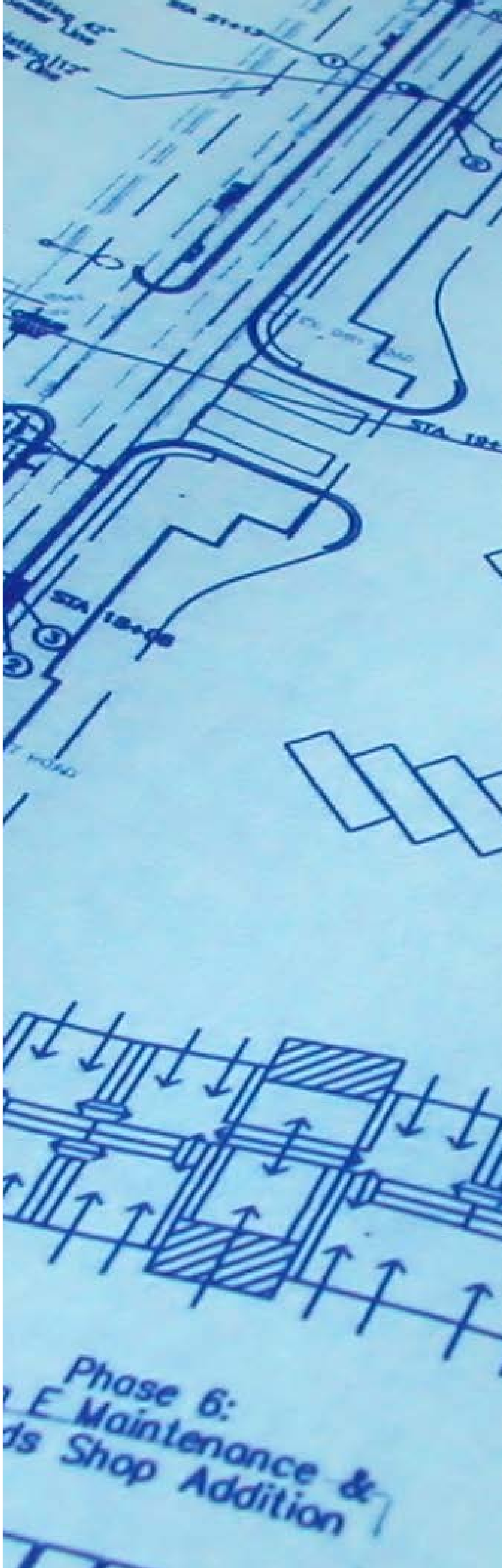
INTRODUCTION

Fostering carbon capture deployment at levels needed to meet mid-century climate goals will result in dramatic growth in employment provided by the carbon capture industry, including both project jobs (primarily construction) and operational jobs featuring a mix of skill levels. If commercially deployed globally to address emissions as part of a broad suite of zero- and low-carbon technologies, the carbon capture industry would employ between 70,000 and 100,000 construction workers and 30,000 to 40,000 facility operators in 2050, with additional employees to build and maintain a CO_2 transport and storage network. Additionally, carbon capture retrofits will decarbonize existing facilities, preventing their retirement and loss of associated high-wage jobs.

Globally, 21 large-scale facilities currently capture approximately 42 millions of CO_2 per year. The U.S. has 13 commercial-scale carbon capture facilities operating today, with the capacity to capture on the order of 25 million tons of CO_2 annually. The IEA estimates that the global carbon capture industry will need to scale-up to over 2,000 facilities capturing 2.8 gigatons of CO_2 per year to limit warming to 2°C. To meet the more ambitious 1.5°C scenario, the IPCC estimates that 10 gigatons of CO_2 per year must be captured.

Reaching this scale of CO_2 capture and storage will require an accelerated, economywide build-out of capture projects across sectors, including heavy industry (e.g. cement, steel, chemicals and other vital industrial processes); ethanol, fertilizer and hydrogen production; refining and natural gas processing; power generation and direct air capture from ambient air.

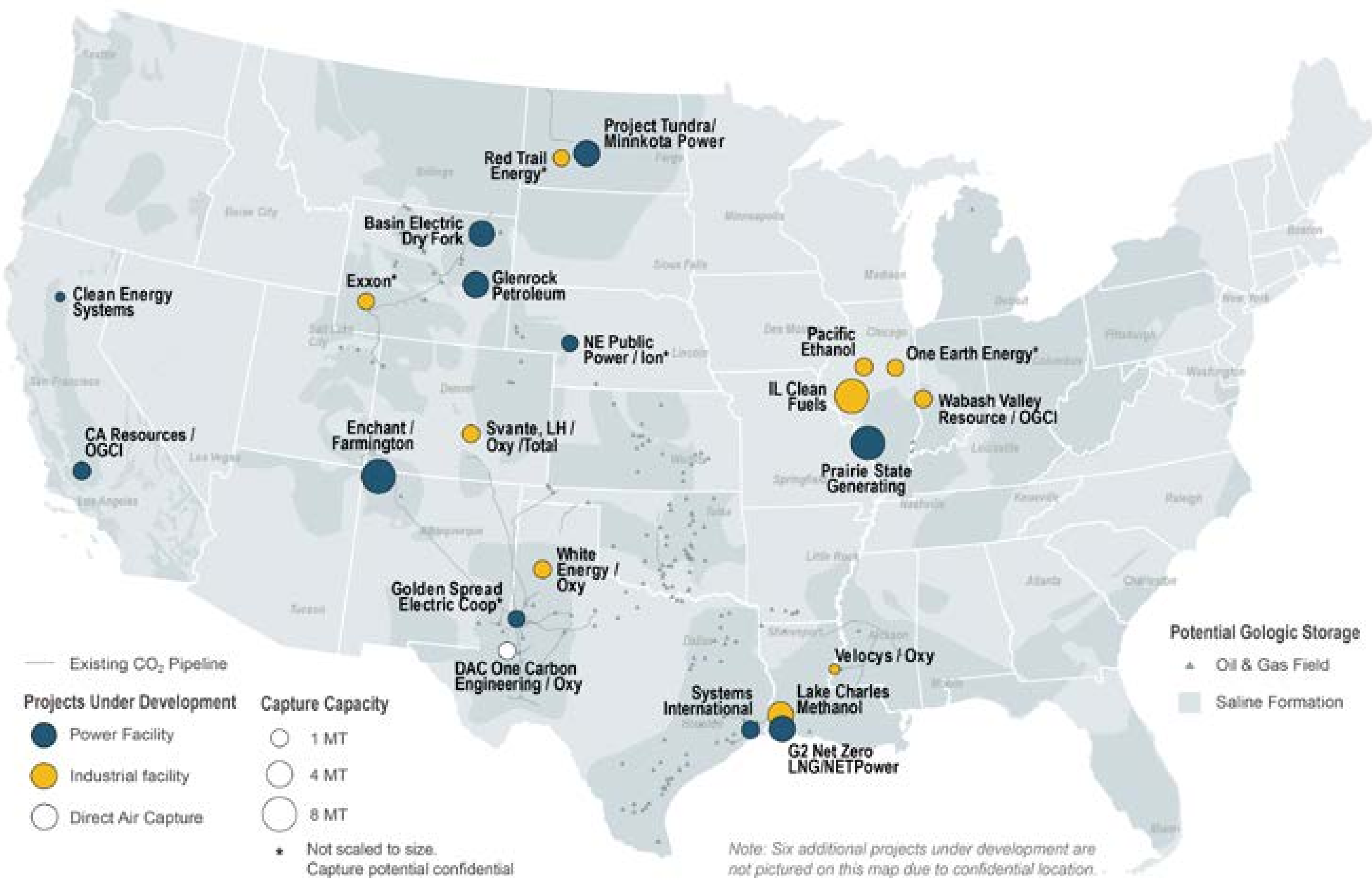
Additionally, a commercial-scale carbon capture industry will require the build-out of CO_2 transport infrastructure to move CO_2 from where it is captured to appropriate geologic storage sites. Not only would this constitute a significant investment in domestic energy, industry and manufacturing, it would preserve and expand a high-wage jobs base in many regions of the country, while decarbonizing economic sectors that are fundamental to modern life as we know it.



CARBON CAPTURE COALITION

45Q ENABLING CARBON CAPTURE PROJECTS

Two years after the landmark bipartisan reform and expansion of the federal 45Q tax credit in 2018, there are approximately 30 carbon capture projects in various stages of project development in the U.S.[1] This includes one project securing financing, two companies that have completed front end engineering and design (FEED) studies for several projects, 15 projects that are conducting FEED studies, five projects in pre-FEED status and seven whose status is confidential. If these projects proceed to construction and, ultimately, commercial operation, it will represent roughly a tripling of commercial carbon capture projects in the U.S. and an essential early down payment on long-term deployment goals. According to the Global CCS Institute, meeting the Paris climate targets will require building between 70 and 100 carbon capture facilities a year for the next 30 years.



Note: Industrial Facility w/ CO2 to Added Value refers to projects where captured CO2 will be repurposed for use in manufacturing of other products.

1 This number is based both on the Clean Air Task Force's carbon capture utilization and storage (CCUS) tracker and from conversations with project developers in the Carbon Capture Coalition.

CARBON CAPTURE IS A HIGH-WAGE JOB CREATOR

Carbon capture retrofits of industrial facilities and power plants support high-wage jobs in particular; indeed, they provide among the most desirable green jobs since employment associated with heavy industry (refining, chemicals, cement, steel, etc.) and electric power generation pays more than the average for states in which such facilities are located. In addition, new and innovative high-skill and high-wage industries will play a role in commercializing the carbon capture industry, including jobs associated with new negative emissions and carbon utilization technologies.

Drawing on Great Plains Institute modeling of economically feasible capture projects, the Rhodium Group has provided preliminary analysis of the jobs potential for a typical carbon capture facility across several industries. The range in jobs numbers reflect differences in project sizes in the Great Plains Institute project database.

			PROJECT JOBS	OPERATION JOBS
CARBON CAPTURE RETROFIT*	INDUSTRY	STEEL MILL	1,680 – 3,030	170 – 310
		REFINERY	440 – 760	40 – 70
		CEMENT PLANT	430 – 690	60 – 110
		HYDROGEN PLANT	175 – 300	20 – 30
		ETHANOL PLANT	30 – 50	5 – 10
	POWER	COAL POWER PLANT	1,800 – 3,350	160 – 300
		NATURAL GAS COMBINED-CYCLE POWER PLANT	1,140 – 2,090	100 – 180
CO_2 TRANSPORT INFRASTRUCTURE		TRUNK LINE (20” DIAMETER PIPELINE, 200 MILES LONG)	1,250 – 2,190	8 – 20
		FEEDER LINE (12” DIAMETER PIPELINE, 50 MILES LONG)	250 – 370	2 – 5

*By facility type

CONCLUSION

Carbon capture is a crucial tool to meet mid-century climate goals, but the pace of development both globally and domestically needs to accelerate dramatically to meet the challenge. Unfortunately, without immediate action from Congress, the economic conditions created by COVID-19 create unprecedented risk for the deployment of carbon capture technology and the associated jobs, economic, and emissions benefits.

Appendix E: Jobs & Economic Impact of Carbon Capture Deployment: Midcontinent Region

JOBS AND ECONOMIC IMPACT OF CARBON CAPTURE DEPLOYMENT
Midcontinent Region

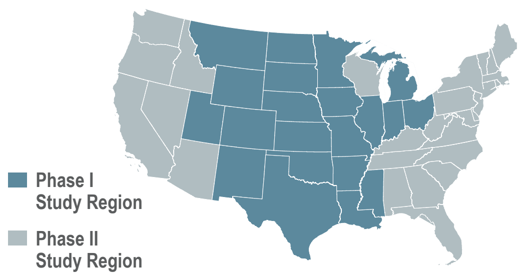
REGIONAL CARBON CAPTURE DEPLOYMENT INITIATIVE

TOTAL JOBS POTENTIAL

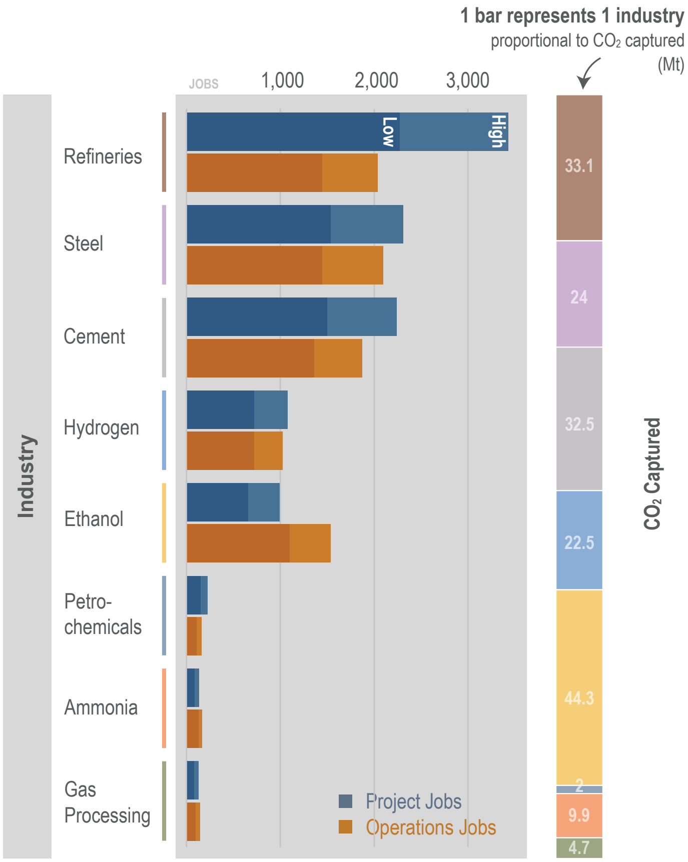
Project Jobs	Operations Jobs	Infrastructure Jobs
59,830	39,672	16,600

The Midcontinent region can create an annual average of up to **76,430 project jobs** over a 15-year period and **39,672 ongoing operations jobs** through the deployment of carbon capture at 444 industrial and power facilities. The retrofit of equipment at these facilities would capture **642 million metric tons** of carbon dioxide (CO_2) per year. Along with the development of CO_2 transport infrastructure, this would generate up to **$232.2 billion** in private investment.

Phase 1 Analytical Region. Phase 2 coming Fall 2020



ANNUAL PROJECT AND OPERATIONS JOBS



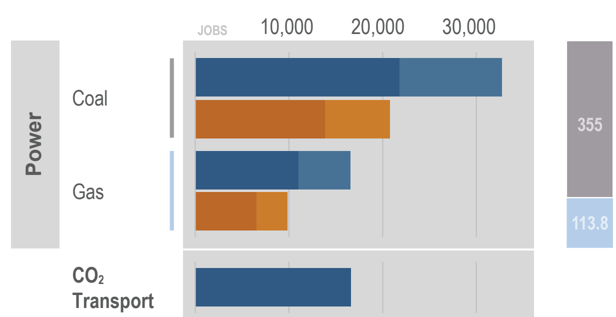
Mt = million metric tons.

The figures above and to the right depict the low and high range of estimated annual average project jobs, transport infrastructure jobs, and ongoing operations jobs that could be created through carbon capture retrofits at industrial and power facilities in the Midcontinent region. The potential amount of CO_2 captured by each industry are shown on the right of each figure.

CREATING JOBS & CAPTURING CARBON

Carbon capture is essential to meeting mid-century emissions reduction goals while retaining and growing a domestic base of high-wage energy, industrial, and manufacturing jobs. Carbon capture retrofits require facilities to be outfitted with capture technologies such as amine scrubbers to remove CO_2 from exhaust gas and compressors to make the CO_2 transport-ready, that are dependent upon the type of industrial plant and vary across industries and facilities. There are jobs associated with the equipment, materials (e.g., cement and steel), engineering, and labor required to install the capture technology, as well as ongoing jobs to operate and maintain the retrofits. These are referred to as **project jobs** and **operations jobs**.

Rhodium Group performed an economic analysis based on the Regional Carbon Capture Deployment Initiative's near- and medium-term capture potential scenario.[1] The Rhodium analysis quantifies the economic impact and employment opportunities of carbon capture retrofit projects by deploying state-specific data in the IMPLAN economic model. The analytical results measure the impact of project investment and operation costs through expected annual jobs. Average annual project jobs were calculated assuming deployment of all projects within the 15-year period from 2021-2035. The jobs reported are in-state jobs, directly associated with carbon capture retrofits. They do not include other jobs at the facilities, nor indirect and induced jobs.



[1] Rhodium Group analytical results: **rhg.com/research/**

REGIONAL CARBON CAPTURE DEPLOYMENT INITIATIVE

JOBS AND ECONOMIC IMPACT OF CARBON CAPTURE DEPLOYMENT
Midcontinent Region

TOTAL JOBS POTENTIAL

Project Jobs	Operations Jobs	Infrastructure Jobs
59,830	**39,672**	**16,600**

CARBON CAPTURE JOBS AND ECONOMIC IMPACT SUMMARY

Industry	**Number of Facilities**	**Total Capture Target** Million Metric Tons	**Private Investment** Million Dollars	**Annual Average Project Jobs** 2021-2035	**Annual Operations Jobs**
Ammonia	6	9.9	$325 - $475	90 - 135	135 - 167
Cement	45	32.5	$4,760 - $7,150	1,500 - 2,240	1,360 - 1,870
Coal Power Plant	62	355	$75,600 - $112,400	21,820 - 32,730	13,890 - 20,780
Ethanol	150	44.3	$2,291 - $3,431	658 - 990	1,098 - 1,535
Gas Power Plant	67	113.8	$35,600 - $56,400	11,030 - 16,570	6,550 - 9,850
Gas Processing	20	4.7	$276 - $407	83 - 125	102 - 146
Hydrogen	39	22.5	$2,375 - $3,485	725 - 1,080	726 - 1,024
Petrochemicals	2	2	$500 - $700	150 - 220	110 - 160
Refineries	45	33.1	$5,720 - $8,570	2,275 - 3,430	1,450 - 2,040
Steel	8	24	$4,890 - $7,340	1,540 - 2,310	1,450 - 2,100
CO_2 Transport Infrastructure	-	-	$31,860	16,600	-

RESULTS

The Midcontinent region has immense opportunity to create jobs and reduce emissions in the industrial sector as well as at coal and gas power plants. Three hundred fifteen of the Midcontinent region's industrial facilities can create an annual average of up to 10,530 project jobs and 9,042 ongoing operations jobs while capturing 173 million metric tons of CO_2 per year. The Midcontinent region also has 129 power plants that, combined, can create an annual average of up to 49,300 project jobs and 30,630 ongoing operations jobs while capturing 468.8 million metric tons of CO_2 per year. The development of CO_2 transport infrastructure would create an annual average of 16,600 project jobs in the Midcontinent region.

ABOUT THE ANALYSIS

The first phase of economic and employment analysis conducted by Rhodium Group uses facilities within the Midcontinent region that were identified as near- and medium-term candidates for carbon capture retrofit in the recently published RDI white paper, *Transport Infrastructure for Carbon Capture and Storage: Regional Infrastructure for Midcentury Decarbonization*, and translates project investment and operation costs into employment potential on a state-by-state basis. Forthcoming analysis will explore theeconomic impacts of carbon capture in the rest of the US lower 48, as well as expanded deployment of carbon capture past 2035 to meet midcentury decarbonization targets nationwide.

The Regional Carbon Capture Deployment Initiative (RDI) brings together state officials with diverse industry, NGO, labor, and other stakeholders to promote broad scale deployment of infrastructure for carbon capture, CO_2 pipelines, enhanced oil recovery (EOR), other forms of geologic storage, and beneficial utilization of CO_2 in the Western and Midwest regions of the country. The Regional Carbon Capture Deployment Initiative is staffed by the Great Plains Institute (GPI), a nonpartisan, nonprofit organization working to transform the energy system to benefit the economy and environment.

For more information on this effort and to view a series of state fact sheets showcasing carbon capture opportunities and economic potential for job creation, go to www.carboncaptureready.org or contact Patrice Lahlum at plahlum@gpisd.net.

[1] Rhodium Group analytical results: **rhg.com/research/**

Appendix F: Standards and Best Practices

- CSA/ANSI ISO 27916:19 Carbon dioxide capture, transportation, and geological storage — Carbon dioxide storage using enhanced oil recovery (CO_2-EOR)
- DNVGL-SE-0473 Edition October 2017, Certification of sites and projects for geological storage of carbon dioxide
- DOE BEST PRACTICES: Monitoring, Verification, and Accounting (MVA) for Geologic Storage Projects DOE/NETL-2017/1847
- DOE BEST PRACTICES: Public Outreach and Education for Geologic Storage Projects DOE/NETL-2017/1845
- DOE BEST PRACTICES: Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects DOE/NETL-2017/1844
- DOE BEST PRACTICES: Risk Management and Simulation for Geologic Storage Projects 2017 Revised Edition DOE/NETL-2017/1846
- DOE BEST PRACTICES: Operations for Geologic Storage Projects 2017 Revised Edition DOE/NETL-2017/1848
- DOE BEST PRACTICES: Geologic Storage Formation Classification: Understanding Its Importance and Impacts on CCS Opportunities in the United States DOE/NETL-2010/1420
- ISO 27914:2017 Carbon dioxide capture, transportation, and geological storage — Geological storage
- ISO 27916:2019 Carbon dioxide capture, transportation, and geological storage — Carbon dioxide storage using enhanced oil recovery (CO_2-EOR)
- ISO 27913:2016 Carbon dioxide capture, transportation, and geological storage — Pipeline transportation systems
- CSA Z741-12 (R2018) Geological storage of carbon dioxide for North America
- ISO/TR 27912:2016 Carbon dioxide capture — Carbon dioxide capture systems, technologies, and processes
- ISO/TR 27918:2018 Lifecycle risk management for integrated CCS projects
- ISO 27919-1:2018 Carbon dioxide capture — Part 1: Performance evaluation methods for post-combustion CO_2 capture integrated with a power plant
- ISO 27919-2:2021 Carbon dioxide capture — Part 2: Evaluation procedure to assure and maintain stable performance of post-combustion CO_2 capture plant integrated with a power plant
- ISO/TR 27921:2020 Carbon dioxide capture, transportation, and geological storage — Cross Cutting Issues — CO_2 stream composition
- ISO/TR 27922:2021 Carbon dioxide capture — Overview of carbon dioxide capture technologies in the cement industry
- ISO/TR 27923:2022 Carbon dioxide capture, transportation, and geological storage — Injection operations, infrastructure and monitoring
- Society of Petroleum Engineers CO_2 Storage Resources Management System (2017)