Carbon Capture, Transport, and Storage

Course No: C04-072
Credit: 4 PDH

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This course was adapted from the U.S. Department of Energy, Publication No. DOE/OP-0001, "Carbon Capture, Transport, & Storage", which is in the public domain.

About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- Carbon capture materials,
- Electric grid including transformers and high voltage direct current (HVDC),
- Energy storage,
- Fuel cells and electrolyzers,
- Hydropower including pumped storage hydropower (PSH),
- Neodymium magnets,
- Nuclear energy,
- Platinum group metals and other catalysts,
- Semiconductors,
- Solar photovoltaics (PV), and
- Wind.

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- Commercialization and competitiveness, and
- Cybersecurity and digital components.

More information can be found at www.energy.gov/policy/supplychains.

Acknowledgments

The United States (U.S.) Department of Energy (DOE) acknowledges all stakeholders that contributed input used in the development of this report—including, but not limited to, federal agencies, state and local governments, U.S. industry, national labs, researchers, academia, non-governmental organizations, and other experts and individuals. DOE also issued a request for information to the public on energy sector supply chains and received comments that were used to inform policy strategies in this report. Dr. Tsisilile Igogo, a detailee at the DOE's Office of Policy from the National Renewable Energy Laboratory (NREL) led the agency's energy supply chain review.

DOE and National Energy Technology Laboratory (NETL) would like to acknowledge Princeton University for allowing the use of their Net-Zero America analysis data in the NETL-NZA model developed for this report. Christopher Greig, Senior Research Scientist in the Andlinger Center for Energy and the Environment and co-author in the Net-Zero America (NZA) study, was the primary point of contact for this data provision.

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Nomenclature or List of Acronyms

ADM	Archer Daniels Midland
API	American Petroleum Institute
CAGR	Compound Annual Growth Rate
CCS	Carbon Capture and Storage (or Sequestration)
CCUS	Carbon Capture, Utilization, and Storage
CDR	Carbon Dioxide Removal
CEQ	U.S. White House Council on Environmental Quality
CO_2	Carbon dioxide
DAC	Direct Air Capture
DOE	U.S. Department of Energy
EO	Executive Order
EOR	Enhanced oil recovery
EtO	Ethylene Oxide
FECM	Office of Fossil Energy and Carbon Management
FY	Fiscal Year
GHG	Greenhouse Gas
GPI	Great Plains Institute
Gt	Gigatons
Gtpa	Gigatons per annum
HVDC	High Voltage Direct Current
ICF	ICF Incorporated
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRS	Internal Revenue Service
ITC	Investment Tax Credit
KOH	Potassium hydroxide
LCFS	Low Carbon Fuel Standard
LTS	Long Term Strategy
MARKAL	Market Allocation Model
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
MOF	Metal Organic Framework
Mtpa	Megatons per annum
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
NZA	Net Zero America
NZE	Net Zero Emissions
O&M	Operation and maintenance
PSH	Pumped Storage Hydropower
PHMSA	Pipeline and Hazardous Materials Safety Administration
PSL	Product Standard Level
PTC	Production Tax Credit
PV	Solar photovoltaics
R&D	Research and development

RDD&D	Research, Development, Demonstration, and Deployment
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
SSAE	Strategic Systems Analysis and Engineering
TEG	Triethylene Glycol
UIC	Underground Injection Control
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States
USDW	Underground sources of drinking water
WGS	Water-Gas Shift
WTI	West Texas Intermediate
ZIF	Zeolitic Imidazolate Framework
°C	Celsius
°F	Fahrenheit

Executive Summary

This report was completed by the Department of Energy (DOE) to examine carbon dioxide (CO_2) capture, transport, and storage technologies and associated supply chains that will be required to support the United States (U.S.) decarbonization goals by 2050. Specifically, the analysis sought to understand supply chain bottlenecks to achieving an upper-bound 2.0 gigatonnes (Gt) of CO_2 capture and storage (CCS) per year in the United States. A literature review shows that in aggressive infrastructure deployment scenarios, the United States' likely upper bound of CCS capacity is 1.7 Gigatons per annum (Gtpa) by 2050. This suggests the study design of 2.0 Gtpa capacity by 2050 is more aggressive yet and represents a conservative upper bound for supply chain analyses.

Across the CCS value chain, there are many technologies available to support the eventual 2050 buildout. After review of technologies most likely to be used at this hypothetical scale, it was determined that solvent-based capture (modeled in this analysis as monoethanolamine [MEA]), CO_2 drying (modeled using triethylene glycol [TEG]), steel pipeline transportation, and geologic storage are most likely to meaningfully contribute to this infrastructure buildout. Other technologies are discussed in this analysis, though in less detail.

Through 2050, the United States will require 13.7 Mt of MEA (833.96 kt in the year 2050), 632.1 kt of TEG (40.57 in the year 2050), 24–32 Mt of steel, and 1.1 Mt of cement. These material estimates were created via synthesis and analysis of information external to DOE in a modeling effort to approximate the scope of CCS infrastructure (e.g., quantities and geographies of capture sites, transportation pipelines, and storage sites) required to construct and operate a 2 Gtpa system of CCS by 2050.

A supply chain risk analysis was then performed by comparing raw material estimates against domestic and global production, examining for opportunities and vulnerabilities. Findings suggest that CCS will not be a technology concept whose deployment is at risk to material or other supply chain constraints, but it does represent a considerable opportunity for the domestic workforce and manufacturing base. Between the primary components of MEA, TEG, steel (and constituent materials for steel alloys), cement, and pumps/compressors, the analysis demonstrates that the only known potential risk lies within scaling MEA to appropriate amounts (which demonstrates a conservative case that MEA-based solvent capture is the only method used). This risk can be mitigated through several methods, as outlined in Section 3.

There are several challenges and opportunities associated with the carbon capture buildout, including potential impacts to American economy and workforce. At a high level, the growth of the CCS market is expected to produce between 390,000 and 1.8 million employment opportunities, maintaining and creating well-paying union jobs in various industries, including, but not limited to, the fields of raw materials (MEA, TEG, steel, cement, etc.), engineering and design (design of carbon capture, pipelines, injection sites, Supervisory Control and Data Acquisition [SCADA], etc.), construction (retrofitting, pipeline development, injection sites, trucking), and operation and maintenance (O&M). Location-wise, these employment opportunities will follow the value chain of CCS, largely being available in midwest, Appalachian, and southern states for the construction and subsequent O&M of capture sites, pipeline sites, and storage sites.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-

year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

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1 Introduction

1.1 The Role of Carbon Capture and Sequestration/Storage (CCS)

Carbon capture and sequestration (CCS) is a set of technologies that can help to meet the United States' most ambitious domestic climate goals by enabling abatement of difficult-to-electrify industrial processes, enabling low-carbon dispatchable power generation, and delivering the physical and market infrastructures necessary for many carbon dioxide removal (CDR) concepts. In the industrial sector (emission-intensive products include cement, ethanol, chemicals, iron, and steel), CCS represents a commercially available abatement solution with established supply chains that will need decades to build and scale.[1] In the energy sector, while renewable power sources are reaching cost parity with incumbent fossil-based sources,[2] studies have demonstrated the value (in terms of consumer cost and system reliability) of maintaining clean, dispatchable resources on the grid.[3,4] Finally, achievement of 2050 net-zero objectives will almost certainly rely on CDR technologies, many of which – e.g. bioenergy with CCS (BECCS) and direct air capture with sequestration (DACS) – will rely on geologic sequestration of captured carbon dioxide (CO_2).[5]

CCS provides a near-term pathway to rapidly reduce the impacts of existing emissions-intensive infrastructure/processes, while zero-carbon alternative solutions mature. CCS technology carries low technological risk (requisite infrastructure is already in widespread commercial use) and low supply chain risk (requisite infrastructure relies on large amounts of common raw materials, not critical minerals). Figure 1 shows the *Long-Term Strategy of the United States* and acknowledges the role of CCS in the nation's goal of net-zero emissions by 2050.

The solution landscape for decarbonization is rapidly evolving, potentially putting large capital investments into CCS infrastructure at risk of stranding or under-utilization. However, there are multiple futures of long-term use, particularly for investment into transportation and storage:

- **Continued CCS**: There may be future conditions where zero-carbon alternatives are technically impossible or impractical for a variety of reasons (e.g., supply chain, workforce, etc.). In that future, a built-out CCS network would allow incumbent infrastructure/processes to continue while avoiding the emissions concerns.

- **Direct Air Capture and Storage (DACS)**: Reaching net-zero emissions will require removing carbon dioxide from the atmosphere, using processes and technologies that are rigorously evaluated and validated. The *U.S. Long-Term Strategy* identifies direct air capture and storage (DACS) as a potential engineered carbon removal strategy that captures CO_2 emissions directly from ambient air (instead of from point sources such as power plants or industrial facilities), for subsequent compression and transportation to a geologic storage site or conversion into usable material such as synthetic concrete.[6] CCS infrastructure not only provides a short-term solution to decarbonizing fossil fuel energy generation but also provides the enabling CO_2 transport and storage infrastructure for DACS. DACS will be easier to implement regionally if the CCS infrastructure is available for use. Additionally, the social concept of "Not in my backyard" may work in the reverse effect, enabling citizens to support and be proud of carbon captured in their local area.

- **Other Pipeline Uses**: Researchers are investigating opportunities to leverage CO_2 pipelines to transport other fluids. In particular, with the expectation that natural gas and CO_2 demand will decrease, hydrogen may be a viable fluid to transport in converted pipelines. The Department of

Energy (DOE) does cite concern about hydrogen causing embrittlement in the steel and welds used to fabricate the pipelines.[7] Complete conversions of natural gas pipelines to hydrogen pipelines have been done at low scales, proving feasibility. It is important to note that natural gas pipelines should not be considered for retrofit to carry CO_2.[8] An example of this was noted by the Congressional Research Service, where "in the 1990s, Air Liquide (one of the Gulf Coast operators) purchased two crude oil pipelines in Texas and successfully converted them to hydrogen service."[9] Additional research is required in the areas of hydrogen compression technology and large-scale pipeline conversion, especially when converting pipelines originally intended to transport CO_2.

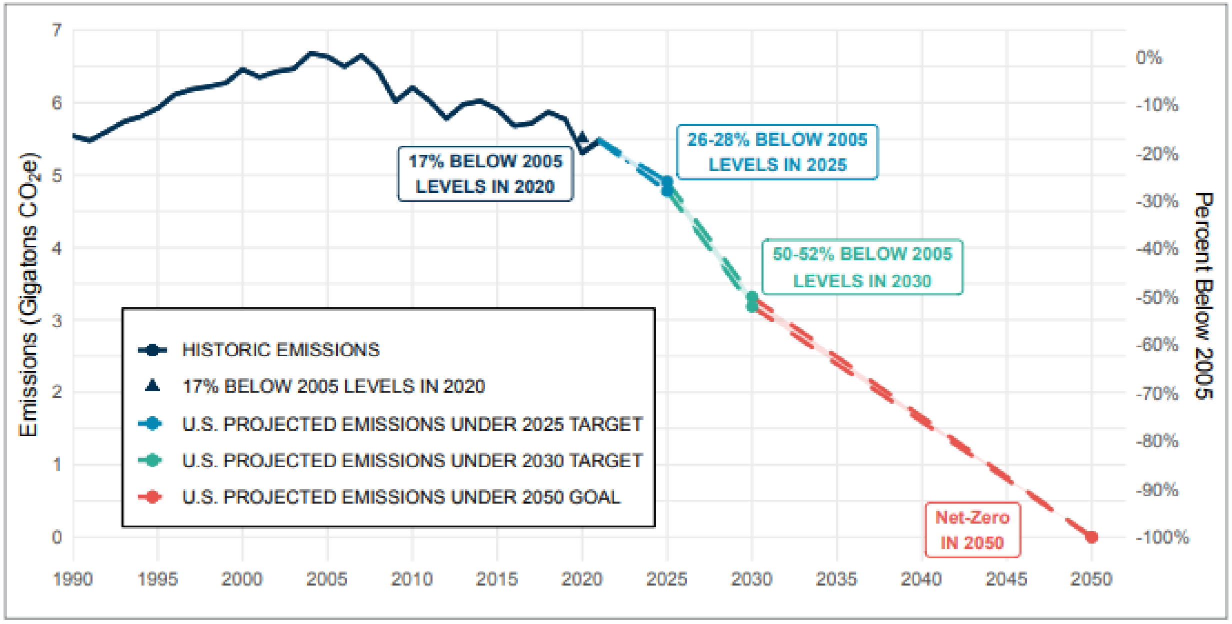


Figure 1: The U.S.-produced "Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050" acknowledges and discusses the role of CCS in the nation's goal of net-zero emissions by 2050.[10]

Additional discussion of this report can be found in Section 1.3.2.

Lastly, CCS can also provide economic benefits, including job creation, especially in some of the communities most affected by emissions reductions (e.g., fossil fuel plants). As highlighted by the Biden Administration's July 2021 Justice40 Executive Order, providing benefits (including job transition) to the communities affected most by the energy transition is a top priority and a crucial challenge to United States' success.[11] As job losses from high-emission industries are not likely to occur in the same geographic areas where low-emission industry jobs are created, CCS can facilitate a transition that helps bridge the gap economically, providing employment (temporary if zero-carbon alternative sites are eventually opened elsewhere, or long-term if zero-carbon alternatives are deemed impossible/impractical). Additionally, CCS can help reduce the loss of valuable, fully functioning infrastructure that may otherwise be closed before their useful lifespan if not for emissions reduction technology, potentially limiting costs that are pushed onto ratepayers. Additional discussion on this topic can be found in Section 4.

1.2 A Representative CCS Process

CCS is a suite of interconnected technologies for capturing CO_2 and storing it so that it is not reemitted into the atmosphere. Agnostic to the specific technologies chosen, CCS will generally involve three main steps: capture, transportation, and storage (Figure 2).

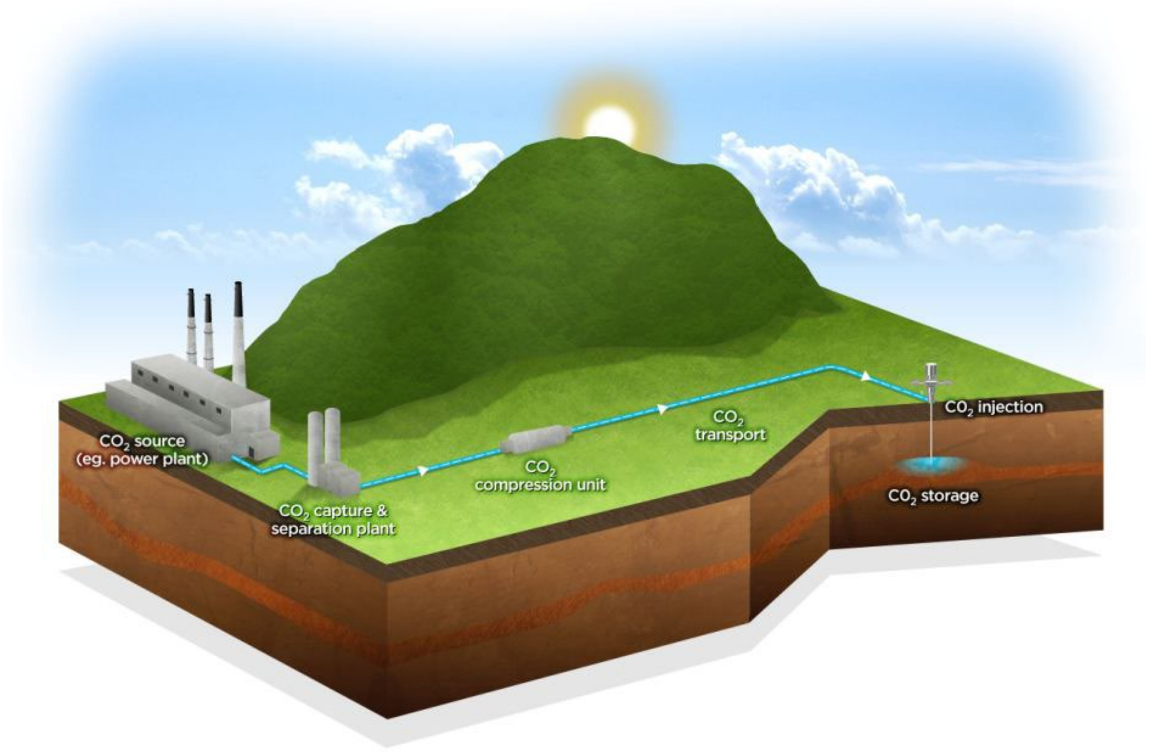


Figure 2: Illustration of a simplified CCS network with one capture unit and one storage facility[12]

CO_2 can be captured either from a facility emitting CO_2 (point source capture) or directly from the atmosphere (i.e., direct air capture, or DAC). In point source capture, CO_2 can be captured from process gases (such as CO_2 from methane reforming to produce hydrogen, production of ethanol by fermentation, or calcining limestone to produce Portland cement), pre-combustion of fossil fuels (gasifying fuel and separating out the CO_2 – more common in industrial processes) or post-combustion of fossil fuels (separated from the exhaust of a combustion process – more common in fossil or bio-energy power plants). There are also oxy-fuel combustion systems, where fuel is burned after separating oxygen from ambient air and diluting it with CO_2, which results in a more-concentrated (and typically more cost-efficient to capture) stream of CO_2 emissions. There are several CO_2 capture technologies that have been or are being developed including solvent, sorbent, and membrane systems, as well as novel concepts (e.g., hybrid systems that efficiently combine attributes from multiple key technologies). Currently, commercially viable capture systems are capable of capture rates exceeding 90% of carbon and newer systems are approaching 100%.[13]

Though many capture technologies may eventually contribute to the United States' CCS capacity, as noted in Section 2.1.1.2, this report primarily examines a case study based on the technology that is currently the most advanced in its technical readiness level and is already in common commercial use: monoethanolamine (MEA) solvent-based capture. In addition to current commercial readiness, and thus available data, in a scenario of 2 Gtpa of CCS, a large proportion of captured CO_2 is likely to result from post-combustion power generation (either fossil fuels or bio-energy, Section 1.3) where complex flue gases make chemical solvents the optimal capture technology. A worst-case scenario, from a materials standpoint, would be if all capture systems used the same technology, thus maximizing demand. Since MEA-based systems have been the first ones deployed, this technology can be an effective case study to determine if its supply chains can bear the strain. Decades of DOE research have documented the utility of a diverse set of alternatives to MEA,[14] however in the absence of limits on CO_2 emissions or incentives for its capture, none have been deployed. As business cases for capture develop, a portfolio of economical solutions are likely to develop, and in the case of solvent systems, most will be drop-in substitutes for MEA, enabling gradual transitions away from those "first generation" systems.[15]

Other technologies may deploy at commercial scales as CO_2 capture is applied to industries with different CO_2 stream characteristics (e.g., more concentrated or more dilute). A selection of these additional capture technologies are discussed, particularly as they relate to their potential material reliance, but are not analyzed in depth because the technical paradigms for their use are not sufficiently established to assess their material or equipment requirements at scale. Alternative capture technologies include mechanical processes (e.g., cryogenic capture) suitable for high-concentration CO_2 streams such as at bioethanol plants as well as physio-chemical processes (e.g., selective solid sorbents) for low-concentration CO_2 streams including capture from ambient air. Alternatives to the solvent-based capture process analyzed here are discussed in Section 2.1.1.2.

After the CO_2 has been captured, it must be dehydrated and compressed before it can be transported to its storage location. The dehydration process is necessary because, if left untreated, the comingled water and CO_2 will damage mild steel over time by forming corrosive hydrides and acids. Anti-corrosion steel could be used but would be considerably more expensive given the large scales of transportation needed in gigaton-level CCS capacity. In the treatment process, CO_2 is transported (via small anti-corrosion steel pipes) to purification and dehydration tanks, where it is purified to levels above 99% CO_2.[16] There are several technologies to dry the CO_2; however, it is anticipated that triethylene glycol (TEG) will be used for most carbon capture in the United States in 2050 due to its effectiveness and widespread use in the natural gas industry.

The treated, gaseous CO_2 is then liquified using compressors and chillers. The liquification process is necessary because gaseous CO_2 would necessitate larger pipelines and additional compression throughout the network.

After treatment and liquification, the CO_2 must be transported. To accomplish gigaton-levels of CCS capacity, large amounts of CO_2 will need to be moved from capture sites (point-source capture from power plants or industrial plants, or direct air capture) to large-scale storage facilities cost-efficiently and effectively. A large-scale steel pipeline network is anticipated to primarily fill this role (over trucking, water, or air freight) due to cost and widespread practicality.

Finally, after traversing the pipeline, the CO_2 will be stored. Geologic storage is currently the best large-scale, verifiable, and permanent CO_2 storage method, and all CCS scenarios examined are based on this type of sequestration. Geologic storage includes natural saline reservoirs, depleted oil/gas fields, or other stable formations with high capacities. Note that in addition to storage, there are also methods for carbon utilization (another common acronym in the CCS space is Carbon Capture, Utilization, and Storage [CCUS]), which aim to extract value from captured CO_2 by using it in other products. Discussion of carbon utilization can be found in Section 4.1.3).

Figure 3 depicts a representative process of CCS, from capture to injection and the materials and equipment required.

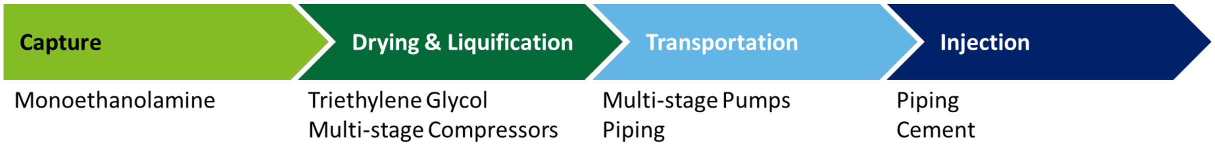


Figure 3: CCS flowchart with required principal materials/components that are examined in this report

1.3 CCS Requirements in the United States by 2050

Currently, global and U.S. CCS capacity is in its infancy compared to the goals established by various studies (discussed in the Sections below). In 2021, global capacity was 40 megatons per annum (Mtpa), and in 2020, U.S. capacity was about 6.8 Mtpa. However, CCS could see rapid expansion under domestic and global decarbonization scenarios.[17] This market assessment includes forecasts of future market size. Though this report is based on an upper-bound target of 2.0 Gtpa CCS capacity in the United States by 2050, it is valuable to compare this target with projections made at global and national scales.

Critically, this analysis does not restrict the emission sources from which CO_2 may be captured, seeking only to understand the market conditions that lead to large CCS deployment; this broad scope enables the subsequent assessment of material requirements and supply chain risk but may result in projections that include capture from fossil assets likely to be retired under net zero commitments. In an effort to focus primarily on materials supply constraints this compromise was deemed appropriate in order to construct an aggressive upper bound.

1.3.1 Global Studies

One method of estimating the amount of carbon capture required for the United States by 2050 is to scale global estimates based on domestic contributions to global emissions.

1.3.1.1 IPCC

In 2018, the Intergovernmental Panel on Climate Change (IPCC) released a Special Report on Global Warming that suggests the world must reach net-zero emissions in the 2050–2060 timeframe to avoid the worst outcomes from climate change (resulting from a 1.5 °C temperature rise).[18] In the report, the IPCC presents four illustrative model pathways to achieve this goal, each showing a unique combination of mitigation approaches and assumptions about future socio-economic developments. In each of the four pathways, CO_2 removal is present. For example, one illustrative model pathway requires more than 6 Gtpa of CO_2 be captured globally by 2050, and another requires over 12 Gtpa by 2060 and 20 Gtpa in 2100. Figure 4 whos two potential scenarios for limiting global temperature rise to 1.5°C.

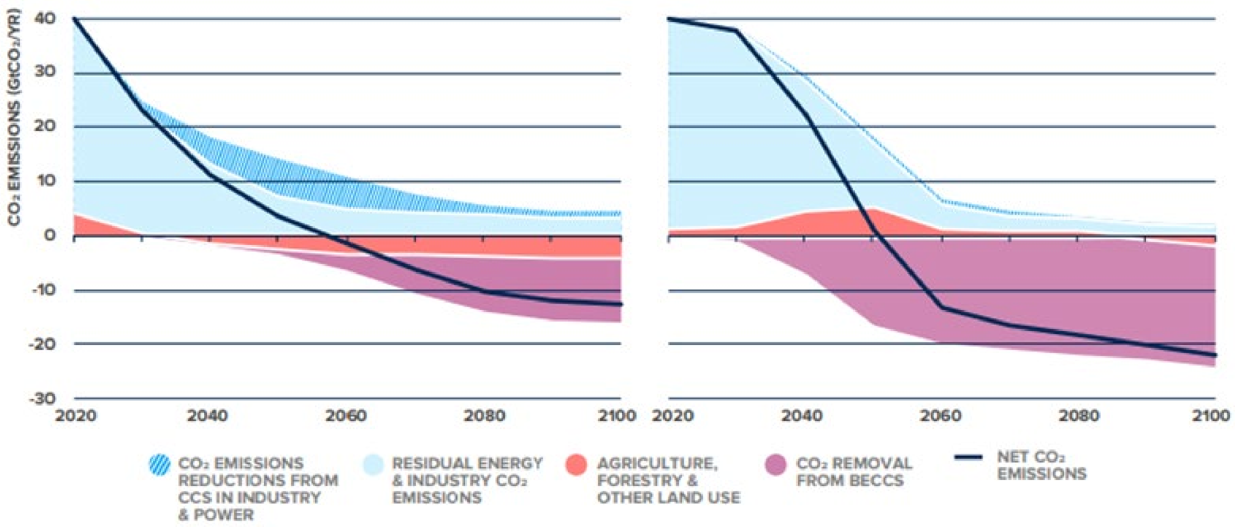


Figure 4: Two potential scenarios for limiting global temperature rise to 1.5°C as presented by IPCC

1.3.1.2 IEA

In 2019, the International Energy Agency (IEA) released the Sustainable Development Scenario (SDS) report, which goes into further detail describing a future where the United Nations (UN) energy-related sustainable development goals (SDGs) for emissions, energy access, and air quality are met. [19] This analysis predicts that meeting these goals will require the mass of CO_2 captured globally to increase from 40 Mtpa in 2020 to 5.6 Gtpa by 2050, as shown in Figure 5.[20] Their prediction includes the global sectors from which carbon is captured.

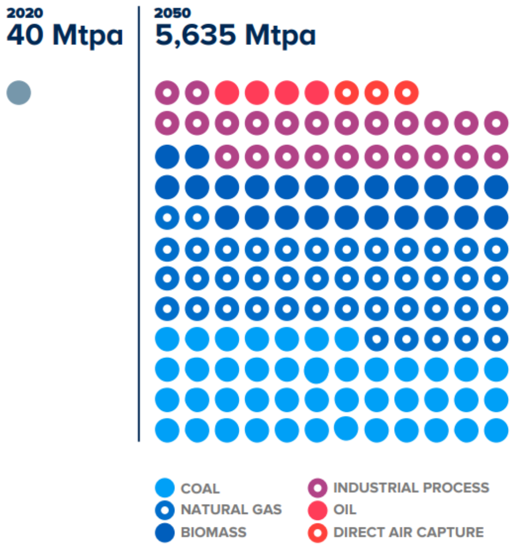


Figure 5: CO_2 capture capacity in 2020 and 2050 by fuel and sector in the IEA 2019 SDS

In 2021, the IEA released their Net Zero Emissions (NZE) by 2050 Scenario report, which focuses on showing a pathway for specifically the global energy sector to achieve net-zero CO_2 emissions by 2050 (also consistent with UN SDGs).[21] The report is also consistent with limiting the global temperature rise to 1.5 °C, in line with reductions assessed in the IPCC in its Special Report on Global Warming of 1.5 °C. This report suggests 7.6

Gtpa of CO_2 is captured globally by 2050 from a diverse range of sources (5.2 Gt captured from fossil fuels and processes, 0.9 Gt from DAC, etc.). Figure 6 shows a potential scenario of CO_2 capture by source, created by IEA.

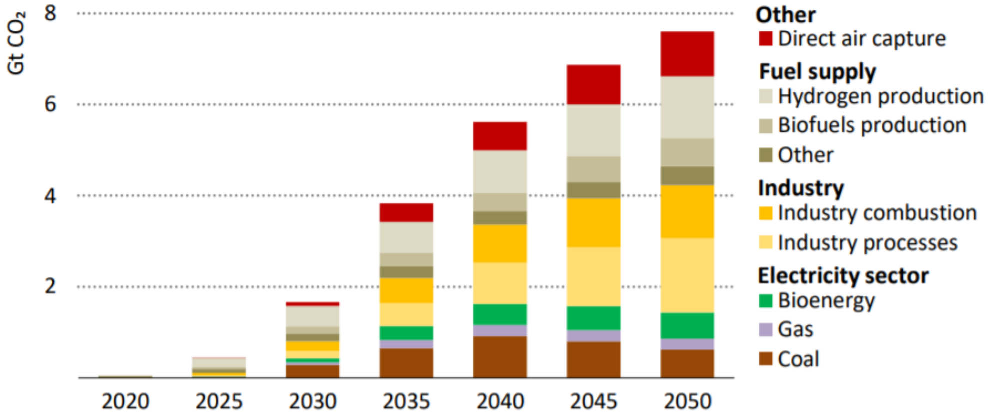


Figure 6: IEA NZE global CO_2 capture by source, 2020–2050

1.3.1.3 Discussion: Estimating U.S. Requirements from Global Studies

In 2021, the United States accounted for 14% of global CO_2 emissions.[22] Several reports have forecasted emissions by country projections for 2050, though there is significant variance. One of the difficulties in predicting is that since developed countries produce more emissions per capita than developing countries, successfully predicting 2050 emissions by country requires corresponding successful predictions of international development, an equally difficult task.

It is likely that the United States will constitute less than 14% of global CO_2 emissions in 2050 (especially as developing countries grow and their energy use expands); however, to continue to examine conservative estimates, one can examine what would happen if U.S. CCS capacity represents 14% of global CCS capacity in 2050. Moreover, if considering cumulative contributions to global emissions, the proportion of CCS required of the United States could be even higher.

Assuming that U.S. CCS capacity will be 14% of global CCS:

- The IPCC estimate of 6 to 12 Gtpa of global CCS capacity by 2050–2060 timeframe (for their two scenarios with higher CCS) would scale to approximately 0.9 to 1.7 Gtpa for U.S. capacity.
- The IEA SDS estimate of 5.6 Gtpa of global CCS capacity by 2050 would scale to 0.8 Gtpa for U.S. capacity.
- The IEA NZE estimate of 7.6 Gtpa of global CCS capacity by 2050 would scale to 1.0 Gtpa for U.S. capacity.

1.3.2 U.S.-Centric Studies

Several studies have focused on CCS deployment in the US specifically. Three, non-exhaustive, examples are described below. Additional reports have been published such as those by the Energy Futures Initiative and the Rhodium Group.[23] [24]

1.3.2.1 Princeton University Net-Zero America (NZA)

In November 2021, Princeton University released its NZA Project, which examined five different scenarios for the United States to reach full decarbonization by 2050.[25]

The only scenario that did not require CO_2 sequestration was a 100% renewable scenario, which has its own drawbacks as discussed in Section 1.1. The other four scenarios require between 1 and 1.7 Gtpa of CCS by 2050.

1.3.2.2 U.S. Long Term Strategy (LTS)

In November 2021, the U.S. Department of State and U.S. White House released *The Long-Term Strategy of the United States*, which lays out how the United States can reach its goal of net-zero emissions no later than 2050 and was submitted to the United Nations Framework Convention on Climate Change (UNFCCC) at the 26th Conference of the Parties.[26] The LTS illustrates numerous plausible pathways through 2050 to achieve a net-zero emissions economy, and offers insights into what the overall energy system for the United States could look like between now and 2050 under a range of assumptions about the evolution of technological costs, economic growth, and other drivers to 2050.

The amount of CCS across the scenarios explored in the LTS ranges from 0.4 to 1.3 Gtpa in 2050. In the case that Figure 7 represents, total carbon sequestered is about 1,300 Mt (point source) and 200 Mt (DAC). Some models deploy much greater levels of DAC than shown here. The Long-Term Strategy also caveats the amount of CCS modeled from industrial applications: "… there is limited representation of CCS on industrial energy in the models we use. Accordingly, it is likely that a greater share of industrial fossil energy emissions could be captured by 2050 than is shown here."[27]

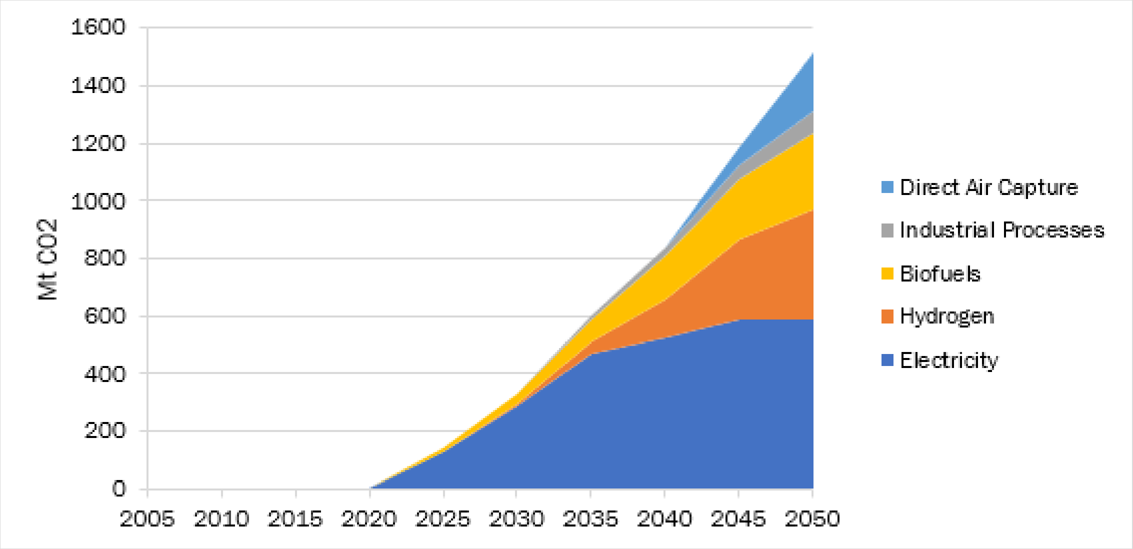


Figure 7: U.S. CCS separated by CO_2 source as predicted by one of the scenarios in the Long-Term Strategy.

1.3.2.3 MARKAL Analysis

Additional external studies were supplemented by DOE runs of technology dispatch models using numeric market allocation (MARKAL). Simulations in MARKAL were used to estimate the amount of domestic CCS that would occur under various policies, particularly to understand what carbon pricing or other policies would be required to achieve the 2.0 Gtpa target. MARKAL is an optimization tool originally developed by IEA for use in energy planning. It has been adapted to analyze CCS under potential incentive policies.

Out of all modeled policies, the policies that produced the highest level of CCS was taxing CO_2 at $35/ton, increasing at 5% per year and a CO_2 cap scenario. These policies would generate an estimated 1.66 Gtpa and 3.19 Gtpa of CCS capacity, respectively, by 2050.

1.3.3 Summary

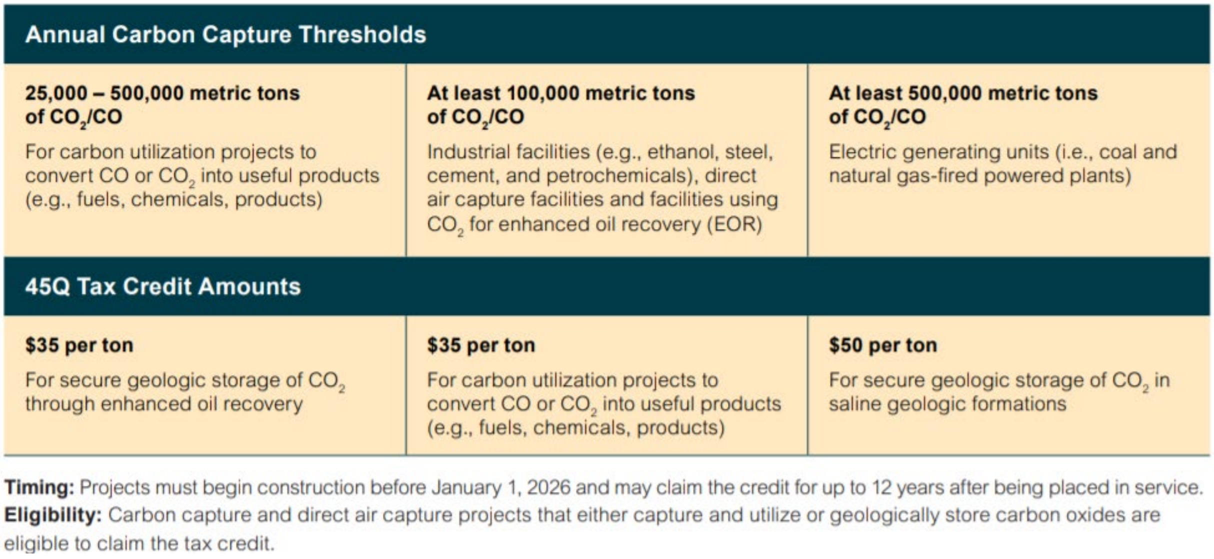
This literature analysis shows that in aggressive infrastructure deployment scenarios, the United States' likely upper bound of CCS capacity is 1.7 Gtpa by 2050. This suggests DOE's goal of 2.0 Gtpa of CCS capacity by 2050 represents a conservative upper bound for supply chain analyses, which served as the capacity goal for this study.

1.4 CO_2 Capture Policies

The United States is currently a global leader in carbon capture technology and projects. As of February 2021, the United States had 13 commercial-scale carbon capture facilities, half of worldwide capacity.[28]

Much of this success can be attributed to the United States' Internal Revenue Service (IRS) tax credit for carbon sequestration, 26 U.S. Code § 45Q ("45Q"). The United States has a history of providing tax credits for fuels and production methods, for example the Investment Tax Credit (ITC) for solar energy and the Production Tax Credit (PTC) for wind energy.

This 45Q tax credit, originally enacted by the Energy Improvement and Extension Act of 2008, is offered for each metric ton of carbon captured and sequestered. It was then enhanced in the Bipartisan Budget Act of 2018 to broadening eligibility of other industries and applications through lowering the annual CO_2 capture minimum, increasing its value, and providing greater flexibility for entities to claim the credit. It was further enhanced in the 2021 Consolidated Appropriations Act (Fiscal Year [FY] 2021 Omnibus) to give carbon capture credits a two-year extension (from ten years to twelve years from construction completion date).[29] Figure 8 provides some details.



Annual Carbon Capture Thresholds		
25,000 – 500,000 metric tons of CO_2/CO For carbon utilization projects to convert CO or CO_2 into useful products (e.g., fuels, chemicals, products)	**At least 100,000 metric tons of CO_2/CO** Industrial facilities (e.g., ethanol, steel, cement, and petrochemicals), direct air capture facilities and facilities using CO_2 for enhanced oil recovery (EOR)	**At least 500,000 metric tons of CO_2/CO** Electric generating units (i.e., coal and natural gas-fired powered plants)
45Q Tax Credit Amounts		
$35 per ton For secure geologic storage of CO_2 through enhanced oil recovery	**$35 per ton** For carbon utilization projects to convert CO or CO_2 into useful products (e.g., fuels, chemicals, products)	**$50 per ton** For secure geologic storage of CO_2 in saline geologic formations

Timing: Projects must begin construction before January 1, 2026 and may claim the credit for up to 12 years after being placed in service.
Eligibility: Carbon capture and direct air capture projects that either capture and utilize or geologically store carbon oxides are eligible to claim the tax credit.

Figure 8: U.S. 45Q Tax Credit structure and eligibility requirements

(Carbon Capture Coalition)

In addition to the 45Q Tax Credit, incentives have also included the DOE Loan Program Office (LPO) Financing, USDA rural financing, other Federal Tax Credits, and other State and Regional policies. The DOE LPO financing options are intended "to support innovative technologies that are typically unable to obtain conventional private financing due to perceived high technology risk", per the CEQ CCUS Permitting Report. USDA offers Rural Development Program Financing which offers some opportunities related to rural electrification and modernization. Other Federal Tax Credits include The Section 48A Qualifying Advanced Coal Project Credit and the Section 48C tax credit "for investments in facilities that manufacture clean energy technologies". To support CCUS development, various states also provide tax and non-tax policies. "These incentives may take form of tax credits, exemptions or reduction of property tax, severance tax, gross receipt tax, and sales tax, among others".[8]

In the years since 2018 when Congress revamped the federal 45Q tax credit to include carbon capture, project developers and investors have announced over 30 new projects spanning electric power, transportation fuels, and direct air capture technologies.[28] As of 2021, there are about 45 CCUS facilities in operation or in development in the United States. There were about 26 commercial scale projects in operation globally that year.[8]

Another factor in U.S. carbon sequestration technology success has been federal research and development (R&D) investments. DOE has funded R&D in aspects of CCS since at least 1997 within its Fossil Energy and Carbon Management (FECM) Research, Development, Demonstration, and Deployment (RDD&D) portfolio. Since FY2010, Congress has provided $7.3 billion in appropriations for DOE CCS-related activities, including annual increases in recent years. In FY2021, Congress provided $750 million to FECM, of which $228.3 million was directed to CCUS.

Some facilities will also benefit from the California low-carbon fuel standard (LCFS). Credits under this scheme were trading up to $212 per ton CO_2 in 2020.

2 Material Requirements

2.1 Capture

As discussed previously, the advanced commercial and technological readiness of MEA-based solvent capture position it to achieve broad, early deployment as the combined CCS system expands in the US. Thus, this report has focused on this technology to understand supply chain constraints during a critical early period of rapid scale-up. There are other solvents and other technologies involving sorbents or membranes, but MEA is the most common and most developed in commercial use around the world.[30] Planning for a scenario that leverages MEA exclusively leads to a conservative estimate on the growth rates required to satisfy the ambitious demand scenario of this analysis. If there are limited supply chain risks with this scenario, then it may be safe to assume that the more realistic situation of multiple capture technologies contributing to the CCS effort also presents very low supply chain risk.

2.1.1 Technology Overview

2.1.1.1 Exemplar Technology: MEA-based Solvent Capture

Monoethanolamide (MEA), also known as ethanolamine, is a solvent common in solvent-based CO_2 capture, which involves chemical or physical absorption of CO_2 into a liquid carrier. The absorption liquid is regenerated by increasing its temperature or reducing its pressure to break the absorbent-CO_2 bond. This process of CO_2 capture with MEA can be seen in Figure 9.

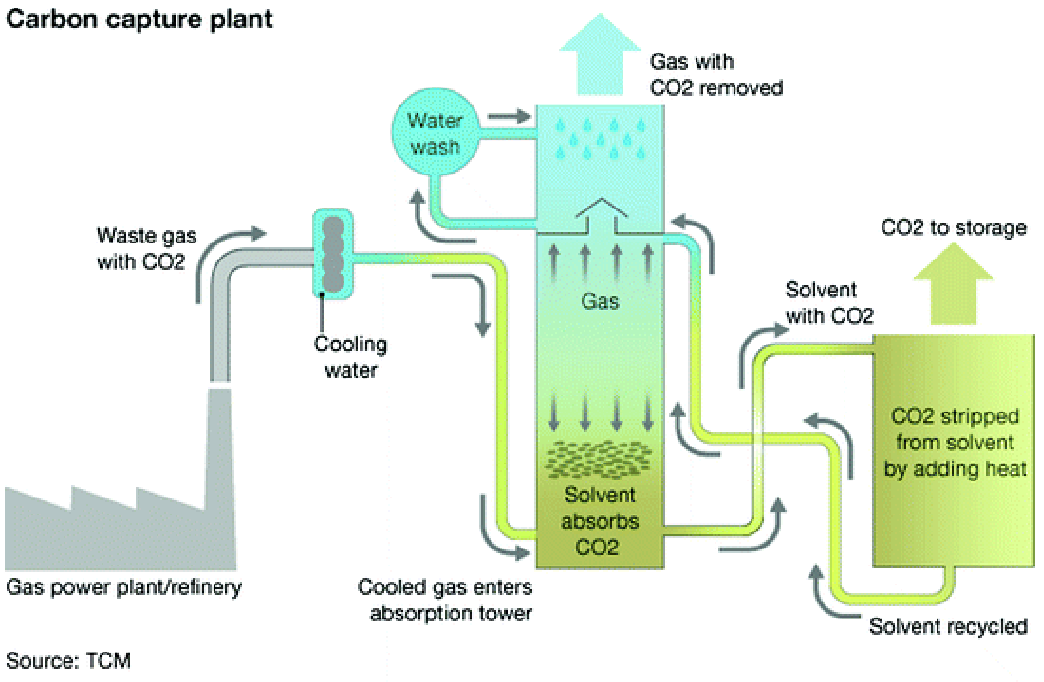


Figure 9: Schematic of solvent-based CO_2 capture

2.1.1.2 Potential Alternative Capture Technologies

As shown in Figure 10, in addition to MEA-based solvent capture technology, there are many other systems across commercial readiness levels designed to capture CO_2. Generally, carbon capture can be split into four main categories: solvents, sorbents, membranes, and cryogenic systems. Within the solvent group, primary materials used include physical and chemical solvents such as: MEA, methanol, methyldiethanolamine

(MDEA), and potassium hydroxide (KOH). The sorbent group implements both synthetic and natural zeolites (specifically Z13, Y, Molecular Sieve 5A, 13X, clinoptilolite, and mordenite) as well as activated carbon and alumina. It is expected that as physical and policy infrastructure appear and mature for carbon capture that many of these alternatives will become economically competitive with the amine-solvents analyzed herein; in fact, next generation solvents are likely to be direct substitutes for amine systems to leverage the maximum amount of capital equipment and systems engineering of first generation systems to keep costs low.

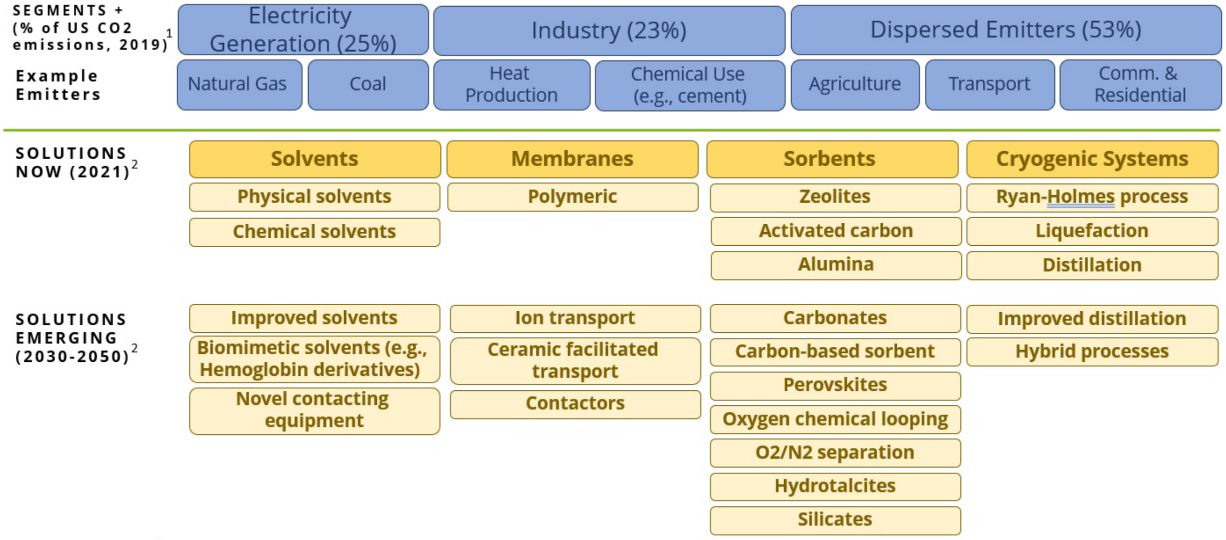


Figure 10: Carbon capture market and technology segmentation. [31]

Note: *Adapted from IPCC*

Figure 9 and the above Section 2.1.1.1 describe solvent based carbon capture. Sorbent based capture involves the chemical or physical adsorption of CO_2 using a solid sorbent. On a high level, adsorption occurs closer to the molecular level where molecules adhere to a surface of the adsorbent. Absorption occurs when molecules are drawn into the material, such as a sponge soaking up water. Similarly, liquid carrier solvents like MEA absorb CO_2 out of the flue gas, while solid sorbents adsorb CO_2. Sorbents are also regenerated by heating or reducing pressure to release the captured CO_2. However, reports from the National Energy Technology Laboratory (NETL) note that "sorbent technologies are generally less developed than solvents and have heat transfer, stability and attrition challenges".[32] The lower heat capacities of sorbents compared to solvents decrease their regeneration energies, making them less efficient. NETL also notes that several research efforts are under way to make sorbents cheaper, more durable, better at absorbing CO_2, and more resistant to oxidation, all while withstanding multiple regeneration cycles. Table 2 lists in detail many of the materials necessary for the carbon capture available today and frequently mentions metal-organic frameworks (MOF) sorbents. Figure 11 depicts how MOF sorbents trap CO_2 in their lattice structure.

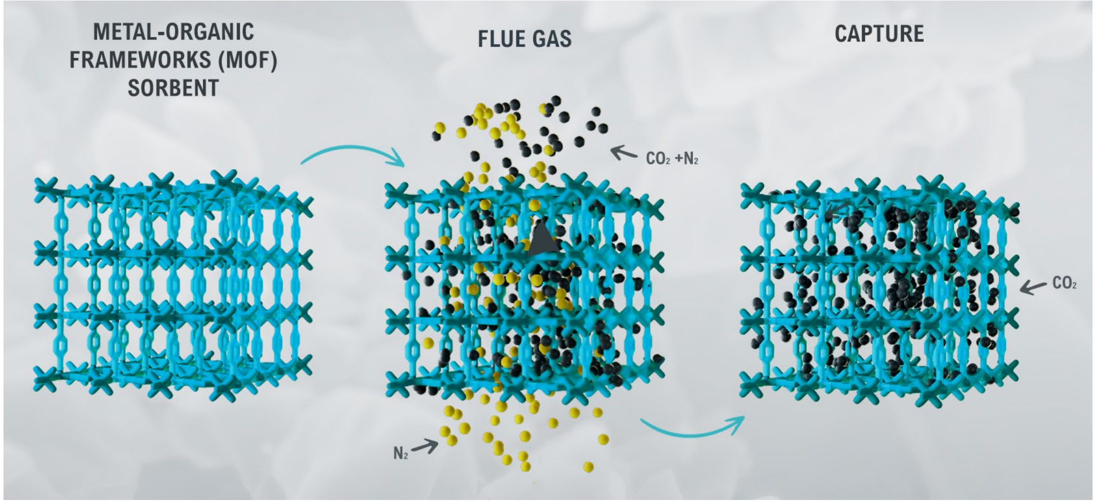


Figure 11: MOF sorbent illustration by Svante[33]

Membrane capture technologies leverage materials with varying degrees of permeability to allow for the separation of CO_2 from flue gas or pre-combustion syngas. These materials offer several advantages such as limited hazardous chemical storage, passive operation, reduced plant footprint, and reduced implementation cost. However, membranes need to improve in their selectivity for CO_2, as well as their thermal and physical stability and tolerance to contaminants in flue gas.

Researchers are also investigating novel capture technologies that may combine several methods into an efficient hybrid system. Cryogenic separation and the use of novel 3-D printed parts are additional research avenues to improve CO_2 capture efficiencies.[34]

2.1.2 Raw Material Requirements

2.1.2.1 Exemplar Technology: MEA-based Solvent Capture

As seen in Figure 12, the production of MEA begins with natural gas and crude oil. To produce ethylene, these hydrocarbons are steam cracked. Steam cracking is a thermal process that breaks down larger molecules into smaller molecules by first mixing the large hydrocarbons with steam, then running them through tubes in a cracking furnace where the feedstock is briefly heated to very high temperatures, then rapidly cooling them to stop the hydrocarbon molecules from being completely consumed. The resulting product streams are separated and purified, leaving valuable compounds called “olefins”: ethylene, propylene, and others.

To produce hydrogen, these hydrocarbons are steam reformed. Steam reforming is a mature production process in which methane reacts with high pressure steam in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. In a final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen. Other methods of hydrogen production such as electrolysis of water avoid hydrocarbons, but are currently more expensive and do not see widespread commercial use. Hydrogen is then combined with nitrogen that is separated from air to produce ammonia through the Haber-Bosch process that has been in use commercially for over a hundred years. Finally, MEA is produced industrially through a reaction of the ethylene oxide with aqueous ammonia.

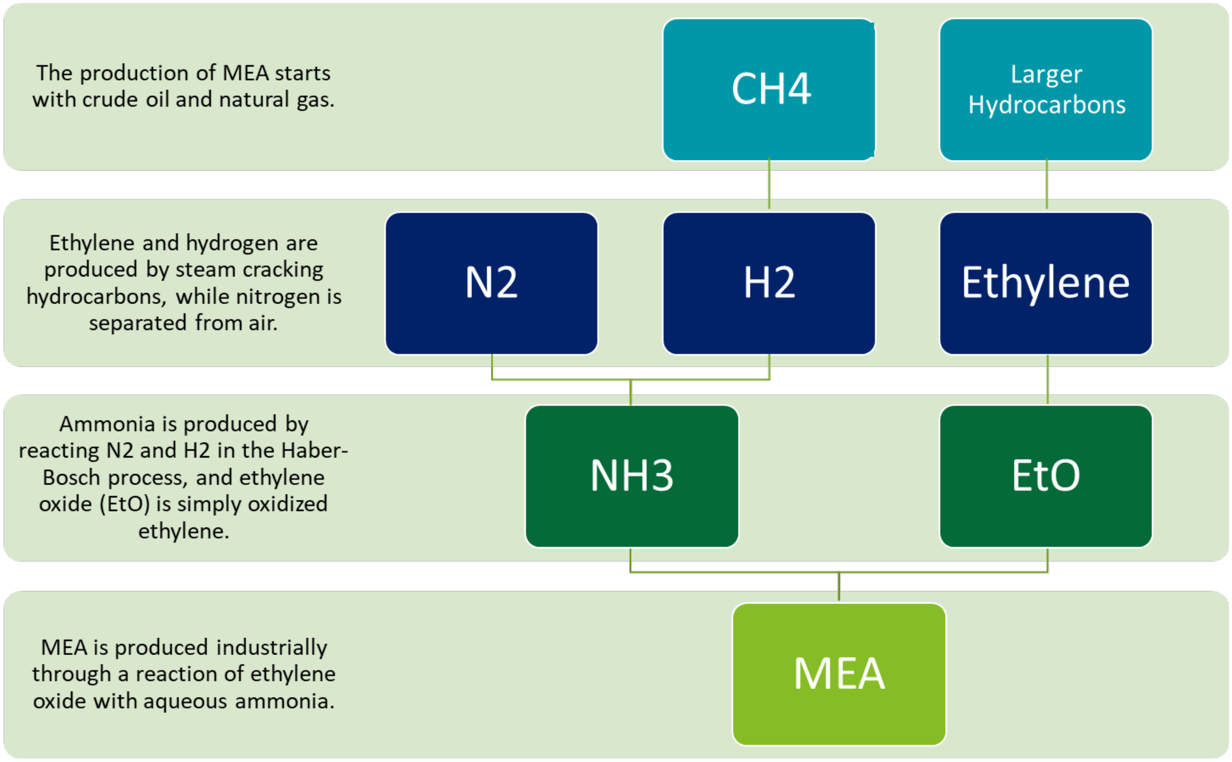


Figure 12: Materials supply chain to produce MEA solvent

The requirements of MEA for a given CO_2 capture capacity can be calculated as a linear scaling. Based on the data from a November 2010 DOE/NETL report that examined CCS via MEA-based capture, the following requirements were calculated: [35]

- **Baseline Loading**: 780 tons of MEA / Mtpa of designed CO_2 capture capacity
- **Operating Losses**: 400 tons of MEA / Mt of captured CO_2

In other words, MEA requires an initial investment of 780 tons of MEA / Mtpa of CO_2 capture capacity plus 400 tons of MEA / Mt of CO_2 captured for continued operations.

To estimate MEA requirements over time, the 5-year interval data from the MARKAL CCS deployment scenario resulting in 1.66 Gtpa by 2050 ($35/ton CO_2 tax increasing by 5% per year) was scaled up to 2.0 Gtpa by 2050.

CO_2 capture requirements for each year were assumed to be spread across the previous five years (for instance, 616.83 Mt of new CO_2 capture in 2030 meant 116.98 Mt in each of 2026–2030). As discussed, MEA is needed for both opening of these plants (baseline loading) and continued operation. Table 1 shows the amount of MEA required in 5-year intervals to capture the CO_2 required in each interval.

Table 1: MEA requirements for 2.0 Gtpa CCS capacity by 2050

Year	2025	2030	2035	2040	2045	2050
Total CO_2 Capture (Mtpa)	31.94	616.83	943.85	1498.62	1782.28	2000.00
Total MEA Required in year (Capital + Operations) (kt)	37.69	337.98	428.55	685.99	757.16	833.96

From 2025–2050, the United States will need a combined 13.68 Mt of MEA (12.12 Mt from continued operation across the 25 years, 1.56 from initial capacity coming online). Year-over-year MEA requirements can be seen below in Figure 13.

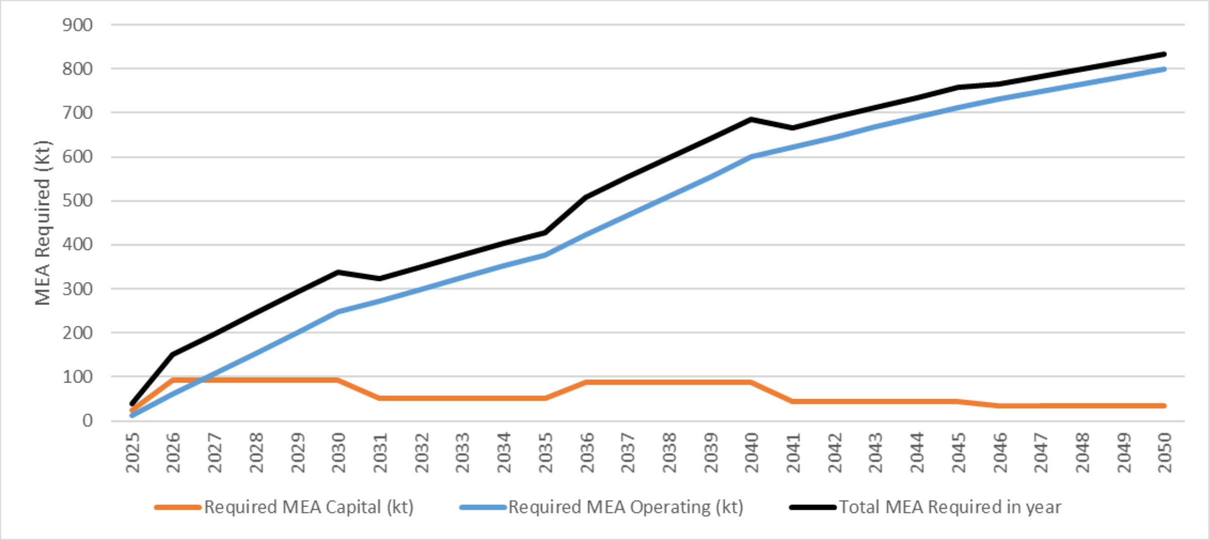


Figure 13: MEA requirements per year, 2025–2050

2.1.2.2 Critical Mineral Use in Emerging Capture Technologies

As previously described, emerging capture technologies will likely prove economically superior to the amine solvent-based processes used for exemplary purposes in this analysis. As some of these new technologies, at varying stages of maturity, come closer to commercialization and practical use, it is essential to develop in parallel the supply chains of required materials and components. **Table 2** lists the critical commodities potentially used in future technologies for CO_2 capture and utilization.

Table 2. List of critical commodities required for carbon capture technologies

Critical Commodities	General Fossil Energy Technology	Specific Technology
Aluminum	CO_2 Capture	Zeolite-based sorbents; sorbent support; trimethyl aluminum as precursor; Al_2O_3 coatings for zeolite-based, metal organic framework (MOF)-based, and ZIF-based sorbents; Al-based hydrotalcite sorbent
Aluminum	CO_2 Capture	Wetting agent in ceramic-carbonate membranes; zeolite-based membrane support
Aluminum	CO_2 Capture	Heat exchanger material; anti-corrosion coating for power generation applications
Antimony	CO_2 Capture	Sorbent
Arsenic	CO_2 Capture	Sorbent
Bismuth	CO_2 Capture	Ceramic-carbonate membranes
Cesium	CO_2 Capture	CaO sorbents doped with cesium Cs/Cao
Chromium	CO_2 Capture	MOF sorbents

Critical Commodities	General Fossil Energy Technology	Specific Technology
Cobalt	CO_2 Capture	MOF sorbents; ceramic-carbonate membranes
Fluorspar	CO_2 Capture	MOF sorbents
Graphite	CO_2 Capture	Membrane seals; graphene oxide-based membranes
Hafnium	CO_2 Capture	Zirconia sorbent support; MOF sorbents; Zr-based sorbents (i.e., lithium zirconate, calcium zirconium oxide, barium zirconate)
Hafnium	CO_2 Capture	Ceramic-carbonate membranes
Lithium	CO_2 Capture	Lithium-based sorbents (i.e., lithium zirconate, lithium silicate)
Lithium	CO_2 Capture	Wetting agent in ceramic-carbonate membranes
Magnesium	CO_2 Capture	Magnesium hydroxide-based and MgO-based sorbents for pre-combustion CO_2 capture; MOF sorbents; Mg-based hydrotalcite sorbents
Manganese	CO_2 Capture	MOF sorbents
Platinum-Group Metals	Carbon Utilization	Catalyst for plasma reactions to produce hydrogen production from water and CO_2
Rare Earth Elements	CO_2 Capture	Lanthanum-based sorbent supports
Rare Earth Elements	CO_2 Capture	Lanthanum in ceramic-carbonate membranes; yttrium in ceramic-carbonate membranes; samarium in ceramic-carbonate membranes; cerium in ceramic-carbonate membranes; gadolinium in ceramic-carbonate membranes; scandium in ceramic-carbonate membranes; cerium catalyst in WGS membranes; yttrium-based, zirconium-based membrane supports
Scandium	CO_2 Capture	Sorbent – CO_2 capture by small pore scandium-based MOFs
Strontium	CO_2 Capture	Strontium oxide high-temperature sorbent
Tin	Carbon Utilization	Catalyst for electrolyzer reactions to produce formic acid
Titanium	CO_2 Capture	Coatings for zeolite-based, MOF-based, and ZIF-based sorbents; MOF sorbents; Ti-based sorbents (i.e., barium titanate)
Vanadium	CO_2 Capture	MOF sorbents
Zirconium	CO_2 Capture	Zirconia sorbent support; MOF sorbents; Zr-based sorbents (i.e., lithium zirconate, calcium zirconium oxide, barium zirconate)
Zirconium	CO_2 Capture	Ceramic-carbonate membranes

Estimating the material demands for precommercial technologies is extremely challenging and the risk to their future supply even more so. The material requirement of an individual process or unit operation is likely to evolve as the technology matures and, when threatened by supply shortages, many materials are replaceable. Further, the global supply chain is dynamic as evidenced by wide swings in the supply risk through time as assessed by USGS for elements such as bismuth and lanthanum.[36]

2.2 Drying and Liquification

After the CO_2 is captured, it must be treated and compressed before it can be transported to its storage location. As discussed, the treatment process is necessary because untreated CO_2 contains impurities and water, which can create hydrides and acids. Water, for example, when mixed with CO_2 forms carbonic acid; a weak acid enhances the corrosion rate of mild steel by accelerating the cathodic reaction.

In the treatment process, CO_2 is transported (via small anti-corrosion steel pipes) to purification and dehydration tanks, where it is purified to levels above 99% CO_2. There are several technologies to dry the CO_2, however, it is anticipated that triethylene glycol (TEG) will be used for most carbon capture in the United States in 2050 due to its effectiveness and widespread use in the natural gas industry. The liquification process is necessary because gaseous CO_2 is more voluminous, and thus would necessitate larger pipelines than liquid CO_2.

2.2.1 Technology Overview

TEG is used for drying/dehydration of the captured CO_2. In the process, wet gas (CO_2) enters the bottom of a glycol contactor and is put into contact with liquid TEG (which can occur via several methods) as shown inFigure 15. CO_2 dehydration units can be combined with impurity removal units.

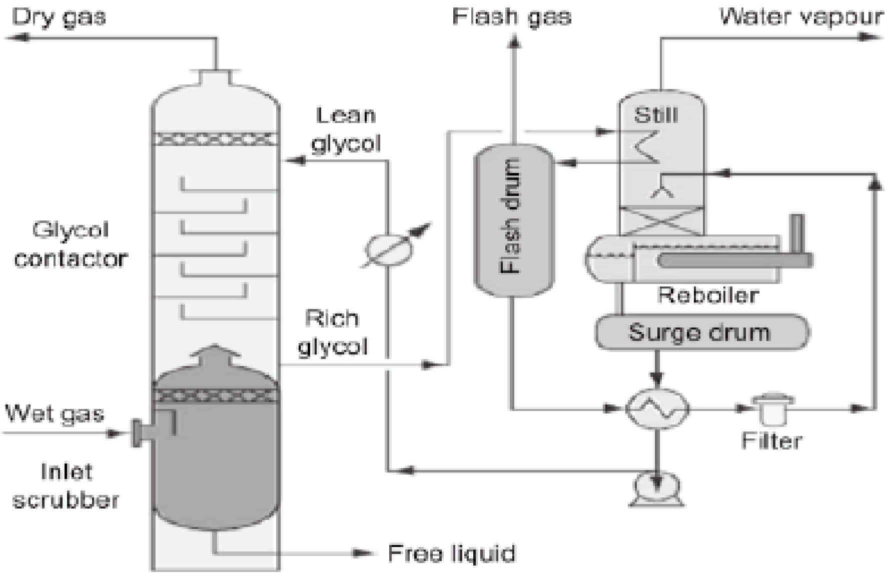
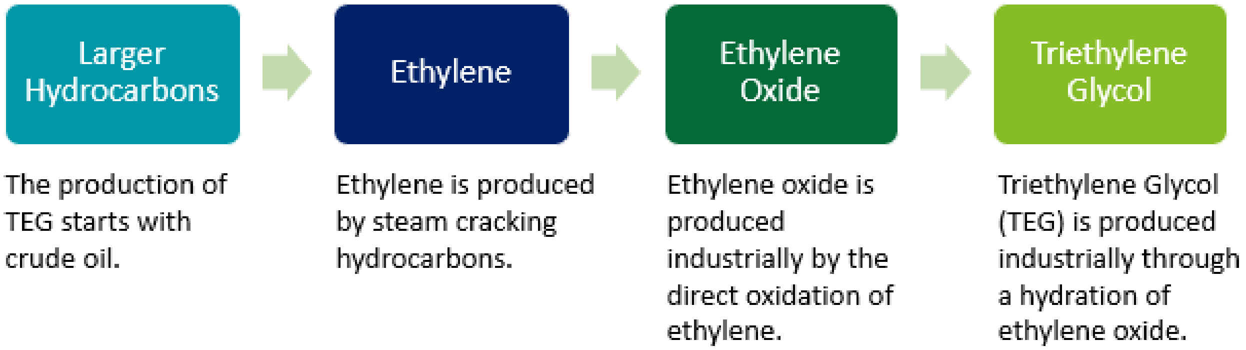


Figure 14: CO_2 dehydration process using TEG[37]

After dehydration and removal of impurities, the CO_2 is liquefied using a compression train to bring the CO_2 stream to the desired pressure and temperature. According to the NETL-NZA model (discussed in Section 2.3), these compressors will aim to pressurize the stream to 2,200 pounds per square inch gauge (psig) (15.3 megapascals, MPa) and 53 °F.

2.2.2 Raw Material Requirements

The production of TEG begins with crude oil (Figure 16). The larger hydrocarbons are cracked using steam reformation to produce ethylene. This ethylene is directly oxidized and then hydrated to produce TEG.



The production of TEG starts with crude oil.

Ethylene is produced by steam cracking hydrocarbons.

Ethylene oxide is produced industrially by the direct oxidation of ethylene.

Triethylene Glycol (TEG) is produced industrially through a hydration of ethylene oxide.

Figure 15: Materials used in TEG production

Like MEA, the requirements of TEG for a given CO_2 capture capacity can be calculated as a linear scaling. Based on data from an April 2012 IEA report that examined CCS dehydration, the following requirements were calculated: [38, 39]

- **Baseline Loading**: 13 tons of TEG / Mtpa of designed CO_2 capture capacity
- **Operating Losses**: 20 tons of TEG / Mt of captured CO_2

In other words, TEG requires an initial investment of 13 tons of TEG / Mtpa of CO_2 capture capacity plus 20 tons of TEG/ Mt of CO_2 captured for continued operations. To estimate TEG requirements over time, the same 5-year interval data for MEA was utilized. As discussed, TEG is needed for both opening of these plants (baseline loading) and continued operation. 5-year interval requirements for TEG can be seen below in Table 3. From 2025–2050, the United States will need a combined 632.1 kt of TEG (606.1 kt from continued operation across the 25 years, 26.0 kt from initial capacity coming online). Year-over-year TEG requirements can be seen in Figure 16.

Table 3: TEG requirements for 2.0 Gtpa CCS capacity by 2050

Year	2025	2030	2035	2040	2045	2050
Total CO_2 Capture (Mtpa)	31.94	616.83	943.85	1498.62	1782.28	2000.00
Total TEG Required in year (Capital + Operations) (kt)	1.05	13.86	19.73	31.41	36.38	40.57

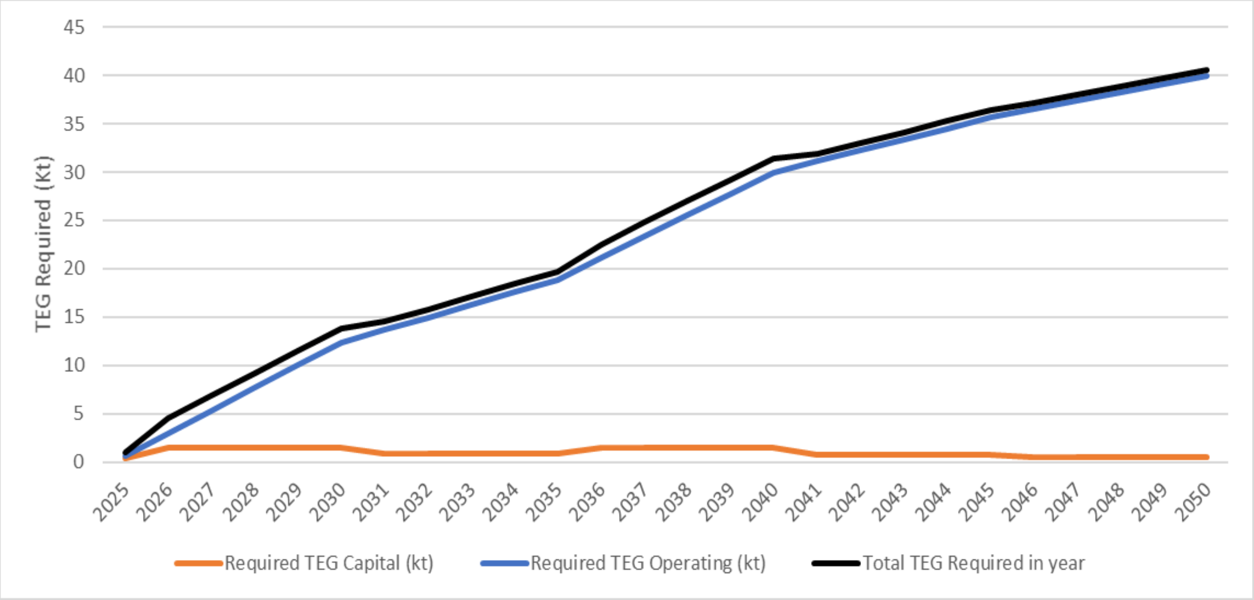


Figure 16: TEG requirements per year, 2025–2050

Selection of a compressor can be a complex task and is based on several variables including ambient temperature of the compressor, required flow rate, power requirements, and more.[40] Additional analysis is needed to understand the number of compressors needed for 2.0 Gtpa of CO_2 capture capacity, as well as typical characteristics of these compressors.

2.3 Transportation Pipelines

2.3.1 Technology Overview

Once the CO_2 is separated, dried, and liquified, the captured carbon will need to be transported to its long-term storage. If the United States is to have tens of gigatons of CCS capacity by 2050, the transportation network will need to be able to transport large amounts of CO_2 from capture sites to regions with large geologic storage facilities cost-efficiently and effectively. This will require a large-scale pipeline network. The process of making pipes and laying pipelines is well-known and straightforward; it is likely that millions of miles of oil and gas pipeline exist globally, as will be expanded upon in Section 3.3. Figure 17 depicts a typical pipeline installation project.

Figure 17: Illustrative pipeline installation[41]

The pipeline types assessed in these analyses include sub-spur, spur, trunkline, distribution, and sub-distribution pipelines, as shown in Figure 18.

- **Sub-spur pipelines** connect small mass flow rate CO_2 point sources to a central aggregation point.
- **Spur pipelines** connect either large mass flow rate CO_2 point sources or central aggregation points to trunklines.
- **Trunklines** operate as the large "highways" of the CCS transportation system, connecting spur lines to storage sites.
- The connecting pipelines from trunklines to storage sites, and from storage site distribution manifolds to individual injection well heads, are called distribution and sub-distribution pipelines, respectively.

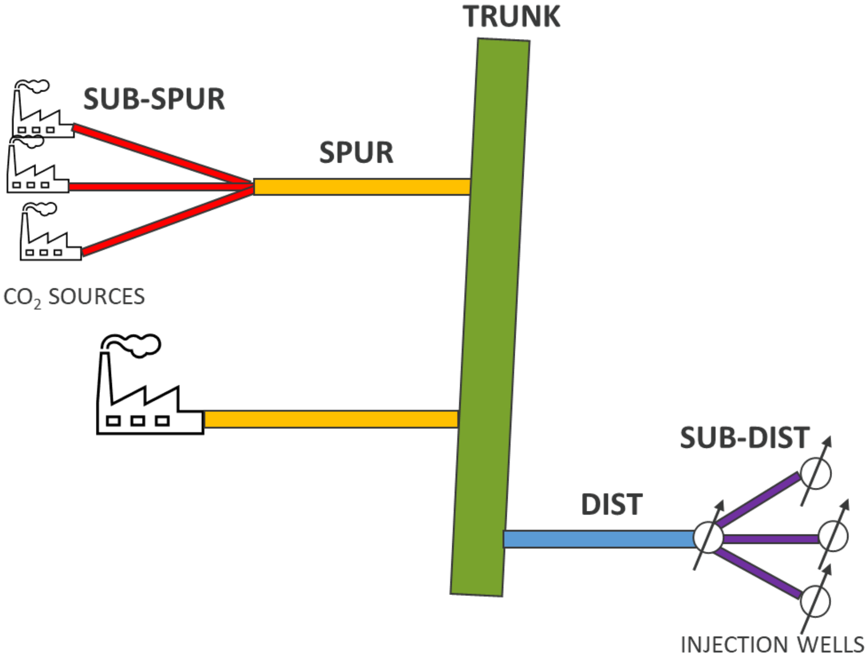


Figure 18: Illustration of pipeline types

Pumps will be required for transporting the liquified CO_2 through the pipeline to the injection sites. Various sized pumps will be required depending on the pipe diameter and required flow.

Figure 19: Multi-stage compressor/pump able to be used for the liquification and transportation[42]

Refrigeration stations and/or additional pumps and compressors may be needed throughout the length of the pipeline to ensure temperature, pressure, and flow specifications are maintained. Redundant pumps may also be necessary to ensure safety and continuous operation in the case of failures. Just-in-case compressors and pumps may also be required at injection sites to ensure the pressure is higher than the backpressure of the storage cavern, especially as time progresses and the sites' pressure builds. Figure 19 depicts a few common pump designs used in these applications.

2.3.2 Raw Material Requirements

CO_2 transport pipelines can be made from the same materials as natural gas pipes, but with slightly thicker walls. This steel will be similar to (or the same as) American Petroleum Institute (API) 5L X65, a low-carbon pipeline steel with less than 1.4% by weight manganese that is commonly used in global pipelines.

Additionally, pipelines are assumed to follow the product standard level (PSL) 2 pipe standard to ensure a higher quality over the looser PSL 1 standard.

To estimate the pipeline characteristics necessary for large-scale carbon transport, (1) an analysis was developed using NETL's modeling capabilities and Princeton University's NZA data (Section 2.3.2.1), and (2) a literature review was performed of an existing Great Plains Institute (GPI) report (Section 2.3.2.2). While the former (known as the "NETL-NZA Model" moving forward) served as the primary method of analysis, the GPI report was also discussed to offer an additional perspective of how a domestic CCS transportation system may be implemented.

2.3.2.1 NETL-NZA Model

In the aforementioned 2020 NZA study, Princeton University researchers calculated the CO_2 mass flow rates, lengths, and 5-year interval deployment schedule of the sub-spur, spur, and trunk lines required for their pipeline network, as well as the number of CO_2 storage projects.[43] NETL contacted the authors of the NZA report to request their data (specifically, the data that resulted in a 2050 CCS capacity closest to the DOE's 2.0 Gtpa goal: Scenario E-B+, resulting in 1.6 Gtpa in 2050) for further analysis. That scenario is depicted in Figure 20 below.

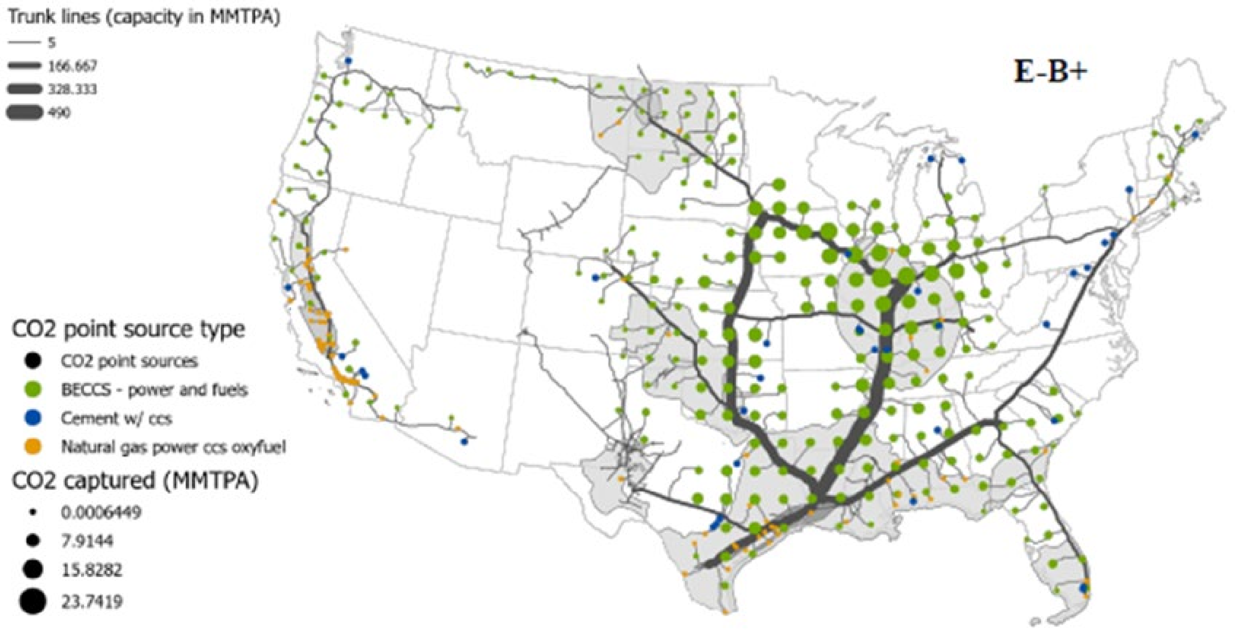


Figure 20: Princeton University NZA pipeline network for 1.6 Gtpa by 2050 (for reference)

After receiving these data, NETL performed additional analysis to calculate characteristics of transportation infrastructure (detailed below in the remainder of Section 2.3.2) and injection infrastructure (detailed in Section 2.4.2) to meet the 2.0 Gtpa by 2050. Detailed data can be found in Section 6, "Appendix -– NETL-NZA Model."

In calculating transportation infrastructure characteristics, the NETL-NZA Model estimates that over 70,000 miles of pipeline are required for a 2.0 Gtpa CO_2 capture capacity, with pipeline construction peaking in 2035 at 21,000 miles of pipeline and continue meaningful buildout through 2045. The NETL-NZA Model sees most pipeline being 6”, 8”, and 42” diameter. Regarding pumps, the NETL-NZA Model estimates that 595 will be required through 2050, with most being installed in the same 2035–2045 range.

Because the NETL-NZA Model uses trunklines that have significantly larger mass flow rates than any CO_2 pipeline in existence today, a sensitivity analysis was also run using trunklines limited to 30” in nominal diameter (hereafter, “NETL-NZA Model Pipeline Diameter Sensitivity Analysis” or the “Sensitivity Analysis”). The Sensitivity Analysis estimates that roughly 27% more pipeline will be needed (96,000 miles), mainly for pipeline of 24” and 30” diameter to compensate for the larger highway pipeline. It also estimates that 37% more pumps will be required (815), again in the 24” and 30” diameter range with the additional pipeline. Table 4 provides a summary of this information.

Table 4: NETL-NZA Model (and Sensitivity Analysis) transportation characteristic summary

Nominal Pipe Diameter (in)	NETL-NZA Model		NETL-NZA Model Sensitivity Analysis	
	Total Pipeline by 2050	Total Pumps by 2050	Total Pipeline by 2050	Total Pumps by 2050
4	3,087	46	3087	46
6	15,387	74	15,387	74
8	24,835	33	24,835	33
10	5,467	21	5,467	21
12	1,535	142	1,535	142
16	846	56	846	56
20	1,336	43	1,336	43
24	1,381	20	3,307	56
30	1,478	14	40,893	344
36	2,292	21	-	-
42	8,855	77	-	-
48	4,002	48	-	-
Grand Total	**70,502**	**595**	**96,694**	**815**

<u>Pipeline material requirements</u>: Based on the pipeline requirements set forward in the NETL-NZA Model and corresponding Sensitivity Analysis, steel calculations were performed. Results indicate that between 24.12 Mt and 30.16 Mt of steel will be required to build pipelines. Additives to this steel will be discussed in Section 3.3.

<u>Pump material requirements</u>: Based on the pump requirements set forward in the NETL-NZA Model and corresponding Sensitivity analysis, and after discussions with pump industry experts who have supported large CCS projects in the past, rough order-of-magnitude pump material requirements were generated. Conversations with a pump original equipment manufacturer provided that 1 MW pumps weigh roughly 62 tons and are 150 m^3 (10 meters long, 5 meters wide, and 3 meters tall). Industry expertise also noted that

pumps are typically roughly 80% cast iron (pump drive, baseplate, gearbox) and 20% stainless steel (pump head). Table 5 and Table 6 showcase the pipeline length required and pump characteristic per diameter of pipe.

Table 5: NETL-NZA Model pump characteristics

Inner pipe diameter (inch)	Sum of pipeline length (miles)	Average of maximum CO_2 mass flow rate (Mt/yr)	Average of average annual CO_2 mass flow rate (Mt/yr)	Average of maximum required power of each pump (kW)	Number of pumps	Pump MW required
4.0	3,086.9	0.2	0.2	74.4	46.0	3.4
6.0	15,386.7	1.0	0.8	309.7	74.0	22.9
8.0	24,835.5	1.4	1.2	439.8	33.0	14.5
10.0	5,466.9	5.5	4.7	1,750.6	21.0	36.8
12.0	1,535.4	5.3	4.5	1,674.2	142.0	237.7
15.2	846.0	8.8	7.5	2,776.6	56.0	155.5
19.0	1,336.4	13.1	11.2	4,151.3	43.0	178.5
22.7	1,380.5	18.7	15.9	5,930.0	20.0	118.6
28.4	1,478.3	29.8	25.4	9,442.3	14.0	132.2
34.1	2,292.1	47.2	40.2	14,949.8	21.0	313.9
39.8	8,854.7	67.4	57.3	21,312.7	77.0	1,641.1
45.5	4,002.5	110.8	94.2	35,065.7	48.0	1,683.2
Grand Total	**70,502.0**	-	-	-	**595.0**	**4,538.3**

Table 6: NETL-NZA Model (with Sensitivity Analysis) pump characteristics

Inner pipe diameter (inch)	Sum of pipeline length (miles)	Average of maximum CO_2 mass flow rate (Mtonnes/yr)	Average of average annual CO_2 mass flow rate (Mtonnes/yr)	Average of maximum required power of each pump (kW)	Number of pumps	Total power required (MW)
4.0	3,086.9	0.2	0.2	74.4	46.0	3.4
6.0	15,386.7	1.0	0.8	309.7	74.0	22.9
8.0	24,835.5	1.4	1.2	439.8	33.0	14.5
10.0	5,466.9	5.5	4.7	1,750.6	21.0	36.8
12.0	1,535.4	5.3	4.5	1,674.2	142.0	237.7
15.2	846.0	8.8	7.5	2,776.6	56.0	155.5
19.0	1,336.4	13.1	11.2	4,151.3	43.0	178.5
22.7	3,307.1	19.5	16.6	6,180.9	56.0	346.1
28.4	40,893.0	28.6	24.3	9,045.0	344.0	3,111.5
Grand Total	**96,694.0**	-	-	-	**815.0**	**4,106.9**

With the assumption that 62 tons of material are required per MW, a total NETL-NZA Model pipeline power requirement of 4,538.3 MW may yield a weight of about 281.38 kt. Breaking this down into the component parts, about 225.1 kt of cast iron and 56.28 kt of steel would be required. The Sensitivity Analysis yielded a slightly smaller power requirement, and so the more conservative estimate will be considered.

A limitation to this analysis is that typical pump sizes were not used. It is far more likely that several 1 MW or 500 kW pumps be used in parallel to create the required MW, versus custom-sized, larger pumps being created. However, if the quantity and placement of pumps changes as more information is obtained, estimations of the raw material requirements should remain relatively constant as it is based on the total power requirement to transport 2 Gtpa of CO_2 across the modeled distances. For example, if further analysis suggests that one pump will be required at each of the 1,758 capture sites and at each of the 3,000 injection wells, those 4,758 pumps will be sized at smaller power requirements. In this case, although there would be 4,758 pumps in the model, the total power requirement would still be approximately 4,538.3 MW. And so, this rough order of magnitude estimate hinges on the assumptions that (1) 62 tons of material are required per MW and (2) 4,538.3 MW of total power is required to pump 2.0 Gtpa throughout the modeled length and cross section of pipeline. There is some inherent error in the 62 tons per MW assumption, as this assumes the weight to power ratio is linear for all pump sizes, which, considering power laws, is probably not the case.

Additional materials are likely required on top of those cast iron and stainless-steel estimates, even with a large redundancy factor of 3x. However, this material requirement is still negligible both holistically and compared to the steel required for the pipes.

A greater level of detail from industry experts is needed for compressors and the supplemental pump and refrigeration stations across the pipeline in order to generate material requirement estimates for those pieces of equipment. However, it is not expected that these flow maintenance stations will increase the raw material demand significantly.

2.3.2.2 Great Plains Institute

The Great Plains Institute's June 2020 whitepaper, "*Transport Infrastructure for Carbon Capture and Storage: Whitepaper on Regional Infrastructure for Midcentury Decarbonization,"* details the results of an extensive study into near and medium-term carbon capture projects in the central United States. The study looked at all stationary sources of CO_2 in this region and optimized a CO_2 pipeline system for the transport of 281.2 Mtpa of CO_2 from 381 emitting facilities. In this scenario, 29,710 miles of CO_2 pipeline are built. This is broken down by diameter in Table 7. These estimates were combined with estimates for the tonnage of steel per mile of CO_2 pipeline per diameter of pipe from ICF Incorporated (ICF) International's 2009 report,[44] and the total estimated tonnage of steel for this pipeline was calculated to be 3.2 million tons. Figure 21 depicts how the Great Plains Institute modeled the pipeline.

Table 7: Pipeline diameters, lengths, and steel tonnage based on GPI analysis[45]

Diameter (inches)	**4**	**6**	**8**	**12**	**16**	**20**	**24**	**30**
Length (miles)	4,712	6,063	8,560	5,834	2,675	1,790	59	16
Steel (tons/mile)	46	67	88	130	184	298	413	645

Note: *Pipeline represents 281.2 Mtpa of CCS capacity*

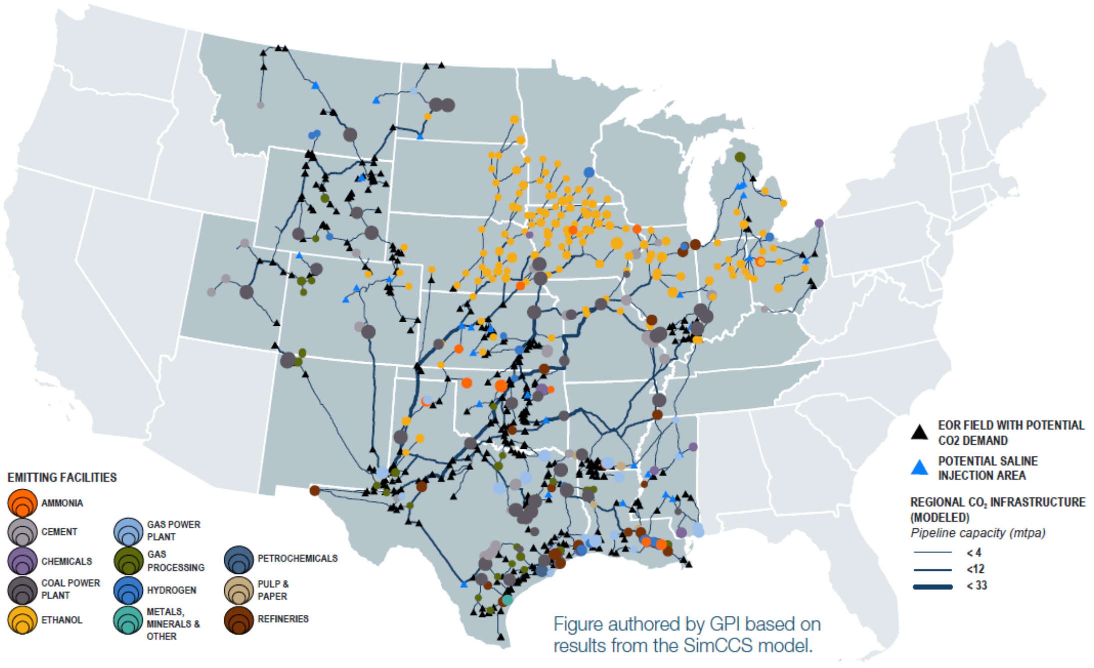


Figure authored by GPI based on results from the SimCCS model.

Figure 21: Map of GPI focus region with the 381 emitting facilities identified for near and medium-term carbon capture[43]

Note the optimized transportation pipeline network in black.

Dividing by the capacity of CO_2 in this pipeline (281.2 Mtpa), the amount of steel per Mtpa of CO_2 is calculated to be 11,363 tons. This is not an exact calculation, but it does provide another datapoint for magnitude of steel required in the 2050 timeframe. Scaling this value, approximately 22.73 Mt of steel are required to capture 2.0 Gtpa. The Great Plains Institute report did not examine pumps required for the pipeline.

2.3.2.3 Summary

From the NETL-NZA Model and GPI analysis, it is estimated that a range of 22.73 Mt to 30.16 Mt of steel is required to build pipelines. The stainless-steel requirements estimated for pumps is expected to increase the pipeline steel requirements in a negligible manner, as outlined in Table 9.

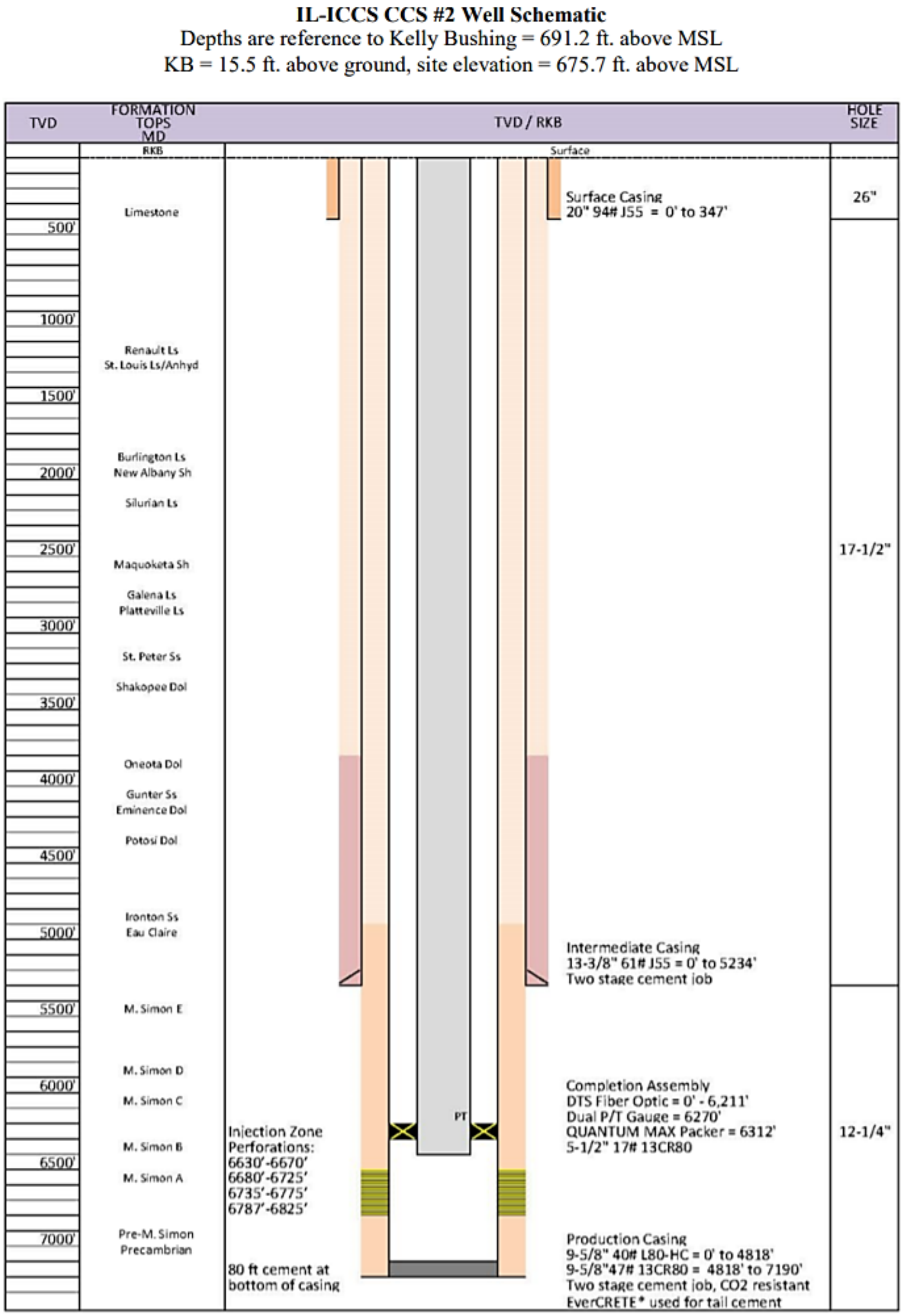
2.4 Storage / Injection

2.4.1 Technology Overview

As discussed in Section 1.2, after traversing the pipeline, CO_2 is injected into geologic storage. In this report, NETL's analysis assumed only saline reservoirs would be used for storage.

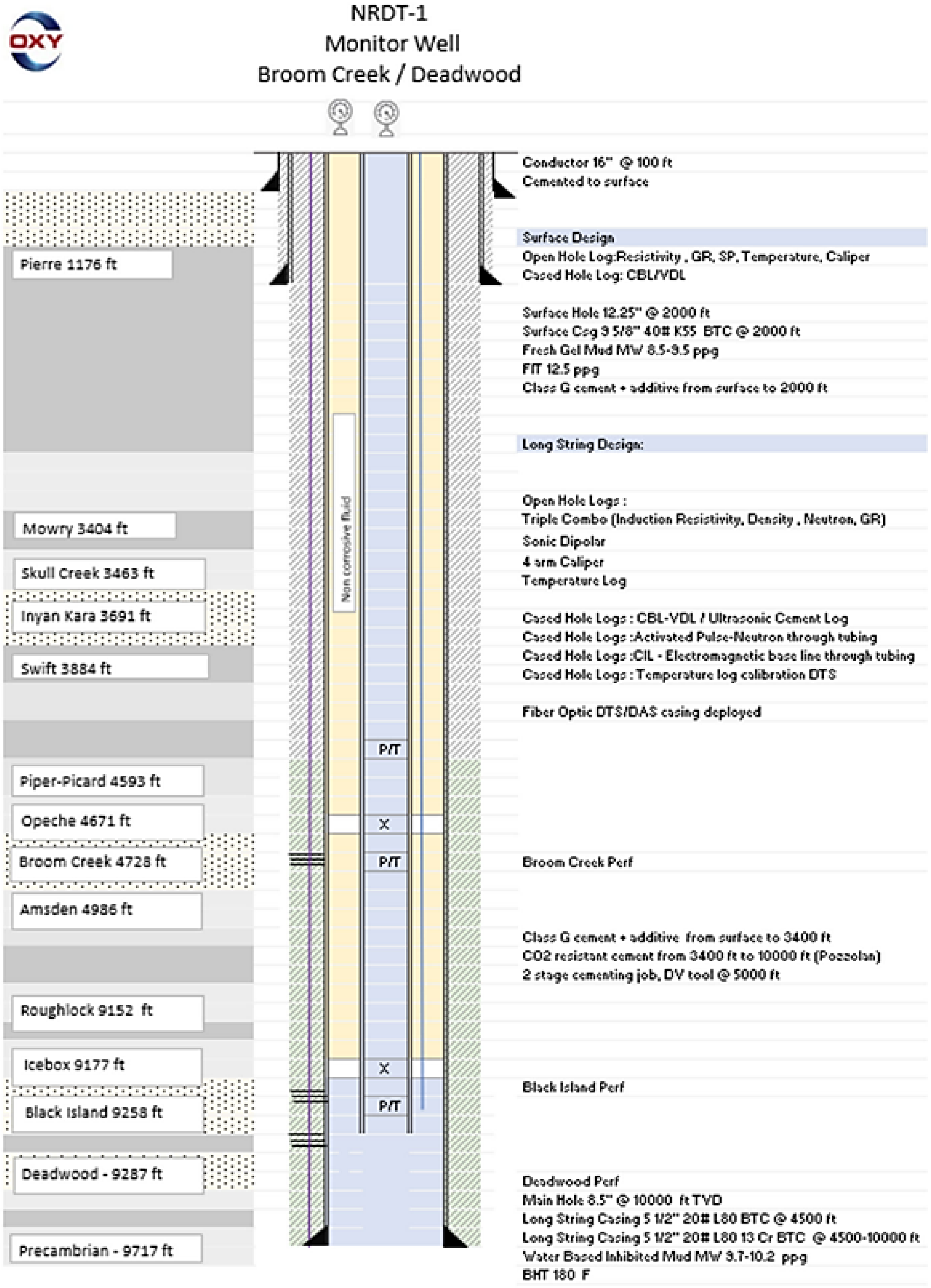
The process of injecting CO_2 for geologic sequestration, under Underground Injection Control (UIC) Class VI regulations, requires the use of both injection and monitoring wells. These wells are constructed using a series of concentric casing strings of varying sizes and lengths that are cemented in place to avoid the migration of CO_2 or formation fluid into shallower zones of underground sources of drinking water (USDWs). Casing and cementing designs largely follow long-held American Petroleum Institute (API) standards for oil and gas wells, with notable enhancements in material to protect casing and cement that may come into direct contact with CO_2 due to its corrosive nature in the presence of water. A typical well design consists of surface casing, intermediate casing, long-string casing, and tubing. Surface casing is set from ground level through the deepest USDW. The intermediate casing is for wells deep enough to require it to add structural integrity and redundancy to protect USDW. A long-string casing is set from the surface to total depth of the well. Tubing is set inside the long-string casing from the surface to above the injection formation, as seen in Figure 22 and Figure 23. All casing is required to be cemented to the surface per Class VI regulations.

According to the NETL-NZA Model, the CO_2 stream exiting the pipeline at each storage site (based on CO_2 critical pressure: 1,057 psig or 7.39 MPa) is assumed 1,200 psig (8.4 MPa), after which it may be increased to a higher value, above the formation pressure, before entering the wellhead.



IL-ICCS CCS #2 Well Schematic
Depths are reference to Kelly Bushing = 691.2 ft. above MSL
KB = 15.5 ft. above ground, site elevation = 675.7 ft. above MSL

Figure 22: Archer Daniels Midland CCS#2 well schematic representing typical casing and cement program for CO_2 injector well[46]



NRDT-1
Monitor Well
Broom Creek / Deadwood

Conductor 16" @ 100 ft
Cemented to surface

Surface Design
Open Hole Log:Resistivity , GR, SP, Temperature, Caliper
Cased Hole Log: CBL/VDL

Surface Hole 12.25" @ 2000 ft
Surface Csg 9 5/8" 40# K55 BTC @ 2000 ft
Fresh Gel Mud MW 8.5-9.5 ppg
FIT 12.5 ppg
Class G cement + additive from surface to 2000 ft

Long String Design:

Open Hole Logs :
Triple Combo (Induction Resistivity, Density , Neutron, GR)
Sonic Dipolar
4 arm Caliper
Temperature Log

Cased Hole Logs : CBL-VDL / Ultrasonic Cement Log
Cased Hole Logs :Activated Pulse-Neutron through tubing
Cased Hole Logs :CIL - Electromagnetic base line through tubing
Cased Hole Logs : Temperature log calibration DTS

Fiber Optic DTS/DAS casing deployed

Broom Creek Perf

Class G cement + additive from surface to 3400 ft
CO2 resistant cement from 3400 ft to 10000 ft (Pozzolan)
2 stage cementing job, DV tool @ 5000 ft

Black Island Perf

Deadwood Perf
Main Hole 8.5" @ 10000 ft TVD
Long String Casing 5 1/2" 20# L80 BTC @ 4500 ft
Long String Casing 5 1/2" 20# L80 13 Cr BTC @ 4500-10000 ft
Water Based Inhibited Mud MW 9.7-10.2 ppg
BHT 180 F

Figure 23: Minnkota Power Cooperative NRDT-1 well schematic representing typical casing and cement program for CO_2 monitoring well[47]

2.4.2 Raw Material Requirements

As discussed, the NETL-NZA Model uses Princeton University NZA data with additional analysis to calculate characteristics of transportation infrastructure (detailed in Section 2.3.2) and injection infrastructure (detailed below) to meet the 2.0 Gtpa by 2050. Detailed data and material estimates can be found in Section 6, "Appendix – NETL-NZA Model."

In calculating transportation infrastructure characteristics, the NETL-NZA Model estimates that 2,938 injection wells will need to be deployed across 403 storage projects, spread across seven basins throughout the United States, as noted in Table 8.

Table 8: Storage project and injection well count by basin (NETL-NZA Model)

Basin	Injection rate (Mtpa/well)	CO_2 storage capacity used in 2050 (Mtpa)	Total storage projects deployed by 2050 (count)	Total injection well count in 2050
A1_Gulf shore	2.0	343	69	276
A2_Gulf shore	1.0	1153	231	1386
B_Midcon	0.5	49	10	110
C_Williston	0.5	159	32	352
D_Illinois	0.5	147	30	330
E_Florida	0.2	37	8	208
F_California	0.5	112	23	276
TOTALS	-	**2000**	**403**	**2938**

Based on these requirements, cement requirements for injector and monitor wells in 5-year intervals were calculated. It is approximated that 25.84 million cement sacks are required for construction to meet these goals. In addition to cement, steel casing and tubing are required for the construction of injection and monitor wells; by 2050, it is estimated that the United States needs an additional 1.6 Mt of steel.

In addition to the pumps and compressors used for CO_2 entering the pipeline, pumps and/or compressors may also be required at the storage sites. However, additional analysis is needed to determine the quantity and characteristics of these pumps and compressors. More discussion on pumps and compressors can be found in Sections 2.3 and 3.5.

3 Supply Chain Risk Assessment

The findings and analysis described in Section 2 are shown concisely in Table 9. For the United States to create a CCS infrastructure capable of capturing 2.0 Gtpa of CO_2 by midcentury, the following quantity of materials are estimated to be used/consumed through the 25 years from 2025 to 2050.

Table 9: Summary of material estimates for 2.0 Gtpa of U.S. CCS capacity by 2050 (from Section 2)

Material			Total Quantity Required	Annual Required (total / 25 years)	Assigned Risk Level
MEA			13.7 Mt	547.3 kt	*Medium/Low*
TEG			632.1 kt	25.3 kt	*Low*
Steel	Total		25 – 33 Mt	1 – 1.32 Mt	*Low*
	Pipeline	*NETL-NZA Model*	*24.12 Mt*	*0.96 Mt*	
		NETL-NZA Model Sensitivity Analysis	*30.16 Mt*	*1.21 Mt*	
		GPI Estimate	*22.73 Mt*	*0.91 Mt*	
	Injection & Monitor wells		*1.61 Mt*	*0.06 Mt*	
	Pumps		*0.056 Mt*	*0.0023 Mt*	
Cement (Injection & Monitor wells)			1,102 kt	44 kt	*Low*
Cast Iron (Pumps)			225.1 kt	9 kt	*Low*
Compressors			*Additional analysis needed*		

Note: *Twenty-five years assumes that construction will begin in 2025, the first 5-year period of the NETL-NZA Model.*

Requisite supply chains necessary to meet these material quantities were examined. Note that smaller volume materials (e.g., electronics) were not considered for this risk assessment. The analysis defined three risk levels by two factors: (1) the required compound annual growth rate (CAGR) to keep U.S. consumption ≤5% of global capacity at any 5-year interval, and (2) the ability of the United States to increase consumption.

Table 10: Analysis risk level definitions

Risk level	Required CAGR for U.S. to consume ≤5% of Global Capacity	Ability of the U.S. to increase consumption
Low	<10%, for any 5-year interval	Relatively easy, either from scaling domestic production, increasing imports from allies, or both
Medium	≤10 and <20%, for any 5-year interval	Medium
High	≥20%, for any 5-year interval	Relatively difficult

Table 10 defines the risk levels. The percentage of 5% of global capacity was chosen as an arbitrary conservative estimate. Some may argue that the United States should receive more than 5% of a material critical to Greenhouse Gas (GHG) abatement; for instance, the United States accounts for 22% of gross domestic product and 14% of global emissions.[48] However, the percentage was kept at a lower 10% to allow for other countries to ensure sufficient material supply to grow their own CCS supply, if needed.

3.1 MEA

3.1.1 Current Supply Chain

Production of MEA begins with crude oil and natural gas. The United States is a world production leader in both hydrocarbons. In 2020, global production of crude oil was 88.4 million barrels per day (bpd) (5.13 trillion cubic meters across the year).[49] Although the majority (31%) of this production came from the Middle East, the United States led all individual countries in production with 18.61 million barrels per day (861 million cubic meters across the year) (21.1% of global production).[50] In 2020, global production of natural gas was 3.85 trillion cubic meters. The United States again led all countries in this production with 914.6 billion cubic meters (23.8% of global capacity); other major producers include Russia and Iran.[51]

MEA production continues with steam cracking these hydrocarbons to produce ethylene (which is then oxidized) and steam reforming to produce hydrogen. Ethylene, due to its widespread use in the petrochemical and agriculture industries, led all organic compound production globally in 2020 at 201.32 Mt.[52] Although estimates vary, the United States and North America contribute a large proportion of the global ethylene production. In 2010, North America led production at about 35 Mt, followed by Northeast Asia with about 31 Mt and the Middle East with about 30.5 Mt.[53] Geographically within the United States, most ethylene production is tightly clustered in the Texas and Louisiana Gulf Coast region due to feedstock availability. Major end-uses of ethylene in 2020 included roughly 60% to polyethylene (the world's most widely used plastic) and roughly 20% to ethylene oxide (EtO), which is used in surfactants and automotive antifreeze.[54] In 2018, EtO global production was 26 Mt, with the United States producing 2.8 Mt (10.9%), predictably clustered in the same Texas and Louisiana Gulf Coast region, as shown in Figure 24.[55]

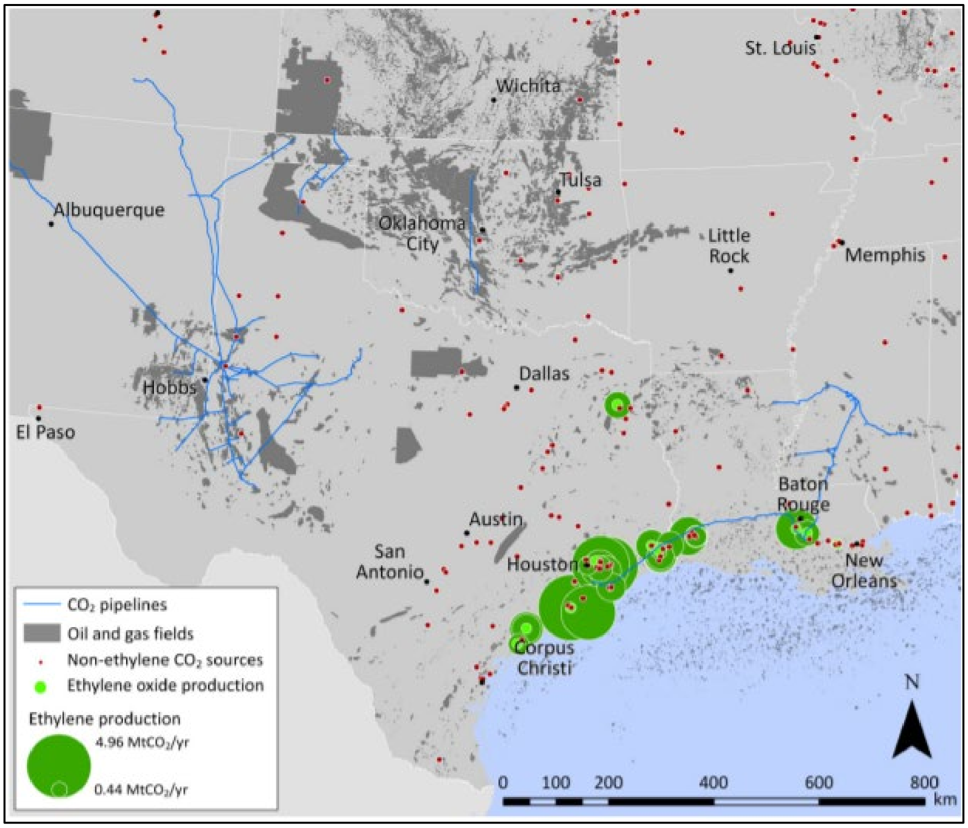


Figure 24: United States ethylene production (2014)[56]

Hydrogen is a comparatively smaller market than ethylene: global demand in 2020 was approximately 91 Mt, with 46 Mt going to chemical production (34.5 Mt to ammonia, 11.5 Mt to methanol), 40 Mt going to oil refining, and the remaining 5 Mt going to steelmaking.[57] Top countries that produced hydrogen in 2020 were mainly within Europe and Asia.[52] Within the United States in 2019, the major hydrogen-producing states were California, Louisiana, and Texas.[58]

MEA production continues with nitrogen and hydrogen being combined to produce ammonia using the Haber-Bosch process. The agriculture industry dominates the global ammonia market, accounting for more than 80% of global ammonia demand in 2018. In 2019, global production for ammonia was over 235 Mt, with top producing countries being China (48 Mt), Russia (12.5 Mt), and India (11 Mt).[59] The United States produced 9.8 MT of this, with production centering in Louisiana, Iowa, Oklahoma, and Texas.

Finally, ammonia and EtO are reacted to produce MEA. In 2020, the global production of MEA was 1.84 Mt.[60] MEA's primary use is for feedstock in the production of detergents, emulsifiers, polishes, pharmaceuticals, corrosion inhibitors, and chemical intermediates.

3.1.2 Discussion - Future Opportunities and Vulnerabilities

From analysis of the materials supply chain and forecasts, MEA risk level for supply chain disruptions is medium/low. MEA requirements, plus required CAGR of global MEA capacity for the United States to use ≤5% of global capacity at each 5-year interval (given global 2020 production was 1.84 Mt), is as shown in Table 11.

Table 11: Required CAGR of global MEA capacity, such that each 5-year interval only requires the United States to use ≤5% of global capacity

Year	2025	2030	2035	2040	2045	2050
Domestic MEA Required (kt) (MARKAL Model)	37.69	337.98	428.55	685.99	757.16	833.96
Required CAGR for U.S. to use ≤5% of Global Capacity	0%	14%	11%	11%	9%	8%

As seen, in general the MEA market only needs to scale approximately 10% per year to allow the United States to consume ≤5% of global MEA production, with a maximum of 14% CAGR in the 2020–2030 period to consume 337.98 kt of MEA in 2030.

Though these are substantial increases, this CAGR can be achieved relatively easily, given the abundant amounts of raw materials needed to produce MEA and the expertise of the existing industry.

Forecasts could not be located, however, of the primary ingredients of ammonia and EtO; neither draws concern for the levels needed by this time range. The ammonia market projects a 2% CAGR until 2026, which will likely increase due to its potential uses across industries, particularly in hard-to-abate sectors such as maritime shipping, and with some countries looking to ammonia for decarbonization.[61] The ethylene oxide market is projected >3% CAGR due to increased demand of feedstocks and plastics.[62]

Further, even in the most limiting scenarios for MEA ingredients (e.g., hydrocarbon slow-down occurs faster than expected, MEA demand spikes worldwide due to carbon capture use, etc.) there is more than sufficient infrastructure and workforce to grow MEA production alongside CO_2 capture capacity. Additionally, if the United States seeks to continue to de-risk carbon capture, they could also diversify the solvents available for capture, or the method of capture entirely (reference Section 1.2 for a discussion on capture methodologies, such as cryogenic or mechanical processes).

Supplier-wise, MEA has globally distributed production with significant competition. MEA and its raw materials are produced globally by major chemical companies including BASF, Dow, SABIC, DuPont, and several smaller companies. In addition, given the significant number of large-scale producers, the growth of MEA can be dispersed across several companies and countries. To support this buildout, MEA producers can be given adequate notice by the public sector, which would provide sufficient lead-time to meet demand since typical process plants take roughly 3–4 years from planning to startup, as shown in Figure 25.[63] Early notice may also result in offtake agreements to incentivize producers to increase global production.

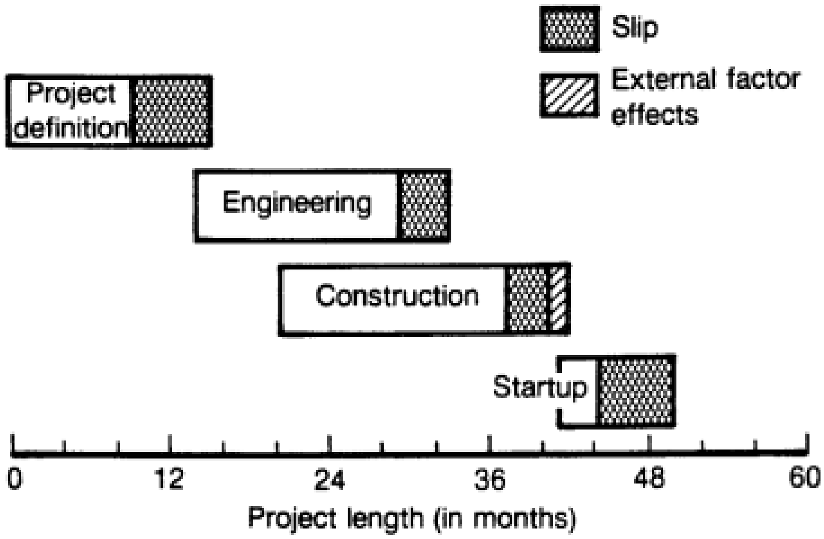


Figure 25: Typical process plant schedule[64]

If the United States were to grow its domestic production of MEA, it would benefit from a trained workforce in the closely adjacent oil and gas industry that it may be able to shift. In 2020, the oil and gas industry employed almost 2.6 million Americans and supported 9.8 million total jobs, representing 5.6% of total U.S. employment. The average wage in the oil and gas industry, across many professions, exceeds the national average rate by nearly $50,000, representing an established, well-paying job for Americans. [65]

However, the oil and gas industry can be more transitory than other industries (for instance, from the short-cycled nature of shales), leading to higher employing cyclicity. During 2014–2019, the sensitivity of oil and gas employment to oil prices was at its highest, especially in upstream and oilfield services sectors.[66] Fortunately, the MEA industry may be able to avoid typical oil and gas cyclicity due to relatively constant product demand. Additionally, the oil and gas industry is experiencing a higher average employment age than other industries. Figure 26 depicts the employment trend of oil and gas related positions.[67]

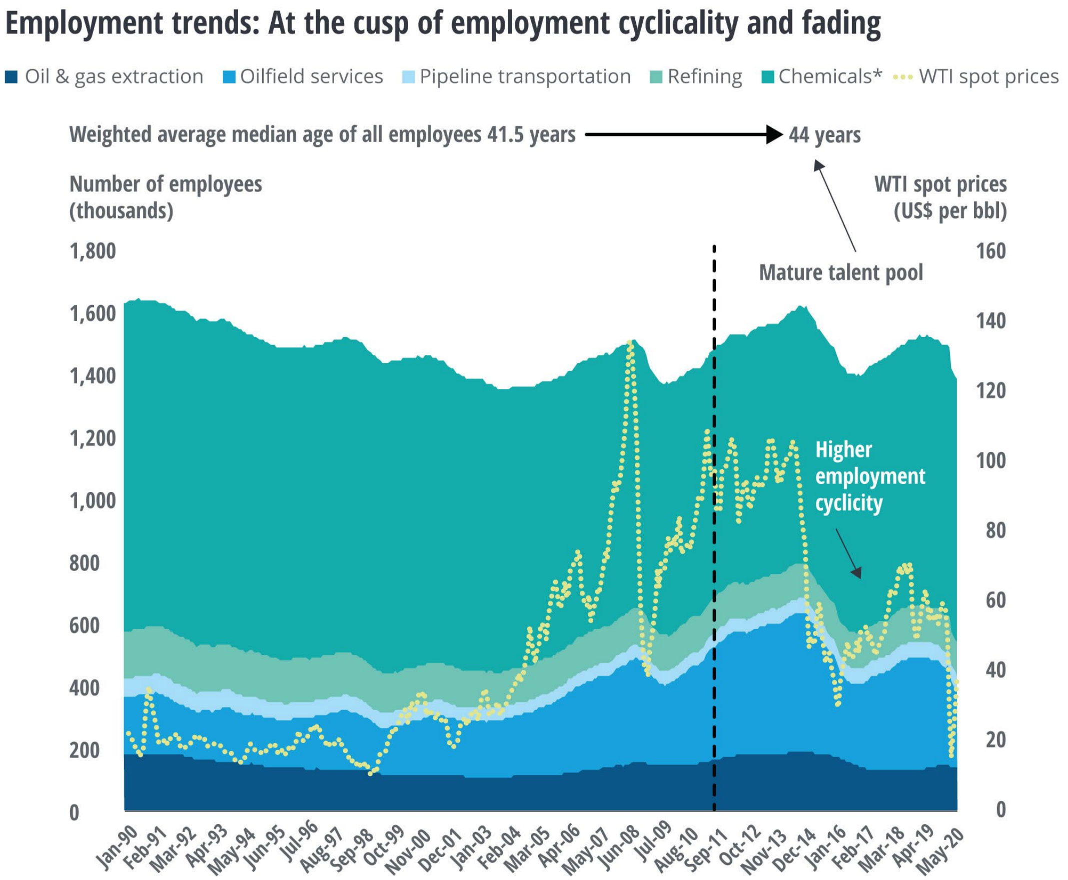


Figure 26: Oil and gas industry employment cyclicity

Other issues that may affect an expanded MEA workforce include robotic automation, which has started entering the oil and gas market in the last decade.[68] However, it is well-documented that where automation replaces one job, an adjacent job typically emerges; "where a robot replaces a worker on an assembly line, an engineer or technician job emerges."[69]

To mitigate these issues, the MEA industry should focus on attracting young talent with applicable skillsets to the required positions (e.g., keeping up with automation) at competitive wage rates. This will ensure a stable and continuously growing workforce can meet increasing U.S. MEA demands.

3.2 TEG

3.2.1 Current Supply Chain

As discussed, production of TEG relies on crude oil, which produces ethylene via steam cracking, which is oxidized to produce EtO, which is then hydrated to produce TEG. Discussion of crude oil, ethylene, and EtO production can be found in Section 3.2.1.

Global TEG production is relatively small. TEG is primarily produced as a coproduct of ethylene glycol. In 2019, global production of ethylene glycol was 42 Mt (U.S. production accounted for 1.63 Mt).[70] In 2019, global production of TEG was approximately 500 kt (U.S.-specific data could not be found). Of this 500 kt, roughly 50% is used for natural gas dehydration systems, with the other 50% going to other chemical processes.

3.2.2 Discussion - Future Opportunities and Vulnerabilities

From analysis of the materials supply chain and forecasts, TEG risk level for supply chain disruptions is low. TEG requirements, plus required CAGR of global TEG capacity for the United States to use ≤5% of global capacity at each 5-year interval (given global 2019 production was 500 kt), is as shown in Table 12.

Table 12: Required CAGR of global TEG capacity, such that each 5-year interval only requires the United States to use ≤5% of global capacity

Year	2025	2030	2035	2040	2045	2050
Domestic MEA Required (kt) (MARKAL Model)	1.05	13.86	19.73	31.41	36.38	40.57
Required CAGR for U.S. to use ≤5% of Global Capacity	0%	0%	0%	1%	1%	2%

As seen, the global TEG market in 2019 was sufficiently large that, should it not grow 2040, it would still be large enough for the United States to use <5% of its capacity.

Because TEG is similar to MEA, this CAGR can be achieved relatively easily, given the abundant amounts of raw materials needed to produce TEG and the expertise of the existing industry. Though TEG-specific forecast data could not be obtained, Section 3.2.1 contains discussion of EtO (TEG's primary ingredient) growth rates, in addition to applicable discussion on further mitigation routes by the United States, and applicable workforce discussion.

3.3 Steel

3.3.1 Current Supply Chain

Steel production begins with the mining of iron ore. Iron ore is mined almost exclusively to be used in the production of steel. According to USGS, in 2020, 2.4 Gt of iron ore was mined, with the United States contributing 37 Mt, mostly in Michigan and Minnesota. Figure 27 depicts how global steel production has changed with time. In addition to the mining states, Louisiana, Texas, and Indiana helped produce metallic iron to supply steelmaking raw materials. The USGS estimates that the United States produced 1.5% and consumed 1.1% of the world's iron ore output.[71]

Iron ore is then mixed with carbon at very high temperatures, typically above 2600 °F, to produce steel. Primary steelmaking uses pig iron, which the producer oxidizes to remove excess carbon. Secondary steelmaking encompasses the process of refining and alloying steel. At this point, if the end-use application of the steel requires a composite, other elements will be required. Producers will add the necessary elements and materials to achieve the proper proportions of different grades of steel.

According to the World Steel Association, global production of steel in 2019 was 1.87 Gt, with the United States producing 87 Mt.[72] According to USGS, domestically "pig iron and raw steel was produced by three companies operating integrated steel mills in 11 locations. Raw steel was produced by 51 companies at 98 minimills."[73] Indiana, Ohio, Michigan, and Pennsylvania are the main producers, while no other state exceeded

5% of total domestic production. USGS also notes that, in 2019, the U.S. allies of Brazil, Germany, India, Italy, Japan, and Korea produced about 376 Mt cumulatively.[66]

The global capacity for steel pipe production is estimated at 80 million metric tons.[74] Due in large part to the oil and gas industry, the steel pipeline manufacturing process is very well established. In addition, steel and pipes can be used for numerous applications, decreasing the risk to suppliers concerned about demand as well as the risk to CCS infrastructure regarding production capacity. Of the estimated 2.1 million miles of oil and gas pipeline globally, about 65% (or 1.37 million miles) are in the United States.[75]

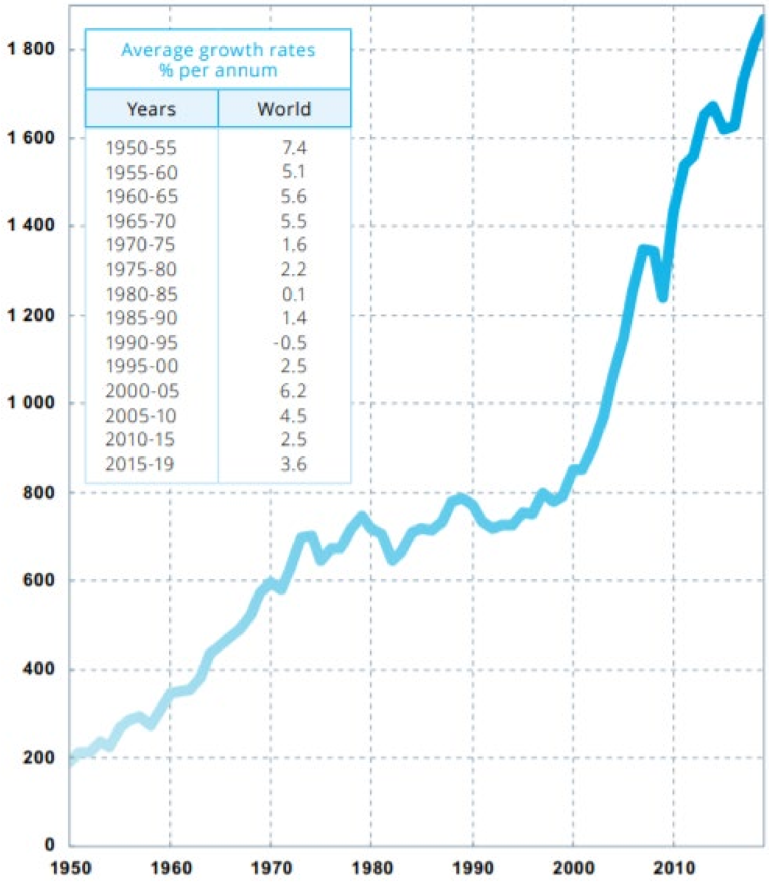


Figure 27: Global steel production (World Steel Association)

Table 13 and Table 14 show the types of steel analyzed throughout this report and identifies approximations for the raw materials required based on the percentage of each component.

Table 13: Raw material breakdown of the components required for steel production (% content by mass)

Steel Grade	Final Form	Application	Iron (Fe)	Mn	C	P	Si	S	Cr	Cu	Ni	Mo	Other (Nb, V, Ti)
J55 STC	Surface Casing	Injection	97.31%	1.5%	0.39%	0.02%	0.35%	0.02%	0.02%	0.20%	0.20%		
J55 BTC	Intermediate Casing	Injection											

Steel Grade	Final Form	Application	Iron (Fe)	Mn	C	P	Si	S	Cr	Cu	Ni	Mo	Other (Nb, V, Ti)
L80-HC	Long (carbon) casing	Injection	96.56%	1.9%	0.43%	0.03%	0.45%	0.03%		0.35%	0.25%		
13CR80 JFE Bear	Long (chrome) casing	Injection	83.00%	1.0%	0.22%	0.02%	1.00%	0.01%	14.00%	0.25%	0.50%		
13CR85 JFE Bear	Tubing	Injection	83.00%	1.0%	0.22%	0.02%	1.00%	0.01%	14.00%	0.25%	0.50%		
L80 Coated Premium Conn	Tubing	Injection	96.56%	1.9%	0.43%	0.03%	0.45%	0.03%		0.35%	0.25%		
C95 13Cr Premium Conn	Tubing	Injection	78.83%	0.6%	0.04%	0.02%	0.50%	0.01%	14.00%		4.50%	1.50%	
B, WELD-API 5L Specs	Conductor	Injection Monitoring	97.59%	1.4%	0.26%	0.30%		0.30%					0.15%
K-55, BTC	Surface Casing	Injection Monitoring	99.40%			0.30%		0.30%					
L-80, BTC	Long-string casing	Injection Monitoring	96.56%	1.9%	0.43%	0.03%	0.45%	0.03%		0.35%	0.25%		
13CR-80, BTC	Long-string casing	Injection Monitoring	83.00%	1.0%	0.22%	0.02%	1.00%	0.01%	14.00%	0.25%	0.50%		
L80 Premium Flush Conn	Tubing	Injection Monitoring	96.56%	1.9%	0.43%	0.03%	0.45%	0.03%		0.35%	0.25%		
API 5L X65	Pipeline	Transportation	97.11%	1.4%	0.28%	0.03%		0.03%		0.50%	0.50%	0.15%	0.001%

Table 14: Cumulative raw material demand (2025–2050) for the alloying constituents required for projected steel requirements (thousand metric tons, kt)

Steel Grade	Final Form	Application	Weight of Steel Required through 2050 (kt)	Iron (Fe)	Mn	C	P	Si	S	Cr	Cu	Ni	Mo	Other (Nb, V, Ti)
J55 STC	Surface Casing	Injection	45	43.91	0.68	0.18	0.01	0.16	0.01	0.01	0.09	0.09	-	-
J55 BTC	Intermediate Casing	Injection	442	442.12	-	-	-	-	-	-	-	-	-	-
L80-HC	Long (carbon) casing	Injection	267	257.40	5.06	1.15	0.08	1.20	0.08	-	0.93	0.67	-	-
13CR80 JFE Bear	Long (chrome) casing	Injection	454	376.75	4.54	1.00	0.09	4.54	0.05	63.55	1.13	2.27	-	-
13CR85 JFE Bear	Tubing	Injection	6	4.65	0.06	0.01	0.00	0.06	0.00	0.78	0.01	0.03	-	-

Steel Grade	Final Form	Application	Weight of Steel Required through 2050 (kt)	Iron (Fe)	Mn	C	P	Si	S	Cr	Cu	Ni	Mo	Other (Nb, V, Ti)
L80 Coated Premium Conn	Tubing	Injection	25	24.19	0.48	0.11	0.01	0.11	0.01	-	0.09	0.06	-	-
C95 13Cr Premium Conn	Tubing	Injection	1	0.42	0.00	0.00	0.00	0.00	0.00	0.07	-	0.02	0.01	-
B, WELD-API 5L Specs	Conductor	Injection Monitoring	6	6.24	0.09	0.02	0.02	-	0.02	-	-	-	-	0.01
K-55, BTC	Surface Casing	Injection Monitoring	80	79.08	-	-	0.24	-	0.24	-	-	-	-	-
L-80, BTC	Long-string casing	Injection Monitoring	91	87.96	1.73	0.39	0.03	0.41	0.03	-	0.32	0.23	-	-
13CR-80, BTC	Long-string casing	Injection Monitoring	111	92.41	1.11	0.24	0.02	1.11	0.01	15.59	0.28	0.56	-	-
L80 Premium Flush Conn	Tubing	Injection Monitoring	81	78.30	1.54	0.35	0.02	0.36	0.02	-	0.28	0.20	-	-
API 5L X65	Pipeline	Transportation	30,160	29,288.07	422.24	84.45	9.05	-	9.05	-	150.8	150.8	45.24	0.30
Totals (kt)			**31,768**	**30,782**	**438**	**88**	**9.5**	**8.0**	**9.5**	**80**	**154**	**155**	**45**	**0.3**

3.3.2 Discussion - Future Opportunities and Vulnerabilities

From analysis of the materials supply chain and forecasts, steel risk level for supply chain disruptions is low. The most significant amount of steel will be needed for the transportation pipeline. According to the analysis performed in Section 2.3 and detailed in the Appendix below, this will be somewhere in the range of 22 Mt (Great Plains Institute) and 30.16 Mt (NETL-NZA Model Sensitivity Analysis), dispersed across 25 years. A smaller amount of steel will be used for injection and monitor wells, estimated at 1.6 Mt of steel.

This analysis will not examine the steel needed for other parts in detail; however, they are not insignificant. The capture, drying, and liquification processes will require steel in the form of absorption towers, contactors, drums, boilers, heat exchangers, and other smaller parts. The transportation process, in addition to requiring steel for pipeline, will require steel for hundreds of pumps. Steel will also be needed for construction of this infrastructure.

High-level steel requirements, plus required CAGR of global steel capacity for the United States to use ≤5% of global capacity at each 5-year interval (given global 2020 production was 1.87 Gt), is shown in Table 15.

Table 15: Required CAGR of global Steel capacity, such that each 5-year interval only requires the United States to use ≤5% of global capacity

Year	2025	2030	2035	2040	2045	2050
NETL-NZA Model						
Domestic Steel Required (Mt) (NETL-NZA Model)	8.23	7.78	6.10	1.80	1.55	8.23
Required CAGR for U.S. to use ≤5% of Global Capacity	0%	0%	0%	0%	0%	0%
NETL-NZA Model Sensitivity Analysis						
Domestic Steel Required (Mt) (NETL-NZA Model Sensitivity Analysis)	3.97	8.47	7.71	7.98	3.38	3.97
Required CAGR for U.S. to use ≤5% of Global Capacity	0%	0%	0%	0%	0%	0%

In fact, the global steel market does not need to grow until the case where the United States plans to use less than 0.05% of global capacity.

The same analysis was performed for global steel pipe capacity (80 Mt in 2020). Although additional depth to this analysis would be needed to break down manufacturing by pipe diameter, growth is only if the United States plans to use less than 5% of global capacity. Table 16 shows the steel in pipe form required and the CAGR needed to meet demand such that the United States uses less than 5% of global capacity.

Table 16: Required CAGR of global steel pipe capacity, such that each 5-year interval only requires the United States to use ≤5% of global capacity

Year	2025	2030	2035	2040	2045	2050
NETL-NZA Model						
Domestic Steel Required (Mt) (NETL-NZA Model)	8.23	7.78	6.10	1.80	1.55	8.23
Required CAGR for U.S. to use ≤5% of Global Capacity	16%	7%	3%	0%	0%	2%
NETL-NZA Model Sensitivity Analysis						
Domestic Steel Required (Mt) (NETL-NZA Model Sensitivity Analysis)	3.97	8.47	7.71	7.98	3.38	3.97
Required CAGR for U.S. to use ≤5% of Global Capacity	0%	8%	4%	4%	0%	0%

As shown, at a high level both the global steel and global steel pipe markets can easily support the United States building a CCS pipeline of 2.0 Gtpa by 2050, in a variety of cases. Interviews with industry experts resulted in a small concern that specialty piping and machining within the U.S. market could be a potential manufacturing gap. This risk is mitigated by the broad global market and allies having piping capabilities.

Generally, the market being able to support a CCS buildout of this size is beneficial, because while most forecasts see global steel production growing by 2050, most do not see considerable growth. For instance, World Steel Dynamics offers a prediction of only 0.91% growth from 2019 to 2050.[76]

The components of steel noted in the tables above are also not expected to pose risks to the supply chain, especially across a global market. Further, many of these mineral markets will grow by 2050 with expansion of the global economy.

- **Iron Ore**: The 30.78 million tons of iron required across 25 years amounts to about 1.23 million tons per year, which is about 3.3% of 2020 U.S. production and <0.05% of 2020 global production. Iron is not expected to lead to supply chain bottlenecks.
- **Manganese**: The 437.53 kt of manganese requires across 25 years amounts to about 17.5 kt per year. Manganese ore has not been mined in the United States since 1970. The imported ore was used by six firms with plants primarily in the east and midwest United States, mostly to produce steel. 310 kt of manganese ore was imported for consumption in 2020, meaning the manganese required for this CCS project would be 5.6% of that consumption per year. Global production reached 18.5 Mt in 2020.[77] The United States would use about 0.09% of global supply per year. Manganese is not expected to lead to supply chain bottlenecks.
- **Carbon**: The carbon required in steelmaking is typically added in via coking coal, or metallurgical coal. Although the domestic coal industry appears to be in decline as the United States transitions away from the fossil fuel, it is still a large market globally and is expected to continue to be in the future. Globally, coking coal production reached 1,007 Mt in 2019.[78] Carbon via coal is not expected to lead to supply chain bottlenecks.
- **Phosphorous**, **silicon**, **sulfur**, **chromium**, **copper**, **nickel**, and **molybdenum** all share similar stories. The United States produced 130 kt of chromium in 2020 via recycling, while the global mine production was 40 Mt. The United States produced 290 kt of silicon in 2020, with global production reaching 8 Mt. The United States produced 7.6 Mt of sulfur in 2020, while global production reached 78 Mt. The United States mined 1.2 Mt of copper in 2020, supporting the globe's 25 Mt of total mine production. The United States mined 16 kt of nickel and imported 110 kt in 2020, while the globe produced 2.5 Mt. The United States mined 49 kt of molybdenum in 2020, while global production reached 300 kt.[79]

In the event the United States does have trouble supporting the pipeline requirement, there is ample opportunity for sourcing some of the 372 Mt of raw steel produced in the allied countries of Brazil, Germany, India, Italy, Japan, and Korea.

Additionally, in the case that oil and gas pipeline expansion may slow in the coming years, it could be expected that the consumption previously seen from that industry may be available for the modeled CCS system. For reference, recall that the modeled CCS infrastructure requires about 70k to 96k miles of pipeline, which is roughly 7% of all currently installed domestic oil and gas pipeline in existence today.

An additional perspective offers a view into the existing oil and gas pipeline infrastructure. As noted previously and shown in the Figure 28, the United States has approximately 1.37 million miles of oil and gas pipeline. The first were built well over 100 years ago, but for the purposes of this analysis and based off the Figure 28 below, the assumption that most modern gas pipelines were constructed no earlier than 1950 will be used. Thus, over the past 72 years this translates to the oil and gas industry having constructed about 19,000 miles of pipeline per year. Using the conservative estimate, the CCS models analyzed in this report only require about 96,694 miles total over 25 years, coming out to about 3,868 miles per year. Based on these rough order of magnitude estimations, it is once again fairly evident that the demand of steel pipelines will not be an issue for the United States to build out the necessary CO_2 infrastructure. The varying miles installed across time periods also lends to the idea that steel production can be ramped up fairly easily depending on demand.

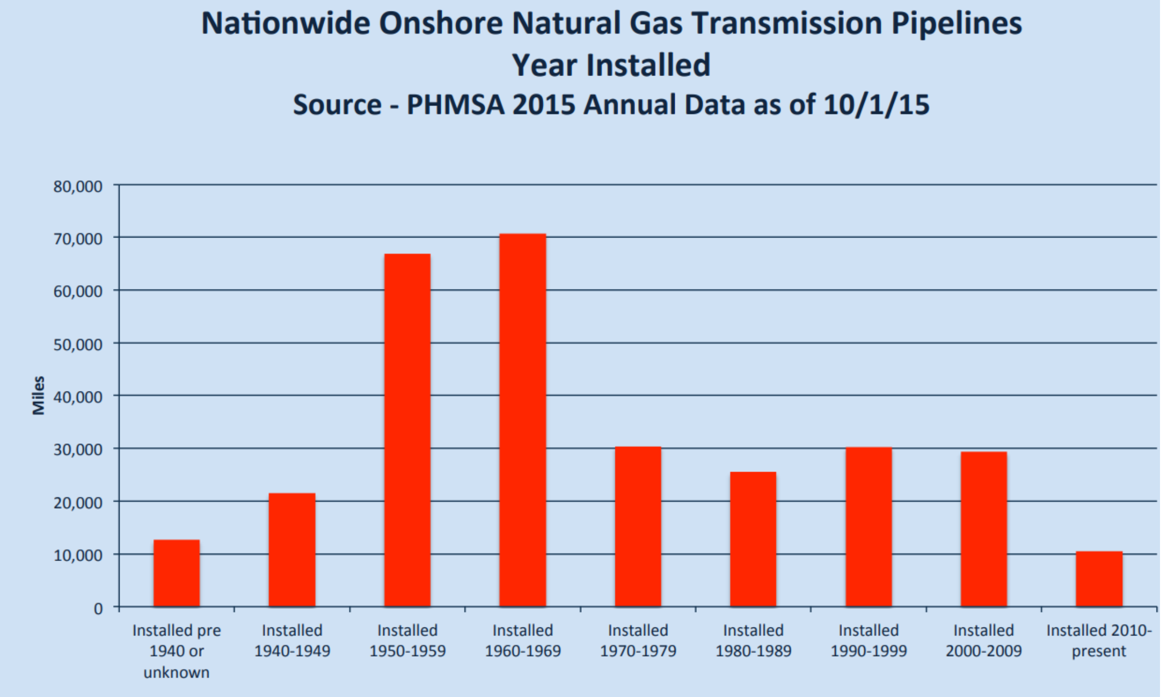


Figure 28: Miles of pipe installed across various time periods[80]

According to the Bureau of Labor Statistics, since 1990, United States Iron and Steel mill employment has decreased roughly 50% (from approximately 185,000 to 90,000).[81] This decline in expansion is not due to a decline in production, but rather an improvement in steel production efficiency, primarily the "minimill." The minimill produces steel from scrap metal using an electric arc furnace, rather than a traditional blast furnace mill. In 2002, minimills overtook the traditional blast furnace mills for steel production, according to a 2003 government report on the changing profile of the U.S. steel industry.[82] Figure 29 show how labor has changed in the industry over time.

Figure 29: U.S. iron and steel mill employment

Note: *Value is in thousands, seasonally adjusted*

3.4 Cement

3.4.1 Current Supply Chain

Global production of cement was estimated at 4.1 Gt in 2019 by USGS; of this amount, the United States produced roughly 87 Mt (it has consistently produced this amount over each of the last few years).

Several of the companies operating in this industry domestically are international corporations with dozens of plants around the world and in the United States. USGS provides that cement was produced at 96 plants in 34 states, as well as a few in Puerto Rico.[83] In 2020, Texas, Missouri, California, and Florida led the United States in production, and accounted for about half of domestic production. The top cement manufacturers in the United States are Lafarge Holcim, Cemex, CRH, and Buzzi Unicem. On top of producing cement, the United States was also the world's top cement importer in 2020 at 17 Mt.[84]

Cement production begins with the mining of mineral compounds containing the main components of cement: lime, silica, alumina, and iron oxide.[85] In nature, these components are generally obtained with a mixture of limestone and marl or limestone and clay. A kiln heats a mixture of those materials, as well as some other mineral additives, to create clinker, typically in the form of small pellets. The clinker is ground with gypsum to become a fine powder known as cement. Table 17 lists the contents of standard Portland cement.

Table 17: Raw material percent content for cement[86]

Constituents of Ordinary Portland Cement	
Constituents	**Percent Content (%)**
Lime (CaO)	60-67
Silica (SiO_2)	17-25
Alumina (Al_2O_3)	3.0-8.0
Iron Oxide (Fe_2O_3)	0.5-6.0
Magnesium Oxide (MgO)	0.1-4.0
Sulphur Trioxide (SO_3)	1.3-3.0
Alkalies (K_2O, Na_2O)	0.4-1.3

About 16,000 kt of lime were produced in the United States in 2020.[87] Approximately 71,000 kt of silica in the form of sand and gravel was produced in the United States in 2020.[88] The other constituents are used in cement production at low levels but are widely available.

3.4.2 Discussion - Future Opportunities and Vulnerabilities

From analysis of the materials supply chain and forecasts, cement risk level for supply chain disruptions is low. At a high level, a total cement requirement of 1.1 Mt over 25 years is also negligible for the U.S. domestic supply chain, as it roughly equals 44 kt per year. Even if this CCS infrastructure buildout occurred in just one year, the cement requirement for storage and injection would only be 1% of the annual 90 Mt produced in the United States.

Further, if the United States does happen to struggle to meet this relatively insignificant demand increase, the global cement industry is vast and is projected to expand over the years leading to 2050. For example, part of the reason the United States led cement importing in 2020 was because of inexpensive imports. This provides further reassurance to the supply chain in that, if there were significant spikes in demand due to or outside of the CCS industry, supply could be ramped up to suffice.

The IEA projects that global cement production will grow about 12–23% by 2050, ultimately reaching a range of 4,592 to 5,043 Mt produced in 2050. Most of this capacity is expected to be consumed by developing regions in India, Asia, Africa, and the Middle East.[89]

Lime can account for 67% of concrete content, amounting to a requirement of 737 kt over 25 years. This quantity is a mere 4.6% of what the United States produces annually. Silica can make up about 25% of concrete content at the high end, amounting to a requirement of 275 kt over 25 years. This quantity is about 0.4% of what the United States produces annually. Thus, the constituent materials of cement are not of concern.

3.5 Pumps and Compressors

3.5.1 Current Supply Chain

Pumps and compressors are both large, global industries, ubiquitous in countless machinery use cases. The global pump market currently exceeds $60 billion. The market is distributed with over 10 manufacturers domestically and at least that many internationally. These are companies such as LEWA, Grundfos, Hayward

Tyler, Baker Hughes, Ingersoll-Rand, and Sulzer. The global compressor market currently exceeds $32 billion.[90]

As noted, pumps require cast iron and stainless steel. In 2020, the United States produced 37 million metric tons of iron ore, 2% of which, or 740,000 tons, were used for non-steel end uses.[91] Since iron ore does need to be refined to reach the cast iron product, a better reference may be the iron content of the ore. The iron content produced in 2020 was about 24 million tons, translating to about 480,000 tons used for non-steel end uses.

3.5.2 Discussion - Future Opportunities and Vulnerabilities

From analysis of the materials supply chain and forecasts, pump and compressor risk level for supply chain disruptions is low.

Because similar pumps are common in the oil and gas industry, there are a wide variety available similar to the ones needed for the CO_2 pipeline. Various market analyses show the global pump market growing by >3% CAGR over the coming years, driven by oil and gas growth.[92] The approximated 500–1000 pumps required for 2.0 Gtpa of CO_2 capture will not be a significant strain on the industrial base, especially over 25 years. Industry experts have noted that a CCS project of the scale modeled in this report would be the largest acid gas handling project to date, but as it compares to the oil and gas industry, it is miniscule. That said, compressor and pump technology may have to scale with this project as the application of acid gas transport is slightly different than oil and gas transport.

Compressors, like pumps, are common in adjacent industries. The compressor market is large and projected to grow at a CAGR of >4% over the next 5 years.[93] Compressors are a key component to the natural gas infrastructure, and so it can be expected that as LNG expands to developing countries, compressor manufacturers will supply. The demand for compressors in the CCS space is not expected to drastically increase in comparison to the natural gas industry, but as growth is expected generally, compressors will not cause a supply chain problem in the buildout of this CCS infrastructure.

The material requirement for pumps is most likely negligible. As noted in Section 2.3.2.1, the estimated pump material requirements are about 225.1 kt of cast iron and 56.28 kt of steel. These materials will not be a hindrance to the supply chain, especially over the 25-year buildout period. The cast iron required comes out to 9 kt per year, only 1.9% of the iron content of iron ore produced in the United States. As 87 Mt of steel were produced in the United States in 2020, the steel requirement in these pumps is only 2.6% of the U.S. annual production. Expanding scope to the entire globe, these material requirements are not of concern.

For both pumps and compressors, there is a large and diverse pool of suppliers in both the domestic and global markets. Although the raw materials are not expected to create supply chain risk, there may be very small concerns with this specific acid gas transport equipment, as it has been noted to be the largest such project to date.

4 U.S. Opportunities and Challenges

4.1 Key Opportunities

4.1.1 Growth to the American Economy and Workforce

Overall, the growing CCS industry provides opportunities for jobs across various industries, including, but not limited to, the fields of raw materials (e.g., MEA, steel), engineering and design (e.g., design of carbon capture, pipelines, injection sites, SCADA), construction (retrofitting, pipeline development, injection sites, trucking), operation, and maintenance.

While the industry is in its infancy, there are clear indications that building out a 2 Gtpa CCS economy will be an enormous employment opportunity. Based on diverse estimates detailed below from literature and NETL modeling, the cumulative employment needed to achieve this ambition range from about 390 thousand to 1.8 million people. Table 19 provides a summary of the wide range of workforce numbers that may be required to implement a CCS plan of capturing 2 Gtpa by 2050.

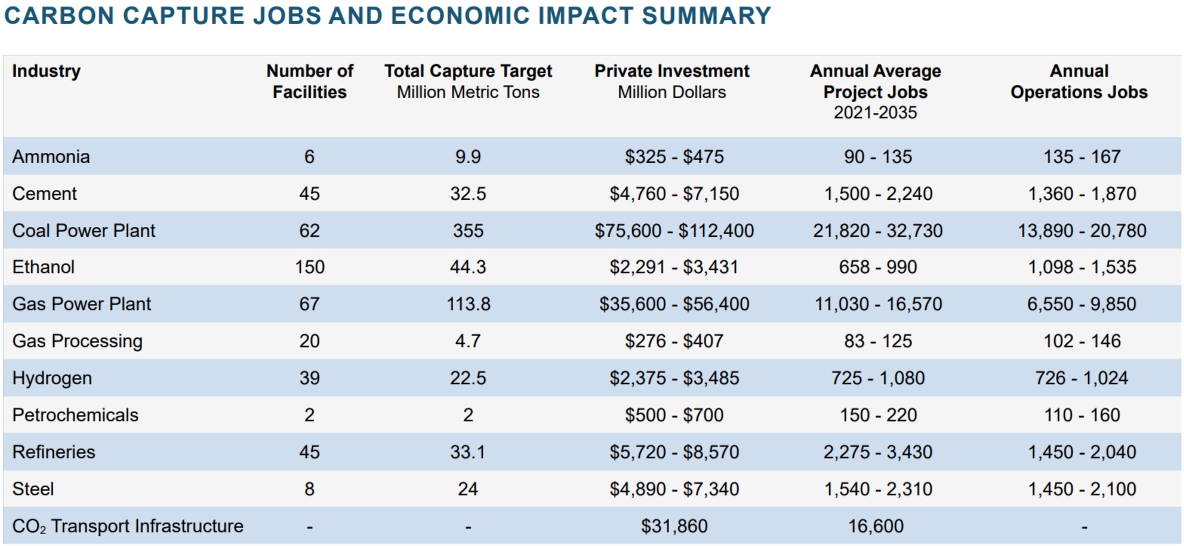
The following sections provide overviews of reports from the Great Plains Institute and the Global CCS Institute, followed by Section 4.1.1.3, which scales workforce estimations from both reports to obtain rough-order-of-magnitude workforce predictions. These reports had to be scaled as their carbon capture goals were both well below 2.0 Gtpa. In this same manner, the amount of capture projects predicted were lower as well, as discussed below.

4.1.1.1 Great Plains Institute and the Rhodium Group

The economic analysis performed by the Rhodium Group, commissioned by the GPI, identified economic and workforce impact in the midcontinent region of the United States from CCS.[23] Throughout the region, 444 industrial facilities and power plants were identified as having potential for retrofitting carbon capture systems, as shown in Table 18. The analysis was carried out with the assumption that all projects would be deployed within the 15-year period from 2021–2035. Although those projects only amounted to capturing about 642 Mtpa of CO_2, the analysis is helpful in understanding the range of workforce possibilities. These jobs strictly pertain to carbon capture retrofits and transport and do not include indirect work or other positions at the facilities.

For the midcontinent region, GPI estimates that there is potential for an “annual average of up to 76,430 project jobs … and 39,672 ongoing operations jobs through the deployment of carbon capture.”[94] By simply scaling these capture estimates by 3.1 to go from 642 Mtpa to the desired 2 Gtpa of CO_2 captured, workforce estimates increase to an annual average of nearly 240,00 project jobs and nearly 123,000 ongoing operations jobs. Table 19 shows a slightly different, but similar estimate based on this GPI report, which will be further detailed in Section 4.1.1.3. Scaling by 3.1 is meant to provide a low fidelity, rough order of magnitude and may imply that carbon capture retrofits and pipeline infrastructure is expanded across the entire United States.

Table 18: Estimated workforce impact of CCS expansion. From Great Plains and Rhodium Group.[23]



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	-

4.1.1.2 Global CCS Institute Report

The Global CCS Institute notes that workforce requirements for construction projects are often temporary and vary from project to project and throughout the timeline of each project. However, it is common to require thousands of workers during peak construction demand for infrastructure projects, as seen with the Boundary Dam CCS facility in Canada (1,700 people) and the Alberta Carbon Trunk Line (2,000 people).[95] Although construction is short-term in nature, as the CCS industry is expected to grow, these employees may have the opportunity to work on a project-to-project basis, working where the demand is prevalent. Based on these examples and for purposes of approximation, the next section notes that an estimated 1,000 employees will be assumed to be required for each capture project.

Additionally, although smaller in terms of quantity of workers, carbon capture facilities require employees consistently throughout the duration of the capture plant's operation. The Global CCS Institute has found that typical carbon capture facilities require about 20 people. These employees vary in skill level, with positions including "managers, operators, maintenance personnel and lab technicians."[96]

Additionally, CCS can help support high-value industries in continuing to make products in a more sustainable manner, increasing their ability to contribute to the economy while lowering their impact on the environment. These industries, such as steel, cement, aluminum, paper, petroleum, and chemicals employ over 29 million people globally and contribute indirectly to a multitude of jobs both down and upstream. Without CCS, these economically important industries may struggle to positively contribute to net-zero goals both domestically and globally.

4.1.1.3 Scaling Workforce Estimates from GPI and Global CCS Using NETL-NZA Model

This section extrapolates and summarizes the findings from the previous two external reports, which both had smaller capture goals, to obtain a workforce estimate for the 2.0 Gtpa scenario modeled in this report. In doing so, the scaled NETL-NZA Model detailing the number of capture projects deployed in 5-year intervals was used, as shown in the first row of Table 19. Since GPI estimates different numbers of employees depending on the type of capture project (industrial versus power), capture sites were broken down by implementing the ratio determined by the GPI report. GPI stated that out of 444 capture projects, 315 would be industrial facilities and

129 would be power facilities. With this ratio of about 2.5:1, industrial to power, the second and third rows of Table 19 identify how many of each type of project are required to meet the 2.0 Gtpa goal. As the GPI report suggests that industrial facilities require about 28 operations jobs on average and power plants require about 237 operations jobs on average, these figures were multiplied by the respective amount of each facility type and summed together to obtain a total number of operations employees. A similar calculation was performed to obtain project employee estimates, given that industrial facility CCS retrofits can create an average of 33 project jobs while power plants can create an average of 382 project jobs. The results of these calculations are seen in Table 19, ultimately totaling 155,975 operations employees and 236,273 project employees, based on the GPI report.

The last two rows are estimates developed by leveraging the Global CCS estimate of about 20 employees per facility for operations positions. Since the GPI report mentioned that it is common for thousands of employees to be hired for infrastructure projects, the estimate for project jobs was assumed to be 1,000 employees for every project. This approximate may be drastically high, as many retrofit projects require significantly fewer than 1,000 project employees. Still, this estimate may offer a top-end range of potential workforce impact.

Table 19: Carbon capture economy: Number of projects and employees (5-year intervals)

Category		2030	2035	2040	2045	2050	Grand Total
Projects	**Total Estimated CO_2 Capture Projects**	35	556	465	431	271	1758
	Estimated Industrial Facility Projects *(GPI extrapolation)*	25	394	330	306	192	1247
	Estimated Power Plant Projects *(GPI extrapolation)*	10	162	135	125	79	511
Employees	**# of Operations Employees** *(GPI extrapolation)*	3,105	49,330	41,256	38,240	24,044	155,975
	# of Project/Infrastructure Employees *(GPI extrapolation)*	4,704	74,726	62,495	57,926	36,422	236,273
	# of Operations Employees (Global CCS extrapolation)	700	11,120	9,300	8,620	5,420	35,160
	# of Project/Infrastructure Employees (Global CCS extrapolation)	35,000	556,000	465,000	431,000	271,000	1,758,000

4.1.2 Development of Diverse Supply Chains

As outlined in Section 4.1.1, there is a substantial opportunity to leverage the CCS buildout for American economy and employment growth. However, the United States has many allies that produce required materials in significant quantities. In addition to developing American capabilities where applicable (and a competitive advantage exists), there are also opportunities to develop diversified supply chains with U.S. allies and partners, where they have a comparative advantage.

4.1.3 Technological Innovations for Other CO_2 Use-Applications and Capture Technologies

Currently, the primary revenue source for capturing CO_2 is the restoring of depleted oil and gas reservoirs for re-use. Secondarily, the IRS 45Q (discussed in Section 1.4) provides a tax credit for 12 years after a carbon capture project is active. While these are a start, without additional revenue sources, there is very limited incentive for private industry to adopt and contribute to this CCS model.

One revenue option is to assign value to the captured CO_2. This option is discussed in the policy suggestion document related to this report. The other revenue option is to commercialize technologies that can extract additional value from the captured CO_2. Potential applications include liquid fuels, chemicals and plastics, acceleration for the growth of algae, novel materials (carbon composites, carbon fiber, graphene), soda carbonization, refrigeration, and more. In June 2020, the White House Council on Environmental Quality (CEQ) delivered a report that discusses the United States' role in CCS to meet its 2050 goals.[97] In this report, additional uses of captured CO_2 are discussed.

Additionally, there are also several technological pathways to explore pertaining to the capture of carbon. These are discussed in Section 2.1.1.2, but additional opportunities arise in the areas of research including capture via forests, biomass, soil, minerals, and the ocean.[98]

4.2 Key Challenges

4.2.1 MEA Production Capacity

As discussed in Section 3.1, MEA is the only studied material that this report highlights as a "medium" risk. This section lists several possible mitigation measures to increase chances that the industry grows at the required CAGR and maintains a healthy workforce level to ensure that capacity increases could be met.

4.2.2 Financing

As discussed in Section 4.1.3, there is a need for other revenue sources for captured CO_2. Currently, one of the primary revenue sources is from the IRS 45Q tax credits, which expire after 12 years of continuous operation of a capture facility. After these 12 years, unless other revenue sources can be located (e.g., from the U.S. government providing a carbon tax or additional carbon capture credits, or from technological innovations that extract additional value from captured CO_2), these facilities will be forced to shut down.

4.2.3 Pore Rights

Across many industries such as railroad, oil and natural gas, and power transmission, access to thin, long stretches of land has been crucial to the success of the project. Traversing hundreds, sometimes thousands, of individual and private landowners is a drastic issue for long distance infrastructure projects. This proposed CCS model is no exception, especially when it comes to pore rights. While pipelines certainly present the issue of landowner agreement, the issue of pore rights may be even more complex and difficult to tackle. Pore rights pertain to the question of who has ownership of "the underground pore space where the carbon would be injected and stored"[99] Typically, property rights are split into two categories: the surface estate and the mineral estate. When the mineral and surface estates have been separated, states in the United States follow either the "American rule" or the "English rule." The American rule gives ownership of any geological formations to the surface estate, while the English rule gives ownership of the pore space to the mineral estate. However, the American rule does allow mineral estate owners to use the pore space during mineral extraction, to a reasonable extent. Complexity is added when considering different state laws and traversing across state borders. Several lawsuits have taken place in various states, including Texas, surrounding pore rights engagements and they had varied and inconsistent outcomes. However, many states are currently undertaking or have undertaken legislative and regulatory actions to clarify these issues and provide developers of CO_2 saline storage projects more certainty with respect to these issues. Examples include the development of provisions like providing pore space holders liability protections if an injection project leaks and developing pooling agreements provisions that allow pore space rights to be combined or consolidated.[100]

5 Conclusion

This report examined CCS technologies and associated supply chains that will be required to support U.S. goals in 2050.

Currently, there do not appear to be any significant materials supply chain risks for CCS even in the most limiting future scenarios. While the materials needed are extensive, the markets for these materials are already quite large and have room to expand. Additionally, the availability of the raw materials needed to produce these materials and components is not a hindrance to increasing production.

In the case of MEA, the market is not currently large enough to accommodate CCS needs, but production could be increased to meet demand with advanced notice. There are several policies that could be enacted to help promote early growth in CCS infrastructure that would spread the need for materials over a longer timeframe, further decreasing already low supply chain risks.

There are various opportunities and challenges in this proposed CCS model. Significant growth to the American workforce is expected, as some estimates approximate this industry could create up to 155,000 operations jobs and potentially 1.76 million temporary project and infrastructure jobs. There are also numerous opportunities for research and innovation in the CCS space, including leveraging the captured carbon for additional revenue streams such as applications in liquid fuels, chemicals and plastics, and novel materials. Alongside these opportunities are a few challenges as well, such as financial incentives and pore rights for a project this large.

Finally, CCS infrastructure can be supplied in a large part by U.S.-made components. Expanding perspective to the global scale by leveraging allied countries and their industrial bases, the modeled CCS infrastructure is not expected to experience any significant supply chain bottlenecks. As noted, the goal of capturing and storing 2.0 Gtpa of CO_2 and the subsequent models analyzed in this report are very conservative, and so since the material requirements at this scale can be easily met, concerns of supply chain risk in any smaller buildout scenarios are largely mitigated.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

6 Appendix – NETL-NZA Model

After receiving Princeton University data, the National Energy Technology Laboratory (NETL) Model methodology involved (1) filling in data not provided by Net Zero America (NZA), (2) scaling the entire dataset from 1.6 gigatons per annum (Gtpa) to 2.0 Gtpa carbon dioxide (CO_2) stored in 2050, and (3) cataloging, on 5-year deployment intervals, transportation and injection characteristics (using several sources: Office of Fossil Energy and Carbon Management [FECM] CO2 Transport Cost Model, CO2_T_COM; the FECM CO2 Saline Storage Cost Model, CO2_S_COM; and Underground Injection Control [UIC] Class VI storage permits), and finally (4) translating data into raw material requirements.

6.1 Filling in Data Gaps

There were several areas that the NETL-NZA Model required that the Princeton University NZA report did not provide.

First, while the NZA report provided total estimated CO_2 storage projections for a 1.6 Gtpa scenario, it did not provide the 5-year deployment schedules. To cover this, NETL derived the schedule by dividing the cumulative spur line mass flow rate for a given 5-year interval by 5 Mtpa. The CO_2 storage project 5-year deployment schedule was further broken down by basin (the NZA study, and consequently the NETL study, broke the United States into seven regions) proportionally based on the reported number of "plays" (presumed to be individual storage projects) per basin, and the reported injection well mass flow rate per basin. Figure 30 is a map highlighting the location of these storage basins with respective mass flow rates, while Figure 31 shows how the pipelines are distributed.

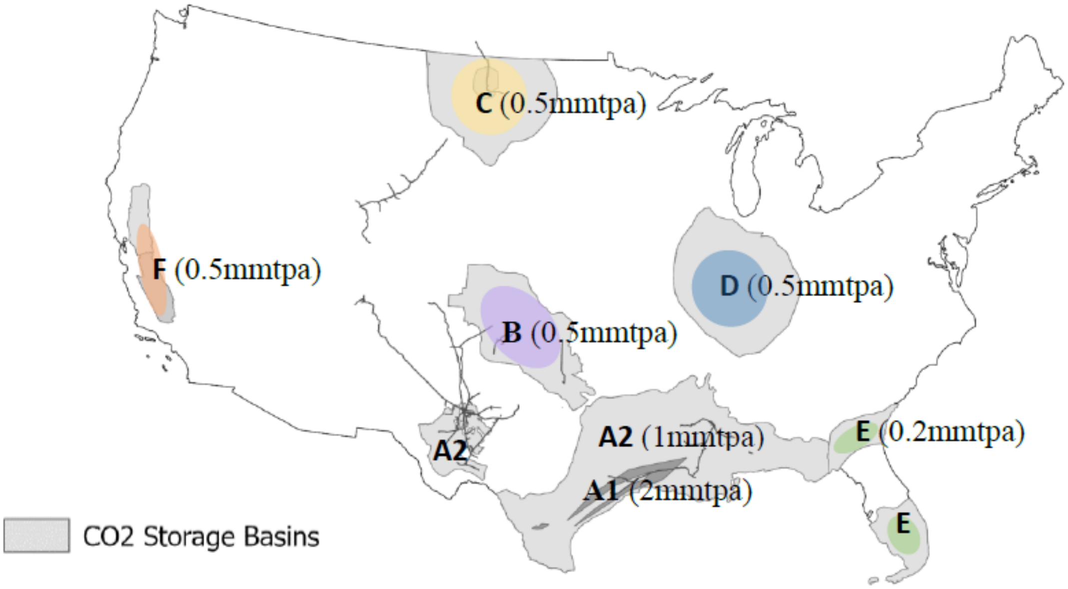


Figure 30: Map of NZA (and NETL analysis) basins for CO_2 storage, and per basin injection well mass flow rates

Note: mmtpa = million metric tons per annum, or Mtpa

The second was a lack of distribution and sub-distribution pipeline modeling. To cover this, distribution pipelines were estimated to be 10 miles in length and were determined to be sized to an average of 5 Mtpa CO_2 mass flow rate, to match the implied mass flow rate size of each storage site in the NZA project. Quantity of sub-distribution pipelines and their associated mileage were calculated based on: (1) the injection well count per project, which is injection rate- (and therefore basin-) dependent, and (2) injection well spacing, assumed to be 10 square miles, based on default values in the NETL-NZA Model.

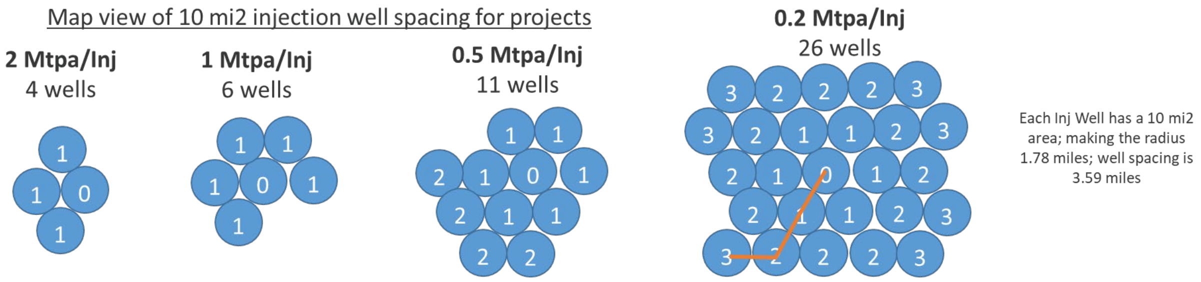


Figure 31: NETL distribution pipeline diagram

Figure 32 is a diagram of the injection wells that shows additional details about how these injection wells are situated along with their distribution lines.

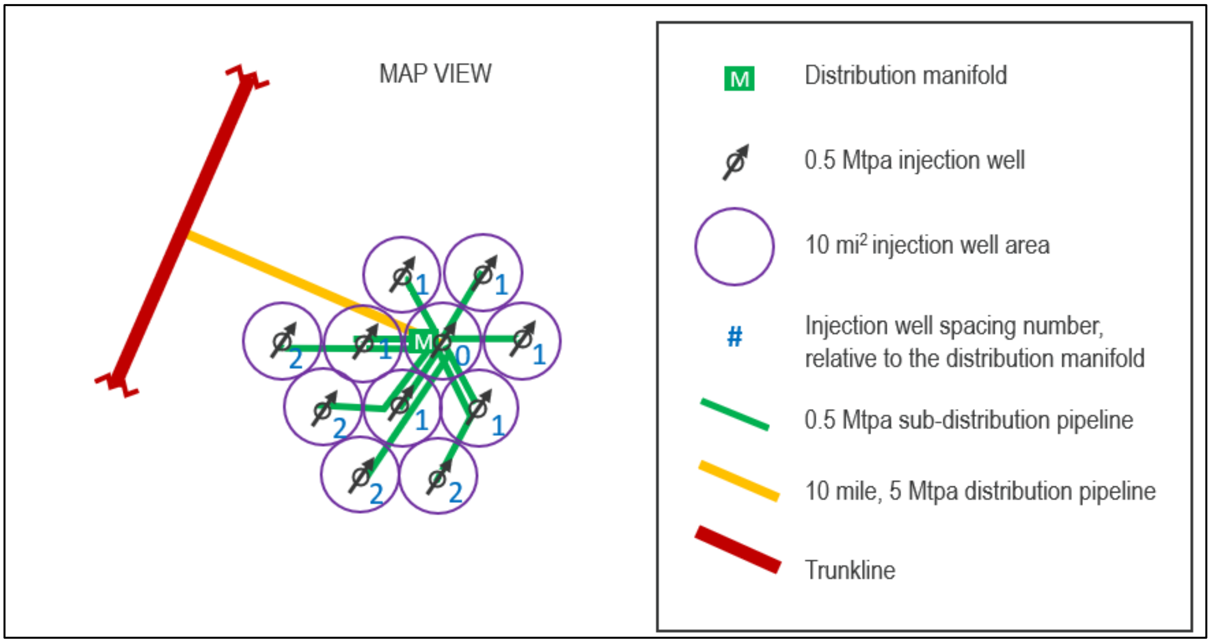


Figure 32: Typical injection site with the well area, sub-distribution, distribution, and trunkline pipelines highlighted

It is important to note that the hexagonal tessellation of 10 mi^2 injection well areas result in linear well spacing of 3.57 miles, making each sub-distribution pipeline segment length a multiple (dependent on injection well spacing number relative to the distribution manifold) of 3.57 miles. In the example shown in Figure 31, 11 injection wells are required for a 5 Mtpa storage project with 0.5 Mtpa injection rate, due to one additional injection well required for redundant use while any other one injection well is not operational during routine maintenance, following NETL-NZA Model logic.

6.2 Scaling to 2.0 Gtpa

As discussed, the NZA scenario closest to the Department of Energy's (DOE's) 2.0 Gtpa goal stores 1.6 Gtpa CO_2 in 2050. To scale, all pipelines were scaled proportionally, by 5-year intervals, to total 2.0 Gtpa in 2050 for both spur pipelines and distribution pipelines. Sub-spur, trunkline, and sub-distribution lines can all vary from a cumulative 2.0 Gtpa in 2050. This variance is caused by several reasons. First, not every CO_2 source is linked to the Carbon Capture and Storage (CCS) network by sub-spurs (as schematically illustrated in Figure 18). Second, trunklines are used to balance CO_2 between basins, resulting in some fluctuation in mass flow. Third, sub-distribution pipelines' mass flow rates will depend on operational variations at individual storage sites.

Additionally, storage sites were also scaled proportionally by 5-year intervals to total 2.0 Gtpa in 2050. Table 20 shows the breakdown.

Table 20: Number of CO_2 capture projects deployed by 5-year interval (NETL-NZA Model)

Year	2030	2035	2040	2045	2050	Grand Total
# of CO_2 capture projects	35	556	465	431	271	1758

6.3 Cataloging Transportation and Injection Characteristics

To catalog the pipeline item needs on a 5-year interval basis, the NETL-NZA Model scaled capture projects (size and count, as described above), pipeline segments (size and length), pumps (size and count), injection wells' casing (sizes and lengths), injection wells' cement (types and amounts), monitoring wells' casing (sizes and lengths), and monitoring wells' cement (types and amounts).

6.3.1 Transportation Characteristics

The NETL-NZA Model estimated unique pipeline segment diameter and thickness, as well as the number of pumps and pump size (with respect to maximum power requirement, in kilowatts (kW)) using each segment's mass flow rate and length assuming an 85% capacity factor. The NETL-NZA Model also optimized for pipeline segment diameter, pipeline wall thickness, and the number of pumps needed by incorporating major components such as operation timeframe, annual mass flow rate of CO_2, pipeline distance, and the elevation change from the input to the output of the pipeline segment.[101]

The NETL-NZA Model also estimates the number of pumps required for a given nominal pipe diameter. The number of pipes estimated can be correlated to a specific kW using the graph below. Note that the y-axis of Figure 33 has been log transformed; the inset is a linear scale. Pipe diameter values are integers and data have been slightly jittered around these to reduce overplotting.

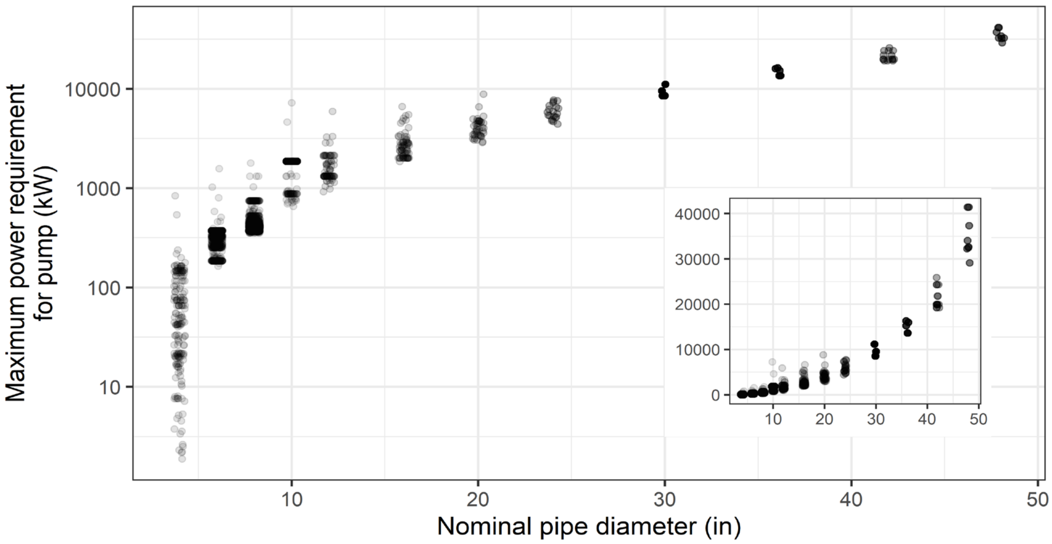


Figure 33: Relationship between pump power requirements and nominal pipeline diameter for the 595 pumps needed cumulatively in model results

Finally, because the NETL-NZA Model uses trunklines that have significantly larger mass flow rates than any CO_2 pipeline in existence today, a sensitivity analysis was run using trunklines limited to 30" in nominal diameter (hereafter, "NETL-NZA Model Pipeline Diameter Sensitivity Analysis"). This scenario increases the number of parallel trunklines needed to achieve the same mass flow rate as a single, larger pipeline. For reference, the largest CO_2 pipeline to date is the 30" Cortez pipeline.[102] This scenario was performed due to the concern that pipelines larger than 30" would put excess stress on the domestic supply chain, as these pipes are not standard. Table 21 through Table 24 describe the difference in material required to accomplish an infrastructure built with the pipes noted in each scenario.

Table 21: Pipeline requirements by nominal pipe diameter (NETL-NZA Model)

Nominal Pipe Diameter (in)	Miles of Pipe - 2030	Miles of Pipe - 2035	Miles of Pipe - 2040	Miles of Pipe - 2045	Miles of Pipe - 2050	Grand Total
4	0	829	821	690	747	3,087
6	288	3,522	4,164	3,575	3,838	15,387
8	76	7,500	7,369	7,315	2,575	24,835
10	40	2,537	1,160	1,100	630	5,467
12	0	374	0	1,161	0	1,535
16	0	0	846	0	0	846
20	478	0	0	0	858	1,336
24	390	990	0	0	0	1,381
30	1,077	401	0	0	0	1,478
36	326	1,630	336	0	0	2,292
42	2,083	2,649	3,103	510	510	8,855
48	2,674	803	526	0	0	4,002
Grand Total	**7,432**	**21,235**	**18,325**	**14,351**	**9,158**	**70,502**

Table 22: Pump requirements by nominal pipe diameter (NETL-NZA Model)

Nominal Pipe Diameter (in)	# of Pumps - 2030	# of Pumps - 2035	# of Pumps - 2040	# of Pumps - 2045	# of Pumps - 2050	Grand Total
4	1	18	15	5	7	46
6	1	7	15	20	31	74
8	0	7	8	15	3	33
10	0	9	2	5	5	21
12	2	30	14	73	23	142
16	0	17	14	19	6	56
20	6	4	5	9	19	43
24	8	12	0	0	0	20
30	11	3	0	0	0	14
36	3	16	2	0	0	21
42	19	23	27	4	4	77
48	30	9	9	0	0	48
Grand Total	**81**	**155**	**111**	**150**	**98**	**595**

Table 23: Pipeline requirements by nominal pipe diameter (NETL-NZA Model Pipeline Diameter Sensitivity Analysis)

Nominal Pipe Diameter (in)	Miles of Pipe - 2030	Miles of Pipe - 2035	Miles of Pipe - 2040	Miles of Pipe - 2045	Miles of Pipe - 2050	Grand Total
4	0	829	821	690	747	3087
6	288	3,522	4,164	3,575	3,838	15,387
8	76	7,500	7,369	7,315	2,575	24,835
10	40	2,537	1,160	1,100	630	5,467
12	0	374	0	1,161	0	1,535
16	0	0	846	0	0	846
20	478	0	0	0	858	1,336
24	716	990	0	1,276	326	3,307
30	5,308	11,089	10,502	10,218	3,775	40,893
Grand Total	**6,906**	**26,840**	**24,862**	**25,336**	**12,749**	**96,694**

Table 24: Pump requirements by nominal pipe diameter (NETL-NZA Model Pipeline Diameter Sensitivity Analysis)

Nominal Pipe Diameter (in)	# of Pumps - 2030	# of Pumps - 2035	# of Pumps - 2040	# of Pumps - 2045	# of Pumps - 2050	Grand Total
4	1	18	15	5	7	46
6	1	7	15	20	31	74
8	0	7	8	15	3	33
10	0	9	2	5	5	21
12	2	30	14	73	23	142

16	0	17	14	19	6	56
20	6	4	5	9	19	43
24	14	12	0	24	6	56
30	47	97	88	80	32	344
Grand Total	**71**	**201**	**161**	**250**	**132**	**815**

6.3.2 Injection Characteristics

The NETL-NZA Model scaling's subsequent effects on sub-distribution piping, storage project, and injection well counts can be seen in Table 25 through Table 28.

Table 25: Sub-distribution pipeline segment lengths per project, by basin (NETL-NZA Model)

Basin	Injection Well Spacing (mi)*	Central (0 distance) injectors	1 Spacing Distance Injector (and sub distribution pipelines)	2 Spacing Distance Injectors (and sub distribution pipelines)	3 Spacing Distance Injectors (and sub distribution pipelines)	Total sub-distribution pipeline length per project	Sub-distribution pipeline segment capacity (Mtpa)
A1_Gulf	3.57	1	3	0	0	10.7	2.0
A2_Gulf shore	3.57	1	5	0	0	17.8	1.0
B_Midcon	3.57	1	6	4	0	50.0	0.5
C_Williston	3.57	1	6	4	0	50.0	0.5
D_Illinois	3.57	1	6	4	0	50.0	0.5
E_Florida	3.57	1	6	12	7	182.0	0.2
F_California	3.57	1	6	4	0	50.0	0.5

**NETL-NZA Model default*

The scaled storage capacity, injection well count, total storage projects deployed, and total injection well counts can be seen in Table 26. Utilization rates for storage sites are slightly higher (approximately 60%).

Table 26: Storage project and injection well count, by basin (NETL-NZA Model)

Basin	Injection Rate (Mtpa/well)	CO_2 storage capacity potential (Mtpa)	NETL-NZA Model			
			CO_2 Storage capacity used in 2050 (Mtpa)	**Injection well count per storage project***	**Total Storage Projects Deployed by 2050 (count)**	**Total injection well count in 2050**
A1_Gulf shore	2.0	500	343	4	69	276
A2_Gulf shore	1.0	1700	1153	6	231	1386
B_Midcon	0.5	80	49	11	10	110
C_Williston	0.5	240	159	11	32	352
D_Illinois	0.5	220	147	11	30	330
E_Florida	0.2	60	37	26	8	208
F_California	0.5	200	112	12	23	276
TOTALS			**2000**	**-**	**403**	**2938**

**Injection rate must exceed 5.0 Mtpa, and must include 1 redundant well per NETL-NZA Model logic*

Table 27: Storage project deployment schedule, by basin (NETL-NZA Model)

5 Year Deployment Interval: Number of Storage Projects						
NZA Basin	**2030**	**2035**	**2040**	**2045**	**2050**	**Grand Total**
A1_Gulf Shore	1	18	20	19	11	69
A2_Gulf shore	3	64	66	63	35	231
B_Midcon	0	2	3	3	2	10
C_Williston	0	9	9	9	5	32
D_Illinois	0	8	9	8	5	30
E_Florida	0	3	2	2	1	8
F_California	0	6	7	6	4	23
Grand Total	**4**	**110**	**116**	**110**	**63**	**403**

Table 28: Injection well deployment schedule, by basin (NETL-NZA Model)

5 Year Deployment Interval: Number of Injection Wells						
NZA Basin	**2030**	**2035**	**2040**	**2045**	**2050**	**Grand Total**
A1_Gulf Shore	4	72	80	76	44	276
A2_Gulf shore	18	384	396	378	210	1386
B_Midcon	0	22	33	33	22	110
C_Williston	0	99	99	99	55	352
D_Illinois	0	88	99	88	55	330
E_Florida	0	78	52	52	26	208
F_California	0	72	84	72	48	276
Grand Total	**22**	**815**	**843**	**798**	**460**	**2938**

6.4 Resulting Materials Estimations

6.4.1 Transportation

Based on the pipeline requirements set forward in the NETL-NZA Model and corresponding NETL-NZA Model Pipeline Diameter Sensitivity Analysis (pipeline diameters limited to 30”), steel calculations were performed. Table 29 and Table 30 show the steel requirements by pipe diameter.

Table 29: Steel requirements by nominal pipe diameter (NETL-NZA Model)

Pipe Inside Diameter (in)	Pipe Outside Diameter (in)	Total Length Required (miles)	Total Volume Required (m^3)	Total Steel Required (Mt)
4.00	4.47	3,087	10,111	0.1
6.00	6.56	15,387	88,253	0.7
8.00	8.64	24,835	217,081	1.7
10.00	10.73	5,467	67,463	0.5
12.00	12.75	1,535	23,241	0.2
16.00	16.84	846	18,985	0.1

20.00	21.05	1,336	46,880	0.4
24.00	25.26	1,381	69,759	0.5
30.00	31.57	1,478	116,681	0.9
36.00	37.89	2,292	260,467	2.0
42.00	44.20	8,855	1,369,347	10.7
48.00	50.50	4,002	803,736	6.3
				24.12

Table 30: Steel requirements (NETL-NZA Model Sensitivity Analysis)

Pipe Inside Diameter (in)	Pipe Outside Diameter (in)	Total Length Required (miles)	Total Volume Required (m^3)	Total Steel Required (Mt)
4.00	4.47	3,087	10,111	0.1
6.00	6.56	15,387	88,253	0.7
8.00	8.64	24,835	217,081	1.7
10.00	10.73	5,467	67,463	0.5
12.00	12.75	1,535	23,241	0.2
16.00	16.84	846	18,985	0.1
20.00	21.05	1,336	46,880	0.4
24.00	25.26	3,307	167,113	1.3
30.00	31.57	40,893	3,227,696	25.2
				30.16

6.4.2 Injection

Each storage project's injection and monitoring wells' casing and cement requirements were estimated based on the injection well count requirement in each basin, the average depth of relatively low-cost saline storage reservoirs in each basin, and casing and cement schedules from UIC Class VI permits. Injection well count per basin was determined by the reported injection rate per basin and the number of projects in each basin from the NETL-NZA Model. Average depth of relatively low-cost saline storage reservoirs in each basin was determined by the geologic data in the CO2_S_COM, filtered for reservoirs where a 5.0 Mtpa storage project has a first-year break even storage cost less than $40 per metric ton (in real 2018$), assuming a dome structural geological setting. 200' was added to each basin's average to account for the rathole. Casing and cement schedules were based on designs from UIC Class VI permits. The following type wells were chosen:

- Injector - Archer Daniels Midland (ADM) CCS#2: Macon County, IL in the Illinois Basin is currently injecting CO_2 at ~1 MMt/yr
- Injector - Archer Daniels Midland CCS#1: Macon County, IL in the Illinois Basin was injecting 0.3 MMt/yr and is currently in the post-injection phase
- Injector - Minnkota Power Cooperative Liberty-1: Oliver County, ND in the Williston Basin is in the permitting phase and plans to inject 2 MMt/yr
- Monitor - Minnkota Power Cooperative NRDT-1: Oliver County, ND in the Williston Basin is in the permitting phase and plans to monitor the injection of a combined 4 MMt/yr of CO_2 from the Minnkota Power Cooperative's Liberty-1 and Unity-1 Injectors

For injectors, ADM CCS#2 was determined to be the most representative due to its active use and for having a 1 MMt/yr injection rate. The ADM CCS#2 casing and cement schedule, except for tubing, is used for all basins. Tubing diameter changes from basin to basin depending on the reported injection rate: Tubing diameter varies from 7" for 2.0 Mtpa (based on the Liberty-1, which is projected to inject 2.0 Mtpa), 5.5" for 1.0 Mtpa and 0.5 Mtpa, and 4.5" for 0.2 Mtpa (based on ADM CCS#1, which injected 0.3 Mtpa). Casing and tubing lengths and cement volumes were proportionally adjusted by basin using the total depth of the well calculated from CO2_S_COM.

For monitoring wells, Minnkota NRDT-1 was used as the type well for all basins. NRDT-1 casing, tubing, and cement schedules are used for all basins. Casing lengths, tubing lengths, and cement volumes were proportionally adjusted by basin using the total depth of the well calculated from CO2_S_COM. Monitoring wells were assumed to deployed on a 1:1 basis with injection wells.

Casing and cement requirements were cataloged based on each basin's project and injection well count, on a 5-year deployment interval basis, as shown in Table 31.

Table 31: Injection site characteristics 5-year deployment schedule scaled-up NETL-NZA Model

Basin	Injection Rate (Mtpa/ well)	Cum 2050 Injection mass (Mtpa)	2.0 project count	Actual 2.0 well count (with redundancy)	Wells per project		Injection well spacing (mi)	# Spacing Distance Injectors				Dedicated pipe mileage per project	Pipe Mtpa per project	5 Mtpa pipe mileage per project
					Injection	Monitoring		0	1	2	3			
A1	2	343	69	276	4	4	3.57	1	3	0	0	10.70	2	10
A2	1	1153	231	1386	6	6	3.57	1	5	0	0	17.84	1	10
B	0.5	49	10	110	11	11	3.57	1	6	4	0	49.96	0.5	10
C	0.5	159	32	352	11	11	3.57	1	6	4	0	49.96	0.5	10
D	0.5	147	30	330	11	11	3.57	1	6	4	0	49.96	0.5	10
E	0.2	37	8	208	26	26	3.57	1	6	12	7	181.98	0.2	10
F	0.5	112	23	276	12	12	3.57	1	6	4	0	49.96	0.5	10
TOTALS	-	2000	403	2938										

Using those estimated number of wells, the amount of cement required for injector and monitor wells in 5-year intervals, broken down by cement type, is shown in Table 32. Summing the totals over all years, approximately 25,841,761 cement sacks are required to implement sufficient injection infrastructure to capture 2 Gtpa of CO_2. While cement sacks may yield slightly variable volumes of cement based on cement type, on average one cement sack weighs about 94 pounds. Table 32 through Table 35 depict the conversion to metric tons, which yields a total cement required of approximately 877 thousand metric tons (kt) for injection wells and 225 kt for monitor wells, or 1.1 million metric tons (Mt) all together.

Table 32: Required cement sacks in 5-year intervals for injector wells (NETL-NZA Model)

Cement Requirements Injector Wells						
Cement Type	Cement Sacks 2030	Cement Sacks 2035	Cement Sacks 2040	Cement Sacks 2045	Cement Sacks 2050	Cement Sacks Total
Class A, 3% CaCl2	17,846	671,788	702,600	662,826	384,341	2,439,401
Class H	34,153	1,285,634	1,344,601	1,268,483	735,533	4,668,405

65/35 cmt-poz 6% gel Class H	76,828	2,892,048	3,024,694	2,853,466	1,654,588	10,501,623
CO_2-Resistant Evercrete	21,639	814,543	851,903	803,677	466,013	2,957,774
Total	**150,467**	**5,664,013**	**5,923,797**	**5,588,452**	**3,240,475**	**20,567,204**

Table 33: Required cement sacks in 5-year intervals for monitor wells (NETL-NZA Model)

Cement Requirements Monitor Wells						
Cement Type	**Cement Sacks 2030**	**Cement Sacks 2035**	**Cement Sacks 2040**	**Cement Sacks 2045**	**Cement Sacks 2050**	**Cement Sacks Total**
Class G with Additives	27,485	1,034,745	1,082,222	1,020,949	592,008	3,757,408
CO_2-Resistant Cement	11,099	417,809	436,972	412,235	239,035	1,517,149
Total	**38,585**	**1,452,553**	**1,519,193**	**1,433,183**	**831,043**	**5,274,558**

Table 34: Required cement (kt) in 5-year intervals for injector wells (NETL-NZA Model)

Cement Requirements Injector Wells (thousand metric tons, kt)						
Cement Type	**2030**	**2035**	**2040**	**2045**	**2050**	**Total**
Class A, 3% CaCl2 (kt)	0.8	28.6	30.0	28.3	16.4	104.0
Class H (kt)	1.5	54.8	57.3	54.1	31.4	199.1
65/35 cmt-poz 6% gel Class H (kt)	3.3	123.3	129.0	121.7	70.5	447.8
CO_2-Resistant Evercrete (kt)	0.9	34.7	36.3	34.3	19.9	126.1
Total (kt)	**6**	**242**	**253**	**238**	**138**	**877**

Table 35: Required cement (kt) in 5-year intervals for monitor wells (NETL-NZA Model)

Cement Requirements Monitor Wells (thousand metric tons, Kt)						
Cement Type	**Cement (Kt) 2030**	**Cement (Kt) 2035**	**Cement (Kt) 2040**	**Cement (Kt) 2045**	**Cement (Kt) 2050**	**Cement (Kt) Total**
Class G with Additives	1.2	44.1	46.1	43.5	25.2	160.2
CO_2-Resistant Cement	0.5	17.8	18.6	17.6	10.2	64.7
Total	**2**	**62**	**65**	**61**	**35**	**225**

In addition to cement, steel casing and tubing are required for the construction of injection and monitor wells. Table 36 through Table 39 provide a breakdown of the grade of steel, size, and length of piping needed. From that, total volume and weight of steel necessary for this application was extrapolated. By 2050, the United States would use a cumulative 1,608 thousand metric tons (kt) of steel for the injection of CO_2, or 1.6 million metric tons (Mt).

Table 36: Required steel for injector well casings (NETL-NZA Model)

Casing Requirements Injector Wells						
Casing/Tubing	**Inside Diameter (in)**	**Casing/tubing Thickness (in)**	**Grade (API)**	**Casing Length (ft) Total**	**Volume of Steel (ft^3) Total**	**Weight of Steel (Thousand metric tons) Total**
Surface	19.124	0.438	J55 STC	1,058,090	197,787	45
Intermediate	12.515	0.43	J55 BTC	15,959,784	1,938,139	442
Long (Carbon)	8.835	0.395	L80-HC	14,691,295	1,168,547	267
Long (Chrome)	8.681	0.472	13CR80 JFE Bear	7,232,825	681,712	156
Tubing	3.963	0.7685	13CR80 JFE Bear	16,489,599	1,308,098	298
Tubing	3.963	0.2685	13CR85 JFE Bear	990,141	24,543	6
Tubing	6.184	0.408	L80 Coated Premium Conn	1,871,510	109,814	25
Tubing	6.184	0.408	C95 13Cr Premium Conn	39,483	2,317	1
Total				**58,332,729**	**5,430,956**	**1,239**

Table 37: Required steel for injector well casings (NETL-NZA Model)

Casing Requirements Monitor Wells						
Casing/Tubing	**Inside Diameter (in)**	**Casing/tubing Thickness (in)**	**Grade (API)**	**Casing Length (ft) Total**	**Volume of Steel (ft^3) Total**	**Weight of Steel (Thousand metric tons) Total**
Conductor	15.25	0.375	B, WELD-API 5L Specs	219,241	28,026	6
Surface	8.835	0.395	K-55, BTC	4,384,824	348,769	80
Long-String	4.778	0.361	L-80, BTC	9,865,854	399,308	91
Long-String	4.778	0.361	13CR-80, BTC	12,058,266	488,043	111
Tubing	2.259	0.308	L80 Premium Flush Conn	20,608,674	355,479	81
Total				**47,136,860**	**1,619,625**	**369**

Table 38: Types and lengths of steel required in 5-year intervals for injector wells (NETL-NZA Model)

5-year Interval Casing Length Requirements Injector Wells									
Casing/ Tubing	**Inside Diameter (in)**	**Casing /tubing Thickness (in)**	**Grade (API)**	**Casing Length (ft) 2030**	**Casing Length (ft) 2035**	**Casing Length (ft) 2040**	**Casing Length (ft) 2045**	**Casing Length (ft) 2050**	**Casing Length (ft) Total**
Surface	19.124	0.438	J55 STC	7,741	291,388	304,753	287,501	166,708	1,058,090
Intermediate	12.515	0.43	J55 BTC	116,759	4,395,173	4,596,761	4,336,539	2,514,551	15,959,784

5-year Interval Casing Length Requirements Injector Wells									
Casing/ Tubing	**Inside Diameter (in)**	**Casing /tubing Thickness (in)**	**Grade (API)**	**Casing Length (ft) 2030**	**Casing Length (ft) 2035**	**Casing Length (ft) 2040**	**Casing Length (ft) 2045**	**Casing Length (ft) 2050**	**Casing Length (ft) Total**
Long (Carbon)	8.835	0.395	L80-HC	107,479	4,045,844	4,231,409	3,991,870	2,314,694	14,691,295
Long (Chrome)	8.681	0.472	13CR80 JFE Bear	52,914	1,991,852	2,083,209	1,965,279	1,139,571	7,232,825
Tubing	3.963	0.7685	13CR80 JFE Bear	114,365	4,469,795	4,783,554	4,495,137	2,626,749	16,489,599
Tubing	3.963	0.2685	13CR85 JFE Bear	0	371,303	247,535	247,535	123,768	990,141
Tubing	6.184	0.408	L80 Coated Premium Conn	27,123	488,220	542,467	515,343	298,357	1,871,510
Tubing	6.184	0.408	C95 13Cr Premium Conn	572	10,300	11,444	10,872	6,294	39,483
Total				**426,954**	**16,063,875**	**16,801,133**	**15,850,076**	**9,190,691**	**58,332,729**

Table 39: Types and lengths of steel required in 5-year intervals for monitor wells (NETL-NZA Model)

5-year Interval Casing Length Requirements Monitor Wells									
Casing/ Tubing	**Inside Diameter (in)**	**Casing/ tubing Thickness (in)**	**Grade (API)**	**Casing Length (ft) 2030**	**Casing Length (ft) 2035**	**Casing Length (ft) 2040**	**Casing Length (ft) 2045**	**Casing Length (ft) 2050**	**Casing Length (ft) Total**
Conductor	15.25	0.375	B, WELD-API 5L Specs	1,604	60,377	63,146	59,571	34,543	219,241
Surface	8.835	0.395	K-55, BTC	32,079	1,207,539	1,262,924	1,191,430	690,853	4,384,824
Long-String	4.778	0.361	L-80, BTC	72,177	2,716,963	2,841,578	2,680,717	1,554,419	9,865,854
Long-String	4.778	0.361	13CR-80, BTC	88,216	3,320,732	3,473,040	3,276,432	1,899,845	12,058,266
Tubing	2.259	0.308	L80 Premium Flush Conn	150,770	5,675,433	5,935,742	5,599,720	3,247,009	20,608,674
Total				**344,846**	**12,981,045**	**13,576,430**	**12,807,870**	**7,426,669**	**47,136,860**

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