MEETING THE DUAL CHALLENGE

A Roadmap to At-Scale Deployment of CARBON CAPTURE, USE, AND STORAGE

CHAPTER SIX – CO_2 TRANSPORT

A Report of the National Petroleum Council
December 2019

This chapter was last updated on
July 20, 2020

Chapter Six

CO_2 TRANSPORT

I. CHAPTER SUMMARY

CO_2 transport refers to the transfer of carbon dioxide (CO_2) from one location to another or between its source and point of use. CO_2 can be transported via pipeline, rail, truck, ship, and barge. The primary mode of large-scale CO_2 transport in the United States today is via pipeline, and in 2017, there were more than 5,000 miles of CO_2 pipelines in operation.

Pipeline transport of CO_2 dates back over 80 years and was initially associated with the dry ice and beverage business. More than 40 years ago, large-scale transport by pipeline began when CO_2 was used for enhanced oil recovery (EOR) operations, and this CO_2 was sourced primarily from natural deposits and gas processing plants. Approximately 90% of the CO_2 pipeline infrastructure in the United States today is used for CO_2 EOR operations. These pipelines were constructed to provide a direct link between a CO_2 source and an associated CO_2 sink (a reservoir), creating a pipeline industry that is independent of the ownership of the various assets involved in CO_2 EOR.

Wide-scale deployment of carbon capture, use, and storage (CCUS) across the United States will require expansion of the existing CO_2 pipeline infrastructure through looping, replacement, or other engineering modifications, as well as the construction of new pipelines. There is no expectation that alternative modes of CO_2 transport—rail, truck, ship, and barge—would be able to support the large volumes of CO_2 associated with wide-scale deployment of CCUS. CO_2 transport by rail and truck may be viable for shorter distances within the United States, and transport by ship using tankers can be scaled to meet international CO_2 transport needs.

There are several challenges to scaling-up CO_2 transport infrastructure that will need to be addressed to avoid construction delays and cost increases, such as permitting requirements, surface use issues, and environmental group activism (see Chapter 4, "Building Stakeholder Confidence," in Volume II of this report). Enabling some form of eminent domain in the states through which construction occurs could help but will not resolve all the issues associated with infrastructure expansion.

Eminent domain is the right of a government (or its agent) to take private property for public use. This right is subject to two conditions: the private property must be for public use, and just compensation must be paid to its owner. Two judicial tests are used to define public use. The first, a narrow interpretation, requires that the end use of the property taken must be open and available for actual use by the public. The second approach includes a broad scope of uses and property interests that yield some public benefit—revenue generation, jobs, tax base, or development of industry.[1,2]

1 Schnacke, G. J., Marston P. M., and Moore, P. A., "Carbon Dioxide Infrastructure: Pipeline Transport Issues and Regulatory Concerns – Past, Present, and Future," *Rocky Mountain Mineral Law Foundation Journal*, 52, No. 2 (2015), 275-313.

2 Righetti, T. K., "Siting Carbon Dioxide Pipelines," *Oil and Gas, Natural Resources, and Energy Journal,* 3 (2017), 907, https://digitalcommons.law.ou.edu/onej/vol3/iss4/3.

Many states have the authority to determine the siting of pipeline infrastructure under the public benefit approach. However, the added cost of construction and the lack of an integrated CO_2 pipeline network will likely be one of the major hurdles for wide-scale deployment of CCUS in the United States. Overcoming this hurdle would require a system-level analysis (current capacity versus future requirement) to optimize the ongoing development of CO_2 infrastructure to achieve widespread deployment.

II. WHAT IS CO_2 TRANSPORT?

CCUS, including transport, combines several technologies to reduce the level of CO_2 emitted to the atmosphere or remove CO_2 from the air. The CCUS process, as shown in Figure 6-1, involves the capture (separation and purification) of CO_2 from stationary sources so that it can be compressed and transported to a suitable location where it is converted into useable products or injected deep underground for safe, secure, and permanent storage.

CO_2 transport refers to the transfer of CO_2 from one location to another or between its source and point of use. In most cases, the CO_2 described in this report is captured at a stationary emissions point source. Once captured, CO_2 must be compressed and transported to long-term geologic storage sites for dedicated underground storage, EOR production operations for incidental or associated trapping, or other sites for subsequent use in the production of products.

The transport of CO_2 is primarily accomplished using pipelines (Figure 6-2) operating at a pressure that enables the CO_2 to remain in

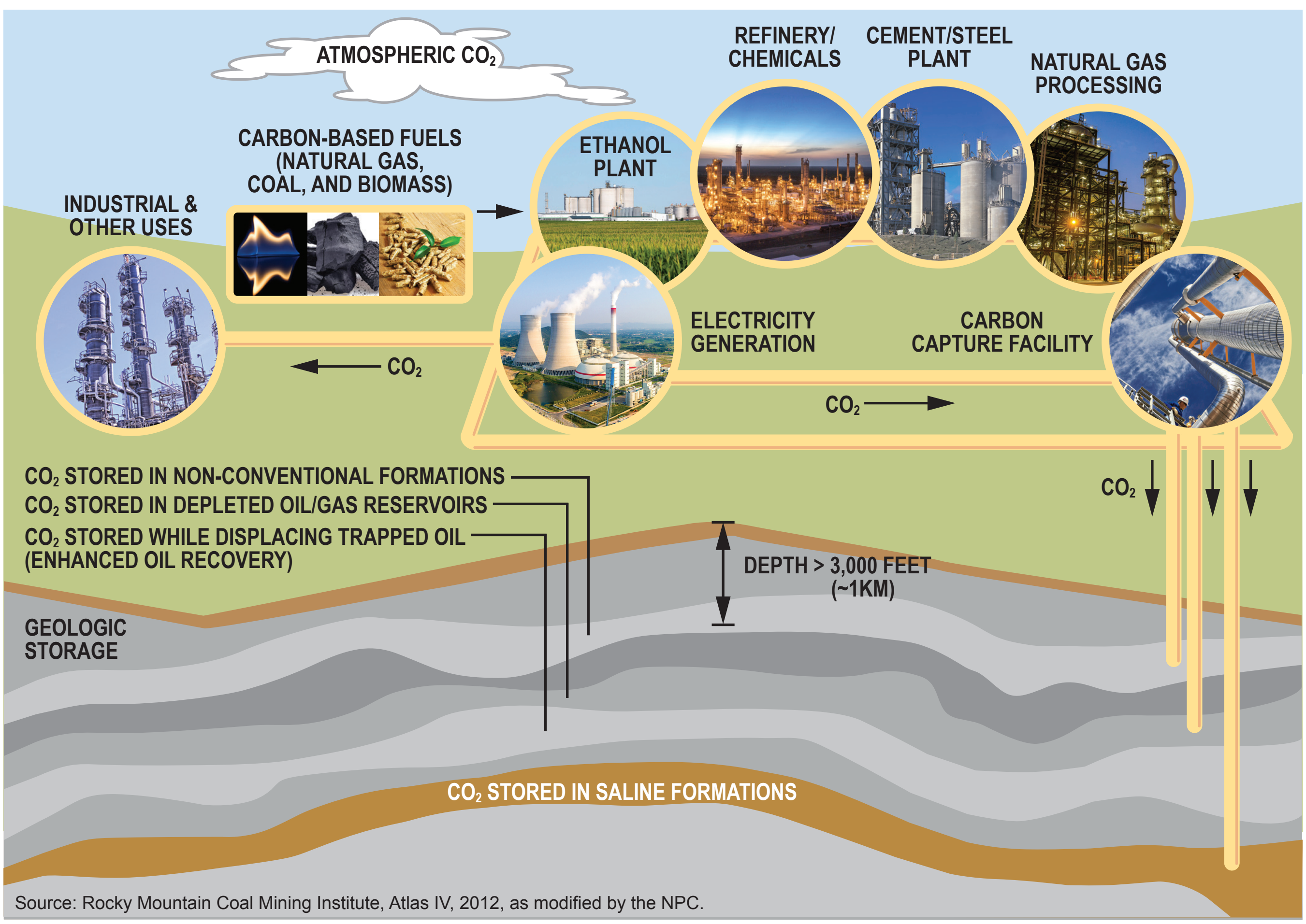


***Figure 6-1.** Supply Chain for Carbon Capture, Use, and Storage*

***Figure 6-2.** Schematic Map of CO_2 Pipelines in the United States*

a dense phase above a critical temperature. In its dense phase, the CO_2 is a highly compressed fluid that demonstrates properties of both a liquid and a gas. It is called a dense fluid, or supercritical fluid, to distinguish it from normal vapor and liquid. The word fluid refers to anything that will flow and applies to gas and liquid. Pure compounds in the dense phase normally have a better dissolving ability than they do in their liquid state. Compounds in dense phase have a viscosity like that of a gas, but a density closer to that of a liquid. The dense phase is the best condition for transporting CO_2 and injecting it into saline formations for geologic storage and into oil and natural gas reservoirs for EOR.

In addition to pipelines, CO_2 can also be transported via rail, truck, ship, and barge. In the United States, CO_2 is primarily transported for industrial purposes through more than 5,000 miles of CO_2 pipelines. The United States has more than 40 years of experience transporting CO_2 from natural deposits and gas processing plants for use in EOR operations.

III. STATUS OF TRANSPORT TECHNOLOGY

A. Current CO_2 Transport Options

CO_2 for industrial purposes is mainly transported in onshore pipelines. Although most of the CO_2 transported by pipeline is from natural sources, industrial or combustion sources do exist and are being captured, stored, and used in the United States. Aligning regulatory requirements and government incentives with environmental, operational, and financial risks would enable an increase in the captured industrial or combustion CO_2 volumes that could be captured, stored, and used.

The first offshore pipeline for transporting CO_2 was the Snøhvit pipeline in Norway. This pipeline has been transporting CO_2 from natural gas extraction through 95 miles of seabed pipeline from Hammerfest in northern Norway to the Snøhvit Field under the Barents Sea since May 2008.[3]

While natural gas is typically transported in gaseous form in high-pressure pipelines,[4] large volumes of CO_2 are easiest to transport in liquid or supercritical form.[5] Pipeline transportation of CO_2 over longer distances is most efficient and economical when the CO_2 is in the dense phase.[6] This means that the pressure in the pipeline must be kept at 1,080 psi and above. CO_2 must also be dehydrated to avoid corrosion of the pipeline.[7] Dehydrating the CO_2 entails removing the water from the gas mixture stream.

Ship transport of CO_2 occurs on a small scale in Europe, carrying approximately 1,000 metric tons (tonnes) of food-grade CO_2 from large point sources to coastal distribution terminals.[8] When Anthony Veder, a Dutch shipping company, built the Coral Carbonic vessel in 1999, it was the world's first purpose-built CO_2 tanker, capable of transporting 1,250 cubic meters, or about 1,250 tonnes of liquid CO_2. The existing fleet is transporting CO_2 with a pressure of around 217 to 290 psi and a temperature of about -22°F. For larger volumes, the parameters are likely to be around 101 psi and -58°F, near the triple point.[9]

Although transport of liquefied gases via barge is possible, dense phase CO_2 has not been transported by barge primarily due to a lack of demand for barge movement. Studies have outlined the use of barges in industrial hubs, such as the Port of Rotterdam, but these are not yet a reality.[10]

Transport of CO_2 by truck and rail is viable for small quantities, from 4 tonnes to a few hundred tonnes. Trucks can complement ship transport, moving small quantities of CO_2 from port CO_2 terminals to industrial sites for subsequent use. Trucks can also be used at some project sites, moving the CO_2 from where it is captured to a nearby storage location.

Given the large volumes of CO_2 that would need to be captured as CCUS is deployed at scale in the longer term, transport of CO_2 by truck and rail are not economical, scalable options. The cost of CO_2 transport by truck and rail ranges from three to ten times more per tonne than by pipeline transport due to economies of scale. Despite this, truck and rail transport could be important for smaller-scale point-to-point value chain solutions (for smaller capture volumes not accessible to pipeline options) during the early years of expanded CCUS deployment in the United States. These point-to-point solutions would require transport over shorter distances (200 miles or less for truck and 1,000 miles or less for rail), carrying CO_2 from a single specific source to a corresponding sink(s) where the CO_2 would be employed for purposes of either EOR or industrial use.

B. Large-Volume CO_2 Transport via Pipeline

Pipelines are the most common method of transporting the very large quantities of CO_2 involved in CCUS. Transporting various fluids via pipeline is a standard industrial practice, and extensive pipeline networks already exist around the world, on land and under the sea. In 2017, there were almost 535,000 miles of hazardous liquid and natural gas pipelines (gathering and transmission) in the United States, in addition to more than 2.2 million miles of natural gas distribution lines.

In 2017, there were more than 5,000 miles of CO_2 pipelines in the United States, the majority of

3 Den Norske Veritas (DNV GL), "Design and Operation of Carbon Dioxide Pipelines," DNVGL-RP-F104, November 2017.

4 Regulated by the Pipeline and Hazardous Materials Administration (PHMSA), Part 192, liquids gaseous pipeline regulation.

5 Regulated under PHMSA, Part 195, liquids pipeline regulations.

6 Den Norske Veritas (DNV GL), "Design and Operation of Carbon Dioxide Pipelines," DNVGL-RP-F104, November 2017.

7 IEAGHG: Presentation by Stanley Santos at CCOP (EPPM Workshop), Indonesia (2012).

8 Global CCS Institute website (2019).

9 Neele, F., Haugen, H. A., and Skagestad, R., "Ship transport of CO_2 – breaking the CO_2-EOR deadlock," *Energy Procedia*, 63 (2014): 2638-2644.

10 Global CCS Institute. (2011). Knowledge Sharing Report, "CO2 Liquid Logistics Shipping Concept (LLSC) – Overall Supply Chain Optimization."

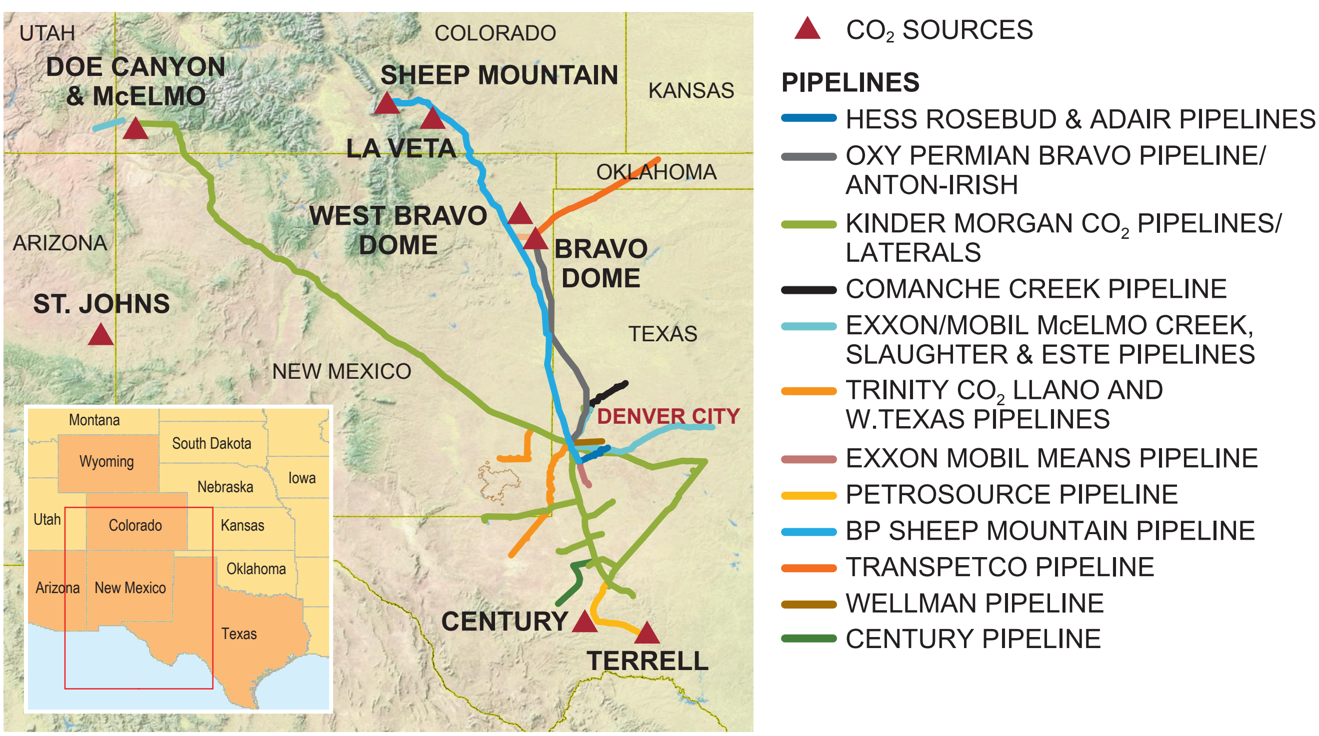
which transport CO_2 from sources to EOR operations (Figure 6-2). These pipelines were primarily developed for CO_2 EOR purposes and it is the most extensive network in the world; elsewhere there is a small number of point-to-point pipelines. Most countries have little or no experience in CO_2 pipeline operation. In contrast, the U.S. pipeline network transports more than 66 million tonnes per annum (Mtpa), which is approximately 3.5 billion standard cubic feet per day (BSCF/D) of CO_2 every year.

The goal of expanding the CO_2 pipeline network to support wide-scale deployment of CCUS in the United States is one that hinges upon creating favorable economic conditions and permitting regulations. This expansion would need to increase by at least an order of magnitude in the next decade to transport the hundreds of thousands of tonnes of captured industrial or combustion source CO_2 needed to support wide-scale deployment.

Several regions in the United States have large CO_2 pipeline networks, including the Permian Basin, the Gulf Coast, and the Rocky Mountain area. The Permian Basin has the most extensive network, and Figure 6-3 shows this pipeline system, owned by Kinder Morgan and Occidental Petroleum. These companies transport nearly 2 BSCF/D (38 Mtpa) of CO_2 to eastern New Mexico, West Texas, and southeastern Utah. The pipelines carry CO_2 to internal and external customers who use it for EOR in mature oil fields.

Kinder Morgan's longest CO_2 pipeline, the Cortez Pipeline, stretches 500 miles from southwestern Colorado to Denver City, Texas, and can transport 1.5 BSCF/D (28 Mtpa). Occidental Petroleum operates the Sheep Mountain and Bravo Dome Pipeline networks, which extend over 500 miles with capacity of nearly 0.7 BSCF/D (13 Mtpa).

Captured CO_2 from industrial sources could be used in the Permian Basin if pipeline infrastructure existed to connect the regions of these industrial sources with the Permian Basin CO_2 network that currently supplies customers. The existing CO_2 pipelines feeding EOR customers in the Permian Basin have transport capacity available and could be expanded. Furthermore, there are several EOR consumers of CO_2



Source: Kinder Morgan and Occidental Petroleum.

Figure 6-3. *Permian Basin CO_2 Pipeline Infrastructure for Kinder Morgan and Occidental Petroleum* in the Permian Basin that have varying demands for additional CO_2 and can facilitate matching industrial sources with other CO_2 consumers, such as existing customers that could use more and are short on CO_2 supply.

C. Alternatives to Pipeline Transport

It is generally understood that pipeline transport offers significant economies of scale for high volumes and flow rates of CO_2, but pipelines are capital intensive investments. In contrast, ship transport is less capital intensive and could be cost competitive for certain situations (i.e., trans-oceanic movements).

Although alternatives to pipeline transport of CO_2 exist—rail, truck, and barge—they are economically viable only over shorter distances and at a small scale. Different transport methods may prove useful in different regions or for smaller-scale point-to-point CO_2 transport solutions.

In the North Sea area, studies have shown that marine transport (by ship) could collect CO_2 from several point sources along a coastline. Large-scale ship transport of CO_2—from 9,800 to 41,000 tonnes—will likely have a lot in common with the shipment of liquefied petroleum gas (LPG). There is already a great deal of expertise in transporting LPG, which has developed into a global industry during the last 70 years.[11]

In Norway, there have been studies about creating a CO_2 transport system based on ship transport concepts. For example, one study assessed CO_2 transport options in Nordic countries.[12] In the Nordic region, most of the stationary CO_2 emissions come from emission-intensive industries such as steel, cement, chemical, and petroleum refining. Because these are relatively small point sources in isolation and they are widely dispersed, ships would be the most cost-effective solution to transport CO_2 for storage in the North Sea.

CO_2 transport systems must consider national or regional conditions. The best approach is to tailor a transport system to a regional market. A tailored approach was used for the Dakota Gasification Company's Great Plains Synfuels Plant, which captures and transports CO_2 to the Cenovus Energy EOR project at Weyburn in Saskatchewan, Canada. When properly designed, a transport system could include a combination of pipeline, rail, truck, ship, and barge transport depending upon the needs of the regional market.

In the United States, other CO_2 transport options are unlikely to replace pipelines for large volumes. However, alternative transport options could complement the necessary pipeline network, supporting transport between CO_2 hubs and clusters depending on the volumes produced (captured) at the sites.

IV. RECENT PIPELINE CONSTRUCTION METRICS

In the past 10 years, the construction of CO_2 pipeline infrastructure in the United States has been limited to establishing point-to-point pipelines that connect an identified source of CO_2 to the corresponding sink(s) where the CO_2 is used for either EOR or industry. Table 6-1 summarizes the features of the known U.S. CO_2 pipelines constructed in the last 10 years and provides the cost per diameter inch mile for pipeline segments, illustrating how widely costs can vary. For example, the Greencore Pipeline is built across private ranchland as well as state and public lands in Wyoming and Montana and cost $68,635 per diameter inch mile. Contrast this with the Webster Pipeline built in a highly concentrated industrial and suburban area just south of Houston, Texas, that cost $199,176 per diameter inch mile. The reason for this broad range in pipeline cost relates to the construction challenges from different types of terrain or conditions (wetlands, flat or mountainous, urbanization) and right of way concerns that restrict access due to pipeline or utility corridors.

V. TRANSPORT OPTIONS AND CO_2 QUALITY SPECIFICATIONS

Table 6-2 recaps CO_2 transport methods covered in this section with typical transport capacities and losses experienced.

11 Global CCS Institute website (2019).

12 Kjärstad, J., Skagestad, R., Eldrup, N. H., and Johnsson. "Ship transport—A low cost and low risk CO_2 transport option in the Nordic countries," *International Journal of Greenhouse Gas Control,* 54, Part 1 (Nov. 2016) 168-184.

Pipeline Name	Green Pipeline	Greencore Pipeline	Seminole Pipeline	Coffeyville Pipeline	Webster Pipeline	Emma Pipeline	TCV Pipeline, LLC
Company	Denbury Gulf Coast Pipelines, LLC (LA) & Denbury Green Pipeline – Texas, LLC (TX)	Greencore Pipeline Company, LLC	Tabula Rasa Energy, LLC	Perdure Petroleum, LLC	Denbury Green Pipeline – Texas, LLC	Tabula Rasa Energy, LLC	Texas Coastal Ventures, LLC
State	LA/TX	WY/MT	TX	KS/OK	TX	TX	TX
Pipeline Constructed (year)	2009/2010	2011/2012	2012	2013	2013	2015	2016
Pipeline Length (miles)	320	232	12.5	67.85	9.1	2	81
Pipeline Diameter (inches)	24	20	6	8	16	6	12
Maximum Operating Pressure (psig)	2,220	2,220	1,825	1,671	2,220	2,319	2,220
Total Pipeline Cost ($/mile)	$3,044,000	$1,372,700	$480,000	$928,500	$3,190,000	$750,000	Not Available
Pipeline Cost ($/diameter inch mile)	$126,823	$68,635	$80,000	$116,062	$199,176	$125,000	Not Available
Notes	Extensive wetlands and marshlands crossed along with Galveston Bay	Right of way on 65% private ranchland with 35% public and state lands		Construction issues with rock on lower section of pipeline; major boring requirements	Entire right of way within suburban high consequence area; more than 60% of pipeline was installed using horizontal directional drilling, which added significant cost to construction		Hilcorp Energy I, L.P. (50%) & Petra Nova LLC (50%); pipeline cost consistent with industry standards for diameter inch mile; primarily rural farm and grazing land; significant portion of line is colocated with other pipelines and utility transmission lines

Source: Individual Companies.

***Table 6-1.** Pipeline Characteristics and Costs*

Method of Transport	Capacity (Tonnes)	Typical Losses
Pipelines	890 to 103,000 Tonnes/Day	Negligible
Shipping	46,000 Tonnes/ Vessel	Not Available
Barge	Not Available	Not Available
Rail	80 to 83 Tonnes/ Railcar	9% to 16%
Truck	18 Tonnes/Tanker	~1%

Table 6-2. *Transport Options*

A. CO_2 Pipelines in the United States

CO_2 has been safely and reliably transported in the United States via large-scale commercial pipelines since 1972, when the Canyon Reef Carriers Pipeline was constructed in West Texas. During the last 50 years, there have been no fatalities associated with the transportation of CO_2 via pipeline. This outstanding safety record can be attributed to the standards that are used to construct, operate, and maintain CO_2 pipelines in the United States. Although CO_2 is not considered a hazardous material by the U.S. Department of Transportation, CO_2 pipelines are regulated because of the operating pressures of these pipelines. These regulations are outlined under Title 49 of the Code of Federal Regulations (CFR), Part 195, Transportation of Hazardous Liquids by Pipeline, which applies to the transportation of hazardous liquids and carbon dioxide.

Under the U.S. Department of Transportation, the Pipeline and Hazardous Materials Administration (PHMSA) is responsible for regulating the movements of all hazardous materials, including pipelines in the United States. PHMSA sets the standards for safe construction and operation of CO_2 pipelines, including technical design specifications and the requirements for mechanical integrity management. States can act as the pipeline regulator if, at a minimum, their regulations comply with federal regulation. The majority of CO_2 pipeline routing, however, is dependent on state law.

To minimize costs, commercial CO_2 pipelines typically operate at pressures between 1,200 pounds per square inch gauge (psig) and 2,200 psig, with some pipelines having a maximum operating pressure of 2,500 psig to 2,800 psig. At these pressures, CO_2 is in a dense phase—either as a liquid or a supercritical fluid—depending on the temperature of the fluid in the pipeline. A dense phase fluid demonstrates properties of both a liquid and a gas. For dense phase CO_2, its density is like a liquid, which results in increased flow capacity for the pipeline. This flow capacity enables use of higher efficiency pumps, instead of compressors, to recover pressure losses in the pipeline due to friction and elevation changes.

Altering a CO_2 stream from a gaseous state in which it is generally obtained from a capture plant to a condition required for pipeline transportation, the gas must be compressed and undergo a phase change—from vapor to supercritical or dense phase. Although its physical and thermal properties are between those of the pure liquid and a gas in the supercritical or dense phase, CO_2 behaves very much like a liquid.

A CO_2 source facility that delivers a gas in a nondense vapor phase must increase the gas pressure from as low as 1 or 2 pounds per square inch (psi) to the supercritical phase of 1,080 psi or higher, which compresses the gas. Most, if not all, CO_2 pipeline systems operate in pressure ranges from 1,080 psi to 2,200 psi. There are three ways to compress CO_2:

1. Use of a nearly adiabatic[13] pathway, such as a single-shaft or multishaft, multistage centrifugal compressor with cooling between the stages (intercooling).
2. Use of a reciprocating compressor where crankshaft-driven pistons compress the gas phase with supercritical compression to the high-density region/area. Once the CO_2 is in the dense phase, it can be pumped through the pipeline.
3. Use of a reciprocating compressor where crankshaft-driven pistons compress the gas phase, equipment to condense/cool to the liquid phase, and pumping to achieve the pressure required.

13 Adiabatic means during the process, heat does not enter or leave the system.

Gas compression is used in the natural gas and process industries. CO_2 compression equipment is similar to the equipment used for natural gas, but the chemical and physical properties of CO_2 require modifications to compressor design, construction materials, and sizing. Factors such as water content and corrosivity, discharge pressures, and inlet volumes may require different combinations of equipment and processes. The equipment can be powered by electricity, natural gas or diesel engines, steam, or a combination of these. Many factors must be considered when choosing which equipment may be the best fit.

The gas compression process can be expensive due to the facilities and operating expenses required. Before determining a unit cost for CO_2, it is important to consider how energy demand and waste heat from the compression process might be integrated with power and the CO_2 capture plant. The final design of a facility involves understanding the stream composition, volume (mass), electricity, heat integration, cooling water or refrigeration, compression, blowers, pumps, and reboiler loading for dehydration of the gas. Each facility has its unique challenges and solutions that will affect the cost per unit. Construction costs for smaller facilities, in the 2,750 tonnes per day range, could be $75 million while larger facilities could be as high as $750 million. In addition to these capital costs, annual operating expenses must also be considered. Life expectancy of a compression facility can be 20 years or more.

The cost of compression impacts the commodity value for the captured CO_2. The CO_2 must be in a dense phase when received by the transport pipeline. As a result, the cost of compression will either be an added expense for the entity that captures the CO_2, or it will create a reduction in the price received from the purchaser if the purchaser is absorbing the expense of the compression cost.

CO_2 pipelines are built using externally coated steel line pipe in accordance with PHMSA regulations. CO_2 composition quality specifications have been established to avoid pipeline corrosion. If liquid water is not present, the CO_2 is not corrosive and will not form corrosive products. Accordingly, CO_2 is dehydrated before introduction into pipelines. Oxygen and hydrogen sulfide concentrations are controlled to remain below the levels that can cause corrosion or stress cracking in the specific grade of steel used in the pipeline. In addition to external coatings, cathodic protection is also used to protect the pipelines from external corrosion.

Critical issues for CO_2 transport include:

- Safety and presence of hazardous substances in the CO_2 stream
- Avoidance of free (liquid) water formation
- Avoidance of hydrate formation
- Avoidance of corrosion or stress cracking
- Reduction of the CO_2 volume (increased density, which increases transport capacity).

The presence of certain impurities in CO_2, such as methane and nitrogen, can lead to reduced pipeline capacity. The presence of impurities shifts the boundary of the two-phase region toward higher operating pressures to keep the CO_2 in the supercritical or dense phase. Furthermore, the impurities can lower the density of CO_2, which also lowers the storage capacity for the CO_2. The type and level of impurities in the CO_2 stream depends on the emission source and the capture process.

Impurities in CO_2 have an impact on pipeline transportation and injection into EOR reservoirs (for incremental oil recovery and incidental trapping of the injected CO_2) and saline geologic formations (specifically for long-term storage of CO_2). The owner and/or operator of Class VI UIC injection wells must analyze the physical and chemical characteristics of the CO_2 stream to be injected for long-term underground storage (i.e., into saline geological formations). The purpose of this review is to confirm that the composition of the CO_2 remains consistent with the permit and the information on which predictions of no adverse interaction between the injectate and well materials or formation fluids were based. Any changes to the CO_2 stream could have implications for well integrity or subsurface geochemical reactions (e.g., reactions that could alter the corrosivity of the injectate or cause mineralization in the reservoir).

Regulated CO_2 used for dedicated, long-term geologic storage could face comingling issues if the pipeline was also transporting food and beverage grade CO_2 for industrial customers or for use in EOR. Therefore, owners of a CO_2 pipeline will have to determine if they can transport a comingled stream without adversely impacting what the CO_2 will be used for.

The impact impurities have on pipeline transportation, EOR, and injection into saline formations include the following:

- *Carbon dioxide (CO_2)* – Lower CO_2 purity causes increased piping diameter or pressure for a given volume of CO_2 to be transported and will require more stringent water specifications.
- *Water (H_2O)* – Can lead to corrosion and hydrate formation in the pipeline.
- *Hydrogen sulfide (H_2S)* – This is a corrosion concern; higher H_2S levels reduce the minimum miscibility pressure (MMP) in EOR and could lead to hydrogen-induced cracking in the pipeline.
- *Nitrogen (N_2)* – Higher N_2 levels require greater pumping/compression and raise the MMP for EOR.
- *Oxygen (O_2)* – The O_2 limits are set according to the technical requirements for storage and EOR; potential downhole problems from higher O_2 levels include microbial and algae growth and corrosion.
- *Temperature* – High temperatures can damage the external pipe coating and affect pipeline integrity; extremely low temperatures may affect the metal used to construct the pipeline.
- *Glycol* – Higher glycol levels can damage pump seals.
- *Delivery pressure* – Maintaining CO_2 in the dense phase for transportation and storage reduces transportation costs.
- *Carbon monoxide (CO)* – If water is present, CO can create acid, which would corrode the pipeline.
- *Incondensable gases* – The presence of incondensable gases increases the pressure, and thus energy requirements for compression to keep CO_2 in dense phase.
- *Methane (CH_4)* – Higher levels require greater pumping/compression, as well as increasing the MMP for EOR.
- *Hydrogen (H_2)* – Higher levels require additional pumping/compression, mitigation for potential fracture issues, and raises MMP for EOR.
- *Argon (Ar)* – Higher energy consumption due to incondensable gas.
- *Sulfur oxides (SOx) and nitrogen oxides (NOx)* – Potentially could form corrosive acids.
- *Mercury (Hg)* – Hazardous waste stream, potential groundwater release issue.

Each pipeline system operating in the Gulf Coast, Permian Basin, and the Rocky Mountain area has defined quality specifications. While the group of impurities or contaminants are common between the systems, the limits for each are slightly different. The following ranges for quality specifications are currently in place across these various systems:

- *CO_2 Purity:* >95% volume
- *Water:* Range of <12 lbs to 45 lbs/MMcf (~250 to 950 parts per million by volume)
- *H_2S:* Range of <10 ppm to 45 ppm by weight
- *Nitrogen:* Range of <0.9% to 4% volume
- *Total Sulfur:* Range of <10 ppm to 35 ppm by weight
- *Oxygen:* <10 ppm by volume
- *Hydrocarbons:* Range of <4% to 5% volume
- *Temperature:* Range of <90°F to 120°F
- *Glycol:* <0.3 gallons/MMcf
- *Delivery Pressure:* Between 1,200 psig and 2,200 psig.

In 2019, more than 3.5 billion cubic feet of CO_2 was transported daily in the United States, equivalent to 66 Mtpa. The majority of CO_2 transported by pipeline is used in the EOR industry and travels in more than one pipeline during the journey from its source to a destination.

1. Is Repurposing Natural Gas Pipelines an Option?

The use of an existing natural gas pipeline is not a practical option for CO_2 transport for large flow rates of 1 BSCF/D (19 Mtpa) or more over long distances of hundreds of miles and more. Existing natural gas pipelines have a maximum pressure rating of 1,480 psig, which are defined by the American National Standards Institute (ANSI) as Class 600 pipelines. A pipeline built for CO_2 service is designed for 2,200 psig, which is an ANSI Class 900 pipeline. There are a few examples of an existing pipeline that was converted to CO_2 service for lower flow rates and/or shorter distances (<100 miles). For longer distances, however, the lower rating of an existing gas pipeline requires many more pump stations along the route compared with a pipeline built for CO_2 service.

Trimeric Corporation developed a simulation model to determine the pumping requirements for transport of CO_2 in a natural gas line that has been repurposed for this operation. Current CO_2 pipeline design guidelines establish the lowest CO_2 pipeline pressure at the pump station suction to be 1,400 psig at 105°F. The analysis showed that it is not possible to meet this guideline on a repurposed natural gas line because the pump stations would be only a few miles apart. The simulation used 1,200 psig (at 95°F) as the minimum suction pressure, because operating below this pressure would create the risk of pump cavitation (formation of bubbles or cavities in the liquid) and vapor lock. This condition could shut down the pipeline, which is a serious concern for the pipeline operator.

The simulation determined that more than 30 pump stations would be required along a 1,000-mile Class 600 pipeline route to move 1 BSCF/D (19 Mtpa) of CO_2 (95% purity) through a 30-inch pipeline with a pressure limit of 1,480 psig. However, this same 30-inch pipeline could potentially transport 200 to 300 MMSCF/D (4 to 6 Mtpa) if the pipeline route was shorter and ground temperatures were cooler. In addition, a favorable elevation profile can counteract friction losses, and the line could be a segment in a network of new lines and pump stations. Thus, there must be a detailed review of project specifics and conditions before determining if repurposing a natural gas pipeline is economically viable compared with constructing an entirely new pipeline.

The simulation also estimated a 20-year life cycle for the pipeline. The life-cycle analysis showed that a repurposed pipeline was, at best, equal in cost to a new pipeline and would more likely cost more than a new pipeline that is designed for CO_2 transport. The likelihood of identifying a viable existing pipeline for a long transport route is low. Even if one was located, the large number of pump stations required would not be operationally practical for a long-distance pipeline.

To answer the question about whether repurposing a natural gas pipeline for use with CO_2 is an option, the answer is that it depends on several factors. If the goal is to transport large volumes of CO_2 100 miles or more, then the lower pressure rating of existing natural gas pipelines makes it impractical to repurpose them for use with CO_2. However, natural gas pipelines could be repurposed if the diameters are large enough and throughput volumes are optimized for a tighter operating range. Each pipeline's potential should be studied based on the project-specific conditions being evaluated and verified that the conversion of the line from natural gas service to CO_2 services complies with PHMSA-Part 195 regulations.

For this reason, it is not anticipated that repurposing existing natural gas pipelines would significantly help develop an expanded CO_2 pipeline network in the United States. There may be some short sections of pipeline, or pipeline laterals, that could use a repurposed natural gas line, but project-specific engineering would be required to evaluate if this would be technically and economically viable.

B. Shipping

Ship transport of CO_2 is currently used only for liquefied food-grade CO_2 in Northern Europe. These ships are small and carry anthropogenic CO_2 captured from hydrogen production units used in industrial processes such as ammonia production. They carry the anthropogenic CO_2 to ports to be offloaded and delivered to the end user via truck transport.

Ships that carry CO_2 are similar in design to the ships currently used to transport LPG. LPG ships are designed to carry gases that are in a liquid or liquid-like dense phase state. The design is a low-temperature, medium-pressure vessel at 250 psig and -40°F. The average-sized LPG tanker could carry approximately 45,000 tonnes of CO_2. Each LPG ship costs about $200 million to build.

Ship transport is more economical if large bodies of water need to be crossed. Thus, ship transport from the East or West Coast of the United States to the U.S. Gulf Coast would likely be more economical than constructing new long-distance pipelines or repurposing gas pipelines where such ships are currently in service. Shipping CO_2 for EOR operations from industrialized countries, such as the United States or European countries, to less industrialized, oil-producing countries could provide climate and economic benefits.

Another economic benefit could come from transporting CO_2 to the United States from Europe or Asia on U.S. LPG tankers, for purposes of CO_2 EOR or paid geologic storage. Owners of the tankers would then be able to transport a commercial product in both directions, which should lower the shipping cost for both products.

The siting of a CO_2 shipping/receiving terminal must be carefully planned due to public safety concerns—exposure to CO_2 can cause asphyxiation. This requires modeling to determine the potential radius of exposure from the site to the surrounding public if the CO_2 were to escape containment.

C. Barge

Currently, there is no barge transport of CO_2 in the United States. However, the design of CO_2 barges would be like those used for LPG, requiring low temperature and medium pressure.

In locations where pipelines are uneconomic or impractical, and rivers or intracoastal waterways provide proximal access to EOR or geologic storage sites, transport of CO_2 via barge might be an economic option.

And, as already mentioned, the siting of a CO_2 shipping/receiving terminal must be carefully planned due to public safety concerns.

D. Rail

In 2017, U.S. and Canadian railroads safely transported more than 10,000 shipments of refrigerated CO_2 liquid, totaling more than 713,000 tonnes. Because the liquid-to-gas expansion ratio of CO_2 is 1:535,[14] it is more economical to transport CO_2 as a liquid—except in pipeline applications where high-density transport is achieved in the dense phase. Typical volumes lost during transit by rail car range from 9% to 16%, depending on the transit days and ambient temperature conditions.

The U.S. Department of Transportation (DOT) and Transport Canada authorize how refrigerated CO_2 liquid may be transported in Specification 105 tank cars. These cars have a capacity of 22,000 gallons (~83 tonnes) and a maximum gross weight of 286,000 pounds (130 tonnes). The current build price of a carbon dioxide tank car is approximately $170,000.

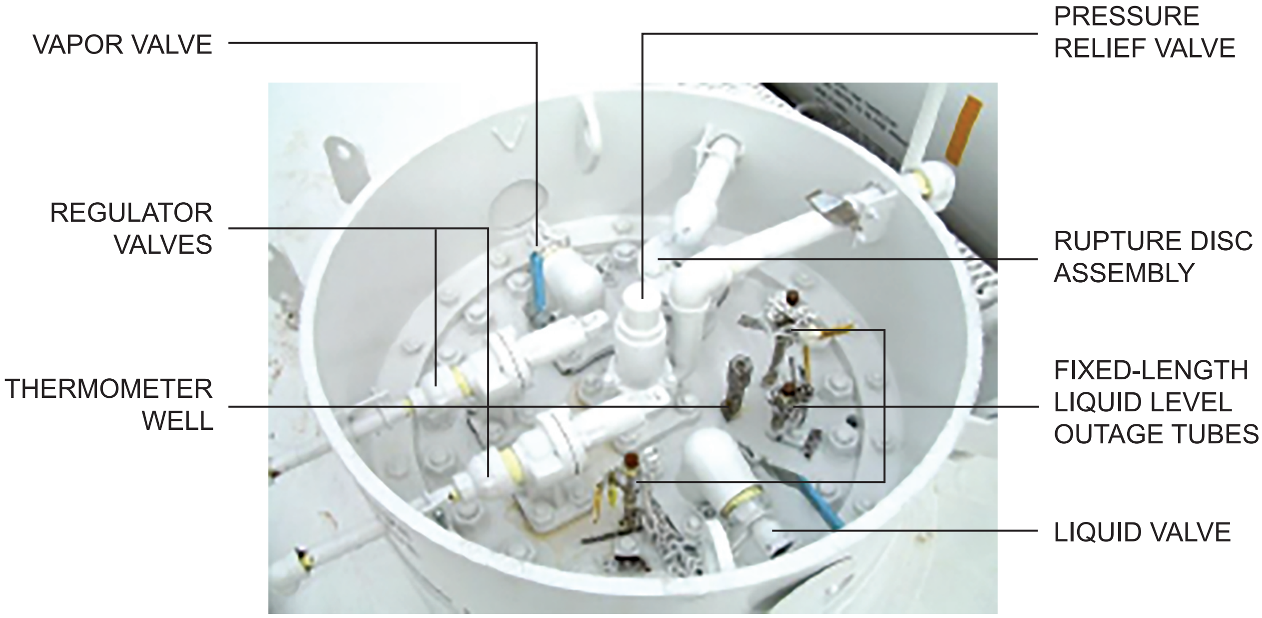
Tank cars transporting carbon dioxide are equipped with three types of pressure relief devices (shown in Figure 6-4):

1. A reclosing pressure relief valve set for no more than 75% of the tank test pressure
2. A nonreclosing safety vent designed to burst at a pressure less than the tank test pressure
3. Two regulating valves set to open at a pressure not to exceed 350 psig on a 500 psig test pressure tank or 400 psig on a 600 psig test pressure tank.

Tank cars transporting CO_2 and NO_2 have the words "REGULATING VALVES VENTING NORMAL" stenciled on each side of the car. The venting of vapor from the regular valve is a normal function to reduce internal pressure through auto-refrigeration.

CO_2 tank cars are loaded at a pressure between 200 psig and 215 psig, and the CO_2 is a temperature of -16°F to -20°F. Tank cars have 5 inches of urethane foam insulation, which provides approximately 8 to 10 days of transport time before the CO_2 warms up. If pressure builds in a 500 psig

14 An expansion ratio of 1:535 means 1 cubic foot of liquid CO_2 produces 535 cubic feet of CO_2 gas.



Source: Association of American Railroads, *Field Guide to Tank Cars*, 3rd edition, 2017.

Figure 6-4. *Pressure Relief Devices on Rail Tank Car*

test pressure tank, the first regulator valve vents at 340 psi. The second regulating valve will vent at 350 psi. If pressure continues to increase, the safety relief valve will open at 375 psi. If the CO_2 temperature continues to increase, the rupture disk will open at 486 psi. If a rupture disc fails and the pressure falls below 60 psig, the CO_2 liquid turns into dry ice.[15]

Recent study has investigated the potential for use of the "DOT113" tank car to transport CO_2. The DOT113, currently used for transport of Argon, would allow CO_2 to be transported without releasing product through regulating valves. Study is ongoing.

E. Truck

Truck transport of CO_2 in the United States is primarily for the beverage industry, traveling short distances to supply local markets. Each truck delivers approximately 18 tonnes of CO_2. Customers are less willing to pay for CO_2 liquid delivered by truck if the sourcing radius exceeds 150 miles, which increases the cost.

Truck transport loses a negligible amount of CO_2 (~1%), most of which occurs during the pressurization and depressurization of the trailer or storage tank while loading and unloading the CO_2. However, ambient temperature conditions can have an impact on total losses.

The design of this equipment is like the equipment used on LPG ships to maintain a low temperature and medium pressure. Truck transport of CO_2 is a good option for CCUS technology development during its project pilot stages because it requires little capital for sourcing the supply of the CO_2.

F. Intermodal Consideration

The conditions in which liquid CO_2 should be shipped via train, truck, or barge may be different from the current conditions in which liquid CO_2 is shipped. A range of temperatures and pressures for liquid CO_2 transport enables the initial compression and chilling to be optimized for injection into a pipeline that operates at the higher pressures and temperature required so the CO_2 remains in its dense phase. Table 6-3 presents the temperature and pressure ranges of interest. Liquid CO_2 transport might be cost effective given the cost of compressing and heating the CO_2 at pipeline intersections.

15 Association of American Railroads, *Field Guide to Tank Cars,* 3rd edition, 2017.

Temp °F	Pressure lb/sq. in.	Volume (liquid) cu. ft./lb.
-60	95	0.0138
-40	146	0.0144
-20	215	0.0150
0	305	0.0157
10	360	0.0161
20	422	0.0166
30	491	0.0172
40	568	0.0179
60	749	0.0197
88	1,073	0.0342*

* Critical point for CO_2.

Source: *Perry's Chemical Engineers' Handbook*, 5th edition, 1973.

Table 6-3. *Physical Characteristics of Saturated Carbon*

VI. ENABLING WIDESPREAD DEPLOYMENT OF CCUS

A. The Need for Planned Expansion

Although the United States currently has the world's most extensive CO_2 pipeline network, more infrastructure is needed to support widespread deployment of CCUS in the United States. The magnitude of expansion required is defined by the future need to transport CO_2 from existing and new emission sources to EOR operations and geologic storage sites.

A few analyses have modeled extension of the U.S. CO_2 pipeline network to achieve CO_2 stabilization in the atmosphere, noted in parts per million (ppm), at different levels. One analysis modeled growth of the U.S. pipeline network under both 450 ppm and 550 ppm stabilization scenarios.[16] The less stringent 550 ppm stabilization scenario estimated that 11,000 miles of CO_2 pipeline must be added between 2010 and 2050 to the CO_2 pipeline system existing in 2009.[17] This scenario also estimated that in the near term, through 2030, the growth in CO_2 pipeline infrastructure that would be required across the United States equates to approximately doubling the CO_2 pipeline system that existed in 2009.[18]

In a more recent analysis by DOE in 2015, it was projected that the scale of U.S. CO_2 pipeline infrastructure would need to triple by 2030 to enable the delivery of carbon captured by the U.S. power sector to oil fields for CO_2 EOR and, to a lesser extent, for geologic storage in underground saline formations.[19] The report also notes that while this scenario would involve an unprecedented scale-up of CO_2 pipeline infrastructure, the pace would be comparable to what has been projected for pipeline construction in other sectors (in which many of the same companies operate).

These modeling approaches were based on climate-driven policy, but different drivers could be used to model the growth in scale of both CO_2 capture and injection, hence providing other means of quantifying the required infrastructure.

Regardless of the rationale for building and expanding existing networks, it appears that rather than constructing a multitude of new point-to-point pipelines, a more considered and strategic approach consisting of key trunk lines and connector pipelines would be economically advantageous for scaling CCUS deployment. Large-scale deployment of CCUS will require a marked increase in commitment by both government and industry to plan and build a CCUS system, of which a functioning transportation infrastructure is a critically important part. Although developing infrastructure will be done by industry in most cases, government commitment and leadership is particularly important in this regard.

16 Dooley, J. J., Dahowski, R. T., and Davidson, C. L. "Comparing Existing Pipeline Networks with the Potential Scale of Future U.S. CO_2 Pipeline Networks." *Energy Procedia,* 1, Issue 1, February 2009, 1,595-1,602.

17 Wigley, T. M. L., Richels, R., and Edmonds, J. A. "Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations." *Nature*, 379, 240-243 (1996).

18 Dooley et al., February 2009.

19 U.S. Department of Energy, National Energy Technology Laboratory. (2015). *A Review of the CO_2 Pipeline Infrastructure in the U.S.,* DOE/NETL-2014/1681.

There is currently some interest in Congress in providing financial support for construction of CO_2 transportation infrastructure, e.g. HR 4905, "Investing in Energy systems for the Transport of CO_2 Act of 2019." As this bill was just recently introduced in Congress, neither the NPC nor the CCUS study team have analyzed the details of the proposed legislation; however, it is encouraging that there appears to be growing interest in supporting CO_2 infrastructure.

A strategic, planned approach will not only help the build-out of pipeline and other transport infrastructure, but will also facilitate the building of CO_2 capture projects in the future. In addition, project proponents—many of whom may not have knowledge nor interest in entering the pipeline business—may be able to tap into trunk lines with minor investment.

VII. CONCLUSIONS

The transport of CO_2 involves well understood technologies and has been done safely at scale for more than 40 years. CO_2 can be transported via pipeline, rail, truck, ship, and barge. In the United States, the primary mode of large-scale CO_2 transport is via pipeline, and there is a network of more than 5,000 miles of CO_2 pipelines operating today. Conclusions of this chapter include the following:

- Wide-scale deployment of CCUS in the United States will require a significant expansion of existing CO_2 pipeline infrastructure.
- Streamlined permitting would facilitate building strategic CO_2 trunk lines in key industrial and oil and gas regions of the country and could best be accomplished on a consultative basis between federal and state governments.
- Federal and state eminent domain authority for pipeline projects would facilitate faster development of infrastructure.
- U.S. industry already has extensive experience constructing and operating large-capacity CO_2 pipelines.
- PHMSA sets the standards for safe construction, operation, and technical design specifications and requirements for mechanical integrity management of CO_2 pipelines.
- Rail and truck transport of CO_2 can be solutions for shorter distances and more point-to-point options.
- The right government incentives (term/value of tax credits) will reduce risk for economic recovery of the development capital required for pipeline construction and operation.

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