Carbon Capture, Utilization, and Storage: Carbon Dioxide Transport Costs and Network-Infrastructure Considerations for a Net-Zero United States

ENVIRONMENT AND NATURAL RESOURCES PROGRAM &
SCIENCE TECHNOLOGY AND PUBLIC POLICY PROGRAM

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Clara Galeazzi
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HARVARD Kennedy School
BELFER CENTER

50 YEARS OF RESEARCH, POLICY, AND LEADERSHIP

PAPER
JULY 2023

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Some of about 500 miles worth of coated steel pipe manufactured by Welspun Pipes, Inc., originally for the Keystone oil pipeline, is stored in Little Rock, Ark., Thursday, May 24, 2012. (AP Photo/Danny Johnston)

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Executive Summary

Carbon capture, utilization, and sequestration (CCUS) is a set of technologies that capture carbon dioxide (CO_2) at point source and either store the CO_2 for permanent storage underground or utilize it in the economy such that carbon will not be released back into the atmosphere. Most national and international models indicate that CCUS will be needed, along with a range of other technologies, to economically reach net-zero emissions by 2050 in the United States. The scale of CO_2 capture via CCUS required to achieve net-zero in the United States is 0.9-1.7 gigatons of CO_2 per year by 2050 in most pathways, according to estimates by Princeton University's Net-Zero America Project.

This brief examines the national challenges related to deploying and scaling infrastructure to transport CO_2 from capture sites to storage or utilization sites at a scale consistent with achieving net-zero by 2050.

Pipelines will likely continue to be the predominant CO_2 transport mode in the future in the United States. Other modes of transport, such as shipping and trucking, are only economical under specific circumstances and are not as attractive as pipelines for the bulk of CO_2 transport needs under large-scale CCUS deployment.

To reach net-zero by 2050, the CO_2 pipeline network in the United States needs to expand far beyond its current five thousand miles and must evolve from the existing model where pipelines are built mostly to serve individual projects to a network model where projects share infrastructure and thereby exploit economies of scale.

A variety of current models appraise potential CO_2 pipeline networks at local, regional, and national levels. Like other types of models, these CO_2 pipeline models are not prescriptive. Instead, they provide illustrative exercises intended to help analysts and stakeholders understand the physical scale and cost implications of the CO_2 transport infrastructure required for net-zero, given current technology and assumptions on future technology advancement.

Here we compare the assumptions, methodologies, and cost estimates from two different CO_2 pipeline models, developed by the Great Plains Institute and the Net-Zero America Project at Princeton University, which fit the time and geographical boundaries of our research question. We also briefly discuss additional studies that focus on near-term potential for localized networks.

Based on the literature and interviews with policymakers, academics, and business executives, we propose the following policy priorities to support the development of CO_2 pipeline transport:

1. Expanding targeted incentives that address the economic viability of pipeline development, building on the momentum of the expanded 45Q tax credits in the Inflation Reduction Act of 2022.
2. Deepening community engagement to address public sentiment around CO_2 pipelines.
3. Increasing federal-state and state-state collaborations on pipeline expansion planning.
4. Streamlining permitting processes across federal and state lands.

1. Introduction

Net-zero pathway models indicate that carbon capture, utilization, and storage (CCUS) is likely to be an essential technology to help the United States achieve net-zero greenhouse gas emissions by 2050.[1] CCUS in the form of carbon capture from point sources followed by geologic sequestration or productive use could play a critical role in decarbonizing both the industrial and power sectors.[2]

In the industrial sector, high-temperature heating processes are expensive to electrify, and direct carbon emissions from the sector make up about 25 percent of the U.S. total. [3] Non-energy processes in cement manufacturing also emit CO_2.[4] In the power sector, fossil-fueled generation cannot be eliminated overnight, and a modest amount of such generation may persist even in the long term to ensure system flexibility in the presence of large contributions from intermittent renewable sources.

Overall, the literature indicates that CCUS can: (1) provide short- and long-term flexibility to the power system; (2) facilitate low-carbon hydrogen production from natural gas; (3) contribute to the use of captured CO_2 to manufacture goods or aid in industrial processes; and, possibly, (4) deliver net-negative emissions when combined with electricity generation from biofuels (BECCS).[5, 6]

As a result, most pathway models incorporate CCUS as a contribution to U.S. achievement of net-zero greenhouse gas emissions by 2050.[7,8] Total carbon storage potential in the country has been estimated to be between 2.6 to 22 trillion metric tons of CO_2,[9] with the "medium" scenario (i.e., at least a 50 percent probability) estimates being 8.3 trillion tons. This can be compared with annual U.S. CO_2 emissions from energy supply in the transportation, commercial, residential, and industrial sectors of 4.9 billion tons of CO_2 in 2021.[10]

Evidently, a clear understanding of the cost structure of CCUS projects and systems under current and realizable future conditions is critical to understanding the likelihood that CCUS can meet the ambitious goals that many have foreseen for it over the next few decades. With this aim, the Belfer Center has been developing a series of briefs addressing the options and current and future costs relating to the components of CCUS systems, seeking in the process to identify the sources of the wide variation in cost estimates found in the current literature.

The first installment of this effort reviewed estimated costs for carbon capture technologies intended for use in different U.S. industries.[11] Costs of CO_2 transport to sites where it will be sequestered or utilized will likewise be important influences on CCUS deployment, as will the costs of sequestration itself and the net costs of utilization alternatives. In this brief, we turn our focus to transport. Future briefs will address sequestration and utilization costs.

Recent years saw multiple public and private U.S. initiatives aimed at advancing CCUS implementation. The main financial incentive supporting deployment of CCUS plants in the United States to date is the Tax Credit for Carbon Dioxide Sequestration (or Internal Revenue Code Section 45Q), originally enacted as part of the Energy Improvement and Extension Act in 2008 and extended as part of the Bipartisan Budget Act of 2018.

Since the first installment in this Belfer Center series on CCUS was published in January 2022,[12] policy has developed considerably. The most significant initiative is embedded in the Inflation Reduction Act of 2022 (the IRA), which was signed into law in August 2022. The IRA includes approximately $369 billion in incentives for clean energy and climate-related programs. Specifically, the IRA increases CCUS tax credits drastically, lowers the criteria for CCUS project eligibility, and allows for easier transfer or direct payment of the credits (see Appendix 1 for more details).[13] Other relevant public initiatives include the bipartisan Infrastructure Investment and Jobs Act (IIJA)[14] and the Justice 40 Initiative.[15]

In the sections that follow here, we examine the various transport options, compare existing modelling efforts to estimate pipeline system costs, and address the policy issues associated with scaling CO_2 transportation infrastructure for net-zero U.S. goals.

2. An Overview of Options for CO_2 Transport

Because suitable sites for either utilization or permanent sequestration rarely match directly with the sites of CO_2 capture,[16] most CCUS projects require some CO_2 transportation infrastructure.[17]

The main transport options for CO_2 are: (1) onshore and offshore pipelines; (2) trucking; (3) railways; and (4) shipping. Understanding the costs, trade-offs, and ideal applications of the possible CO_2 transport options is essential to the design of any CCUS project and to assessing the overall requirements for CCUS deployment at scale.

To better compare and discuss the available transport options, we reviewed key literatures and developed appropriate metrics for the four major CO_2 transport modes. Table 2.1, located at the end of this section, summarizes the technical and financial considerations for four CO_2 transport modes and offers conclusions about the approximate cost ranges and ideal applications for each.

The first three columns of Table 1 address technical characteristics and show why CO_2 transport technologies are not interchangeable in each application. The suitability of each transport option depends on specific project characteristics. One important factor is the differing compression requirements when CO_2 is transported via pipeline, shipping, or trucking. There are also considerations around the influence of terrain and existing infrastructure on the different methods. Note that while CO_2 capture costs depend heavily on the CO_2 concentration of the source, the costs for transport are largely independent of the source of the emissions.[18]

The fourth column in Table 1 shows the technological and market maturity of each transport mode, and the fifth and sixth columns address the current cost estimates for each. The seventh column identifies the ideal application for each transport option.

Table 1 concludes that pipelines are ideal for large-scale deployment, as they are more cost-effective than other transport modes at high volumes. The estimated scale of CCUS required to achieve net-zero carbon emissions in the United States by mid-century (reaching 0.9 to 1.7 gigatons of CO_2 per year by 2050 in most pathway studies)[19] motivates the "clear consensus that CO_2 pipelines are critical to the future deployment of CCUS nationwide," per the White House Council on Environmental Quality (CEQ).[20]

According to the U.S. Department of Transportation, CO_2 pipelines only constituted about 2 percent (around 5,000 miles) of total non-gas pipelines in 2021 and caried about 66 million tons per annum (Mtpa) of CO_2.[21,22] (See Appendix 2 for a map with U.S. CO_2 pipelines up until 2018.) In comparison, gas pipelines totaled about 2.6 million miles. Most of the existing CO_2 pipelines are currently used for enhanced oil recovery (EOR) and have been commissioned since the 1970s. CO_2 pipeline transport is "similar to transporting fuels such as natural gas and oil."[23] The relatively low CO_2 pipeline mileage is more a function of the underdevelopment of CCUS overall than the technological readiness of CO_2 pipelines themselves.[24,25]

Trucking and railway are cost-effective for small-scale CCUS projects, in large part because they require less pressurization than pipelines (a costly step). A likely outcome could be a combination of multiple transport modes, first via feeder pipeline, trucking, or railway before aggregation into trunk pipelines toward the final sequestration location. The potentially prohibitive compression costs for pipelines can also be mitigated by combining volume from multiple sources in a common compression facility, a point that we discuss further below. Admittedly, comparing transportation cost estimates across studies is difficult. First, assumptions on project characteristics used in different models vary, and definitions do not always align. For example, some studies bundle compression and transport cost, while others model them separately. Second, project costs rarely scale linearly, given economies of scale—a reality that results in wider cost spreads across studies. Third, costs differ across sites and regions for a variety of reasons. Given these limitations, in addition to the scarcity of publicly available information, Table 1 might not fully reflect all variations, and actual project costs might fall outside the ranges.

The next section delves into pipeline cost composition, explores key technical factors to maximize economies of scale, and illustrates the importance of considering CCUS infrastructure networks on the systems level.

Table 1. Technical and financial requirements of CO_2 transport technologies

	TECHNICAL CHARACTERISTIC		COST CONSIDERATIONS AND MARKET MATURITY			APPLICATION
Transport method	**CO_2 state**	**Other technical considerations**	**Relative market maturity & technical readiness level (TRL)***	**Key variables affecting cost estimates**	**Approximate current cost range (2019 US$)**	**Ideal usage**
Pipeline (onshore/ offshore)	Dehydrated and compressed to dense-phase (liquid) state (9-15 MPa, 10-35°C)	•Pipeline design is critical to realize economies of scale -Trunk pipelines (multiple sources) vs. feeder pipelines (single source) -Integrated network design to aggregate sources and lower costs by increasing flow •On/offshore depending on location of capture, utilization, and sequestration sites as well as the terrain between them (e.g., presence of mountains, nature reserves, rivers, and freeways)	**HIGH** •Over 5,000 miles of CO_2 pipelines have been built in the United States, primarily for EOR[26] •Highly mature pipeline planning and construction technology *TRL: 8-9, given existing experience of building and using CO_2 pipelines*[27]	•Distance (+) •Relationship between pipeline diameter (+) and CO_2 flow (-), •Terrain (e.g., offshore pipelines tend to be more expensive due to specialized equipment for the ocean floor)[28] •Legal and regulatory costs (e.g., siting, permitting, public engagement)	US$4-45/t$CO_2$[29] •Cost range captures variability in transport distance, scale, extra monitoring assumptions, geologic characteristics, and other determinants of pipeline construction costs	Large-scale transport if CCUS is deployed at scale (to fully leverage economies of scale)
Shipping (port-to-port / port-to-offshore)	Refrigerated to liquid state and compressed (0.7 MPa [7 bar], -50°C)	•Additional supporting facilities needed (e.g., for power, temporary storage for liquefied CO_2, cargo handling facilities, etc.)[30] •Port-to-port transport has demonstrated technology readiness, while port-to-offshore transport is still in large-prototype phase[31]	**LOW** •Large-scale CO_2 shipping has not yet been demonstrated •Small quantities (capacities between 800-1000m3) in the food and beverage industry[32] *TRL: 3-9, depending on injection modes (lowest for offshore injection from a ship, highest for transporting CO_2 between onshore sites)*	•Distance (+) •Loading/unloading CO_2 flow rate (-) •Tanker utilization (-) •Fuel cost (+) •Harbor fee (+) •Ship lifetime (-) •Ship size (-), since increasing size reduces the number of ships needed and the number of trips Limited economies of scale due to fixed tanker capacities (current CO_2 ships typically have a capacity of 1,060-1,800 tons of CO_2)	US$35-64/t$CO_2$ •Based only on the Northern Lights project in Norway because of limited published estimates of shipping costs[33]	Long-distance transport (>1,000 km, equivalent to around 620 miles)[34] with shorter project duration (due to lower initial outlay)[35]
Trucking (with tanker trucks)	Refrigerated to liquid state and compressed (1.7-2.6 MPa, -30°C)[36]	•Limited capacity of 2-30 tons per vehicle	**MEDIUM** •Commercialization for short-distance/ low-volume CCUS operations *TRL: 8-9, given widespread application for short-distance CO_2 transport*	•Distance (+) •Loading/unloading CO_2 flow rate (-) •Tanker utilization (-) •Truck/tanker size (-) •Fuel cost (+) Limited economies of scale due to fixed tanker capacities	US$50-70/t$CO_2$[37]	Smaller-scale CCUS operations when volume is too low for cost-effective pressurization, or for point-to-point solutions Decision between the two would likely be based on actual project constraints. Rail is in general less expensive at longer distances (≥40 km, equivalent to around 25 miles)
Railway (with tank cars)		•Rail access is limited; costly to build new rail spurs (small branches) •Need staging and loading facilities at origin/ destination	**LOW** •Some commercial application (e.g., Green Cargo in Sweden) but limited *TRL: 7-9, technology is ready but has not been deployed in large scale yet*	•Distance (+) •Loading/unloading CO_2 flow rate (-) •Tanker utilization (-) •Tanker size (-) •Fuel cost (+) Limited economies of scale due to fixed tanker capacities	US$24-36/t$CO_2$[38], not including capital costs of new rail spurs required	

Notes: *Technical Readiness Levels (TRL) rank a technology's maturity on a scale from 1 (basic principles observed) to 9 (full commercialization). Originally used by NASA and the Department of Defense, the TRL framework has since been tailored for the Department of Energy Program Offices to assess energy-related projects. See more here: https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04-admchg1 04-admchg1

3. Key Determinants of CO_2 Pipeline Costs and System Costs Estimated by Infrastructure-Network Planning

In this section, we first highlight the interdependency among the determinants of CO_2 pipeline costs Then, because economies of scale dictate considering the costs of CO_2 transport infrastructure in networks as opposed to pipelines for individual projects, we compare the cost projections of two existing regional and national modeling efforts for pipeline transport infrastructure networks in the United States.

3.1 Key Determinants of CO_2 Pipeline Costs

The relevant costs for CO_2 transport include the costs of transport between the capture facility and the storage or utilization location, as well as the costs of compressing the gas for transport and for storage, as shown in Eq.1:

Costs of CO_2 pipeline transport = Pipeline costs (capital & operating) + Compression costs (capital & operating)[39]

Just as with oil and gas pipelines, several factors contribute to CO_2 pipeline capital (Capex) and operating (Opex) costs, including distance, capacity, and terrain.[40] The Department of Energy's National Energy Technology Laboratory (NETL) has developed a techno-economic model that is helpful for calculating capital and operating costs of transporting CO_2 by pipeline. Table 3.1 summarizes the key inputs to the engineering part of the NETL model. Additional financial assumptions, such as the weighted cost of capital (WACC) are required to calculate the costs (at NPV) of the pipeline projects.[41]

Table 2. Key engineering factors that affect pipeline and compression costs

KEY FACTORS CONTRIBUTING TO COST		
Pipeline cost	Capital cost	• Distance (in miles or kilometers) • Flow rate and capacity (Mtpa), which determines the pipe size (in diameter) required • Terrain constraints (e.g., elevation change) • Onshore vs. offshore • Right of way access • Additional pipeline-related costs (e.g., CO_2 surge tank, pipeline control system)
	Operating cost	• Leak and pressure monitoring and maintenance
Compression cost	Capital cost	• Number of booster pumps • Pump efficiency
	Operating cost	• Electricity needed to operate the pumps

Source: Morgan, David, Guinan, Allison, and Sheriff, Alana, 2022, "FECM/NETL CO_2 Transport Cost Model (2022): Description and User's Manual," United States, https://doi.org/10.2172/1856355.

Compression costs are non-negligible. CO_2 is usually captured at close to ambient pressure (around 1 bar), transported in gas phase or dense-liquid phase, and stored in the supercritical state (around 73.8 bar and at a temperature of over 31.1 degrees Celsius).[42] While compression costs are often represented by "one-stage" compression at the source before transport and storage, two-stage CO_2 compression may be cheaper when there are multiple capture facilities. In two-stage compression, CO_2 is compressed to a certain pressure near the capture site and transported to a shared facility for further compression before transport to a sequestration site.[43] Appendix 3 provides details of how pipeline capacity, length, the phase in which CO_2 is transported, and compression details interact to determine total transport cost.

Examining CO_2 transport infrastructure through a network lens – instead of focusing on individual projects – illuminates scenarios in which infrastructure develops organically to take advantage of economies of scale and costs are shared among neighboring facilities. Such a "systems" perspective is crucial to correctly assessing the overall cost of CCUS deployment at scale.[44,45,46,47]

Business models are still evolving and might materialize in different forms. Current federal incentives, namely the Infrastructure Investment and Jobs Act passed in November 2021 (detailed further in Section 4), encourage the development of pipelines by publicly and privately owned "common carriers," which can provide transport (and potentially storage) as a service for a fee.[48]

For example, Summit Climate Solutions, a subsidiary of Summit Agricultural Group, a diversified agribusiness operator and investment manager with operations in the United States and Brazil, aims to "[connect] industrial emitters via strategic infrastructure" to store CO_2. The company is developing a $2 billion USD pipeline project that will carry and capture CO_2 from biorefineries, power plants, and fertilizer producers through Iowa, Nebraska, Minnesota, and the Dakotas, aiming eventually to transport and store 10 million tons of CO_2 annually.[49]

In Section 4 on Policy Recommendations, we discuss further the financial challenges and current federal incentives for investment in CO_2 pipelines.

3.2 CO_2 Infrastructure-Network Models and Estimated Capital Costs

One line of CO_2 transport studies focuses on models around potential local, near-term, and low-cost CCUS hubs. These include, for instance, CO_2 captured in biorefineries in the Midwest and transported for EOR to the Permian Basin in Texas,[50] as well as CO_2 captured at localized emitters in the Los Angeles and the San Francisco Bay areas for sequestration in California.[51]

Such studies highlight the benefits of economies of scale in CO_2 pipeline transport where emitters share transport infrastructure. Additionally, they highlight the potential long-term benefits of building localized hubs today. Constructing and operating localized hubs can lead to technological advances that make CCUS projects increasingly economical, including bringing down costs for low-concentration emitters such as coal-fired power plants (as opposed to high-concentration emitters such as ammonia and ethanol production) in the longer term.[52]

Given that our focus here is regional/national, multi-industry, and longer-term, we have centered our analysis on two of the most comprehensive regional/national models—by the Great Plains Institute (GPI) and Princeton's Net-Zero America

(NZA)—based on the localized-hub approach. While the models were published before the passage of the Inflation Reduction Act in 2022, which changed the economics of specific projects, comparing the models and their scenarios provides valuable insights related to the development of CO_2 transport projects and their networks.

Among other metrics, these studies include estimates for the mileage of CO_2 pipelines and the associated capital investments out to 2050 in the regions they cover—21 Midwest and Gulf states in the GPI study, the entire continental United States in the NZA case. In developing these estimates, the studies consider a range of CCUS scenarios, building upon existing infrastructure and the geographies of capture and storage sites.[53]

The GPI model determines the most efficient regional pipeline network connecting existing facilities that qualify for the 45Q tax credits for sequestration or utilization (the latter currently limited to EOR in practice) in the study region, as well as two alternative scenarios.[54] The NZA model instead examines five distinct technological pathways to achieve the 2050 net-zero goals for the nation, assuming energy spending in line with historical average of 4-6 percent of gross domestic product (GDP).[55] As part of that effort, the NZA model calculates the volume of CO_2 requiring permanent sequestration and estimates the pipeline costs required to transport it. They assume that utilized CO_2 either does not require transportation or can be accommodated within the mileage they estimate that is needed to sequester CO_2.

A comparison of the results of different scenarios within the GPI model reinforces how economies of scale can reduce the costs CO_2 pipeline transport, as discussed in previous sections. In GPI's "Mid-century" scenario, 669 million tons of CO_2 produced by 947 facilities are captured and stored annually, but its capital investment cost of $19.3 billion USD is only 16 percent higher than the "Near/Medium term scenario," which with a capital investment cost of $16.6 billion USD captures and stores only 281 million tons of CO_2 produced by 381 facilities. GPI's work also shows that there is some immediate potential for CCUS projects under current market conditions and the 45Q incentives that prevailed at the time of the study. Additionally, the GPI results underscore the importance of adequate financing for near-term deployment of CO_2 pipelines, which would ultimately facilitate CCUS deployment overall.

As a result of the differences in their geographic scope and approach, NZA's estimates of total annual U.S. CO_2 stored in 2050 are 1.5 to 2 times higher than those of GPI, depending on the scenario. Appendix 4 offers a detailed comparison of the scope, modeling approach, and scenarios on which the two models are based. While the scopes and assumptions of the GPI and NZA studies are different, both demonstrate how modelling efforts can help stakeholders better understand the magnitude of the capital investment required to build a suitable CO_2 pipeline network.

Cumulative capital cost estimates in the two models range from $19.3 million to $225 million 2018 USD in 2050, with GPI on the lower end and NZA on the higher end. The spread is partly due to the differences in geographic scope and amount of CO_2 captured in the two models, which ranges from about 700 to 1400 million tons of CO_2 in GPI and NZA for the scenarios that we compare, respectively.

Even so, unit costs (cost of CO_2 transport per mile) are about 4-5 times higher in NZA compared to GPI. They range from a low of $65 million 2018 USD per hundred miles of pipeline in GPI to a high of $325 million 2018 USD per hundred miles of pipeline in NZA.

NZA's unit-cost estimates are higher for several reasons. As opposed to GPI's analysis, which calculates the optimal pipeline network between existing plants under CCUS incentives at the time of study and two alternative scenarios in 21 states, NZA's proposed network is mapped to be flexible enough to support infrastructure needs for CO_2 transport in all except one of its six net-zero scenarios in the United States. The NZA model also accounts for the retirement of several existing facilities by 2050 and an over-investment in the pipelines connected to various storage basins to allow for uncertainty of suitability and capacity of individual basins.[56]

NZA builds these features into the model to help overcome the "chicken-and-egg" problem between investment in capture/storage and pipeline infrastructure. This challenge resides in the fact that owners of emitting facilities are reluctant to invest in capture without the guarantee of transport infrastructure at a suitable cost, while investors in transport and storage are simultaneously unlikely to commit without the assurance of sufficient supplies of CO_2. Partly as a hedge against uncertainty arising from this problem, NZA does not always optimize for distance between capture and storage sites to minimize costs.[57]

A lack of detailed information provided by the two studies precludes us from making further definitive conclusions on the potential sources of discrepancy in their unit cost estimates. One additional hypothesis is that the discrepancy comes from the different assumptions about pipeline sizes. Most pipelines modeled in GPI's scenarios are 6 to 12 inches in diameter, but NZA models most pipelines to be up to 48 inches. As illustrated in Table 2, this assumption changes the capital cost structure and may directly contribute to the discrepancies in the unit costs.

Appendix 4 provides more detail on the results of the GPI and NZA models and compares the results of the two models in greater detail. It also discusses missing information that would have been helpful to unveil further reasons behind the discrepancy between the two models.

Overall, a comparison of the two models demonstrates that extending past eligible 45Q facilities, aiming for net-zero, and accounting for uncertainty yields major increments in capital costs. But, just as with the GPI model, a comparison of the results of the different NZA scenario analyses underscores the importance of economies of scale for CO_2 pipelines.

4. Recommendations for CO_2 Infrastructure Deployment

While there might be alternative pathways to achieve net-zero emissions by 2050 without significant CCUS effort, most scenarios entail enough CCUS that scaling CO_2 infrastructure beyond individual projects would be economically necessary.

Under such scenarios, the CO_2 pipeline network could develop into a range of sizes and structures. At one end of the spectrum, CO_2 pipeline networks could cover the nation and resemble – at a smaller scale – the natural gas network, facilitated by eminent domain authority among other measures. It is also possible to repurpose natural gas pipelines into CO_2 pipelines, although these existing pipeline networks are optimized around legacy natural gas infrastructure and not necessarily efficient for CCUS sites.

On the other end of the spectrum, the country could rely entirely on local CCUS hubs that are unconnected to each other. Because of economies of scale, it is unlikely that hubs do not form at all. Still, since the development of pipelines depends on several technical, economic, and social conditions, future small- and large-scale pipeline networks built through individual projects may look substantially different from the optimized networks described in the preceding sections.

Having considered the scale of CCUS required to make a significant contribution to achieving net-zero, and taking into account the inherent economies of scale of pipelines, our finding is that adequately sized regional or national networks, where capture sites organically connect to shared CO_2 transportation and storage networks, are achievable in the next decades given the right policies and associated market conditions. Based on the considerations outlined above and interviews with policymakers, business executives, and other experts, we have identified four key priorities for U.S. government policies to facilitate scaling CO_2 transport infrastructure to what is likely to be required under a net-zero future, as follows:

1. Expanding incentives and facilitating financing for CO_2 pipelines and other transportation modes, building on the momentum of the expanded 45Q tax credits under the IRA and transport-specific incentives under the IIJA.

2. Addressing public sentiment around CO_2 pipelines by deepening private and public community engagement, with the goal of enhancing the social license to operate.
3. Facilitating pipeline network expansion through federal-state and state-state modeling collaborations, including modelling efforts that integrate expansions for CCUS infrastructure across states.
4. Further streamlining permitting processes in anticipation of the scale of CO_2 pipelines needed across federal and state lands.

In what follows, we address—for each of these priorities—specific policy proposals informed by our study of pipeline infrastructure modeling.

4.1 Expanding Transport-Specific CCUS Incentives

In the United States, CO_2 transport infrastructure and CCUS deployment will be broadly driven by government incentives.

Incentives for CO_2 transport infrastructure include the CO_2 Infrastructure Finance and Innovation Act (CIFIA),[58,59] which resides within the Storing CO_2 and Lowering Emissions (SCALE) Act in the Infrastructure Investment and Jobs Act passed in November 2021. CIFIA is modeled on the effective Transportation Infrastructure Finance and Innovation Act (TIFIA) and Water Infrastructure Finance and Innovation Act (WIFIA) programs.

CIFIA requires the Secretary of Energy to provide grants or federal credit instruments for planning, permitting, construction, legal, and other costs related to the development of common-carrier CO_2 transport. Eligible projects may include pipelines, shipping, and rail, as long as project costs are at or over $100 million.[60,61,62]

Common-carrier CO_2 transport projects that propose large-capacity transport, enable geographic diversity in CO_2 capture, and are sited close to existing pipelines or other linear infrastructure corridors are eligible. The last requirement aims to minimize environmental disturbance and other siting concerns.[63] Government entities and privately and publicly owned utility providers offering services such as electric power, gas, or water are equally eligible, as long as they use materials exclusively produced in the United States.

The 45Q tax credit, well summarized in the previous policy brief in this series and updated in Appendix 1 of this brief, provides an indirect incentive for the deployment of CO_2 transport today. Following the passage of the "Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions" (FUTURE) Act of the wider 2018 Bipartisan Budget Act, the owner of the carbon capture equipment can transfer the credit to another entity in the CO_2-management value chain, including pipeline developers outside the limits of a single project.[64] Today, the practice is muted because there is a relatively low incentive to transfer 45Q credits to pipeline developers,[65] but the transfer possibility enables "the accommodation of different ownership and business models for carbon capture projects."[66] With the third-party transfer regime relaxed under the IRA, the practice may be further encouraged so that the 45Q tax credits may also be partially passed through to pipeline developers.

In any case, 45Q is the main overall direct incentive to spur CCUS deployment in the United States today. Its overall effect is that it provides a degree of certainty about returns for the developers of CCUS projects. The increase in 45Q credits under the IRA is an important step forward,[67] and adding to such credits with state policies in key regions, especially targeting the transport component, would be influential in driving CCUS implementation further.

As an example of state leverage, the California Air Resources Board (CARB) incorporated CCUS projects into its low-carbon fuel standard (LCFS) regulation in 2019, allowing facilities in California that capture CO_2 to generate tradable credits.[68] State-level direct incentives specifically for CO_2 transport are also vital. Eight states have committed to establishing and implementing the Regional CO_2 Transport Infrastructure Action Plan.[69] They have outlined plans to support the expeditious buildout of CO_2 transport infrastructure, including complementary tax incentives to 45Q.

Finally, it will be important to assess the full panoply of federal and state CCUS deployment incentives together, in order to identify inadequacies within the transport component that could be remedied by additional carefully targeted measures.

4.2 Strengthening Community Engagement

Today's pipelines transport 66 Mtpa of CO_2 in the United States.[70] Estimates vary, but reaching net-zero by 2050 will require transporting nearly 1,400 Mtpa of CO_2 according to NZA, an increase of more than a factor of twenty. The social license to operate, defined here as "a society's or local community's acceptance or approval of a company's activities or operations,"[71] clearly will be necessary at a large scale for the deployment of sufficient CO_2 pipelines for CCUS to make a significant contribution to achieving net-zero emissions in this country by 2050.

There is recent precedent for such a large growth of pipelines. While it is important to be mindful of the many contextual differences between scaling gas and CO_2 pipelines, between 2010-2017, the Shale Revolution added 54.5 billion cubic feet per day (Bcfd) of incremental gas-pipeline capacity, increasing total mileage to 1.5 million miles.[72,73] CO_2 pipelines today transport 3.5 Bcfd, so the 20-fold expansion considered in the NZA model would require almost 70 Bcfd more.[74] While this growth in CO_2 pipelines would be almost 30 percent larger than the change that occurred in natural gas between 2010-2017, it would be distributed over several decades.

Overall, studies across several countries have shown that many citizens are uninformed about CCUS and its requirements.[75,76,77,78] For instance, a 2020 study on the social license of several technologies related to the future of energy in Wyoming showed that while 37.8 percent of residents are open to supporting CCUS in its capacity to mitigate climate change, another 32.3 percent are unsure and feel they need more information.[79] There is also international evidence across countries including Brazil,[80] Indonesia,[81] the Netherlands,[82] the UK,[83] and more[84] that public support is related to the perceived value of CCUS projects for the local population on topics such as employment and safety, with varying but generally increasing interest in its climate-mitigation potential.

While the desire for more information before deciding on support is a common factor, local conditions and past experiences with other technologies produce differences in the public perception issue across communities.[85] For private-sector project developers, meaningful engagement within the framework of existing legal, social, and environmental concerns is key. Addressing public safety issues through comprehensive and enforced safety regulations from the Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) should go a long way towards allowing the development of CO_2 pipelines at scale.[86]

Safety considerations specific to CO_2 pipelines must be thoroughly discussed and considered through community engagement activities, especially as new project proposals have started to expose existing regulatory gaps. These gaps include issues such as whether the PHMSA has the authority to regulate CO_2 pipelines that are predominantly gas-phase (instead of predominantly dense-phase CO_2 pipelines such as the ones that currently exist) or whether it has the authority to regulate natural gas pipelines that have been converted to carry CO_2.

Unlike natural gas pipeline ruptures that cause explosions and fires, CO_2 pipeline ruptures can displace oxygen and, in extreme cases, asphyxiate people. When CO_2 is released in a supercritical phase, which is common for CO_2 pipelines, it naturally vaporizes into a heavier-than-air gas and dissipates. If the dissipation is delayed, however, the likelihood of asphyxiation increases.[87] This is likely the case for the rupture of a CO_2 pipeline in Mississippi in February 2020, which resulted in the hospitalization of nearly 50 people.[88] The subsequent PHMSA report revealed that the pipeline owner, had given no information to the nearby communities, hospitals, and emergency responders about the potential dangers of and immediate responses needed after a rupture.[89] The incident shows that there is precedent for a lack of community engagement in existing CO_2 pipelines projects, which likely contributes to lukewarm perceptions on CCUS in the United States.

Other considerations include the risk of corrosion caused by increasing the acceptable levels of hydrogen sulfide in CO_2 pipelines[90] and the impact on air quality caused by the potential increase of ammonia emissions when using conventional amine-based solvents.[91]

From an environmental justice perspective, it is crucial to ensure that communities have sufficient resources to effectively evaluate whether CO_2 pipeline projects result in a net-positive impact to them. Many advocates argue that the Council of Environmental Quality (CEQ) and other relevant agencies should offer more guidance for underserved communities so that they can arrive at their own independent judgement about projects during community engagement sessions.[92]

Purposeful communication with local media, stakeholders, and leadership underpins trust and consent. Both public and private efforts in raising the public's awareness of CCUS would also likely benefit from widening the conversation from short-term objectives such as the development of pipeline mileage in a specific location, and the role of fossil fuels, to long-term objectives such as inclusive regional economic development, and community participation.[93]

4.3 **Planning for Expansion**

As discussed in Section 3 on pipeline costs and modeling efforts, an efficient CO_2 pipeline network will factor in extra capacity required to accommodate future CCUS projects. In the current market, however, individual pipeline capacity is generally designed to support only the transport needs of a particular project.[94] When determining the capacity of a new pipeline project, developers often must balance between short-term financial returns, based on revenues from current confirmed CCUS projects and long-term revenue potential, which requires a projection of future demands for CO_2 transport.

Both federal and state governments should continue to sponsor modelling studies. Open-access models such as the ones discussed in this report allow private and public stakeholders to have a common reference to compare and discuss against their existing and planned activity. Since many CO_2 pipeline networks will likely cross state lines, it will be crucial for neighboring states to form coalitions to help align infrastructure plans and encourage the development of pipelines that optimize for cost and transport needs. The 2020 GPI study is a notable example of such an effort: it was the result of two years of interstate collaboration through the Regional Carbon Capture Deployment Initiative.[95]

In addition, federal and state incentives should continue to encourage pipeline developers to construct projects that accommodate higher capacity than immediately necessary, as CIFIA already does. Other countries have opted for models with greater central planning, including Canada's Alberta Carbon Trunk Line system. It is the world's largest capacity CO_2 pipeline and became fully operational in June 2020.[96] The system currently gathers 1.6 Mpta of CO_2, which is only 10 percent of the full capacity of the system. With the aim of encouraging large systematic efforts over piecemeal projects, the Canadian federal government has contributed 53 million Canadian dollars (equivalent to about 40 million USD at the time of publication) for the Carbon Trunk Line system,[97] while the Alberta government has contributed 495 million Canadian dollars (equivalent to about 372 million USD at the time of publication) until 2025.[98]

Depending on the evolution of the climate challenge, other emission-reduction technologies, and political will, U.S. policymakers may explore similar initiatives to encourage systematic expansion, if current incentives fail to attract the investment necessary to develop CO_2 transport infrastructure.

4.4 Streamlining Permitting

Like conventional pipeline projects, CO_2 pipelines are subject to a layered permitting process involving various federal, state, and local agencies, the number depending on the lands through which the pipeline passes.[99] A typical project with mixed federal, state, and privately owned lands in a single state may require up to 30 reviews and approvals from various authorities,[100] with the number of reviews increasing further for projects crossing multiple states.

Congress has recognized the relevance of CO_2 pipelines for meeting U.S. climate goals and has passed bills to expedite the approval process of these projects and a revision of PHSMA's safety regulations are expected in 2024. One example is legislation allowing CCUS projects to be covered by the FAST-41 program, which is designed to improve efficiency and transparency of federal environmental reviews.[101] Nevertheless, the practical application of FAST-41 to CCUS remains to be seen, because until now no CCUS projects have applied for the program.[102]

On the federal level, the White House Council on Environmental Quality (CEQ), which is the agency responsible for implementing the National Environmental Policy Act (NEPA), should continue to explore avenues to streamline permitting. CEQ should also seek to understand and solve the lukewarm response toward FAST-41. CEQ has already proposed developing programmatic environmental reviews for CCUS. These could be an effective way to speed up pipeline permitting process in the long run, as subsequent individual projects could build upon analyses already approved in the programmatic review process.

States vary in terms of their CO_2 pipeline strategy and siting regulations. Some states, such as Illinois and Texas, have declared CO_2 pipelines to be in the public interest and, accordingly, have provided eminent domain authority.[103] Eminent domain grants the government the power to take private property and convert it into public use, contingent on the provision of just compensation to the property owners. Other states have so far been reluctant to provide eminent domain authority due to political opposition.[104] States should be encouraged to review their current processes; even single-state pipeline projects that do not pass through federal lands could benefit greatly from simplified state permitting.

In addition, state and federal agencies should collaborate in exploring ways to streamline existing processes, which is all the more important because many state projects would need to cross federal lands regulated by the Bureau of Land Management (BLM). Fortunately, CEQ already has reinforced the Council's priority to "convene the relevant agencies to assess opportunities for improvement in CO_2 pipeline planning."[105] Such interagency collaboration is particularly relevant to addressing cross-cutting themes, such as balancing the need to shorten permitting timelines against the importance of appropriately weighing environmental justice and equity considerations in the process.

State governments should also work with BLM to designate corridors for potential pipeline development. A model for this approach is the Wyoming Pipeline Corridor Initiative, which has identified over a thousand miles of potential CO_2 pipeline corridors crossing federal lands[106] and then has worked with the BLM to get federal resource management plans amended to make such pipeline corridors possible.[107] This effort did not automatically authorize rights-of-way,[108] nor has it led immediately to new projects by pipeline developers,[109] but it has helped create a favorable environment for CO_2 pipeline development and, presumably, has contributed to reduced permitting time.[110]

5. Concluding Remarks

This policy brief has examined the national challenges related to deploying and scaling national infrastructure to transport CO_2 from capture sites to storage or utilization sites at a scale consistent with achieving net-zero by 2050 in the United States. Pipelines will likely continue to be the predominant CO_2 transport mode, but they will require a major expansion to reach net-zero goals by 2050. Our appraisal of two of the most comprehensive regional and national models on CO_2 pipeline expansion, combined with our analysis of models that focus on near-term localized networks and interviews with a wide variety of experts, led us to the recommendations summarized above. We hope these considerations, together with the preceding policy brief on capture technologies and the briefs to follow on sequestration options and CO_2 utilization possibilities, will help advance the needed national conversation on the role of CCUS in meeting the U.S. goal on net-zero carbon emissions by 2050.

A. Appendix

A.1 Summary of Relevant Policy Changes for CCUS Under the Investment Reduction Act of 2022

The Inflation Reduction Act of 2022 (the IRA) was signed into law in August 2022 and substantially increases the support to CCUS projects. The most relevant changes are that the IRA: (1) increases CCUS tax credits; (2) lowers the criteria for CCUS project eligibility; and (3) makes the monetization of credits more accessible. Such changes directly reduce the costs of CCUS projects and incentivize business owners to advance CCUS implementation.

First, the IRA has drastically increased the 45Q credit amounts, ranging from $60 USD per ton for enhanced oil recovery projects to $180 USD per ton for direct air capture and storage.[111] Table 3 illustrates the increase in 45Q credits under the IRA.

Table 3 45Q credits under the Bipartisan Budget Act and the Inflation Reduction Act

PROJECT TYPE		45Q TAX CREDITS (IN USD PER TON)		
Capture method	**End use**	**Bipartisan Budget Act (2018)[i]**	**Inflation Reduction Act (2022)[ii]**	**Increase in tax credits**
Industrial and power facilities	Enhanced oil recovery (EOR)	$35 per ton	$60 per ton	+71%
	Storage	$50 per ton	$85 per ton	+70%
Direct air capture	Enhanced oil recovery (EOR)	$35 per ton	$130 per ton	+271%
	Storage	$50 per ton	$180 per ton	+260%

Source: Inflation Reduction Act of 2022 (H.R. 5376), §§13104, 13801.

Note: (i) Figures under the 2018 Bipartisan Budget Act reflect the targets for 2026 tax credits, which were lower when it was implemented in 2018 and increased annually thereafter. (ii) The full amount of tax credits under the IRA is realized only if prevailing wage and apprenticeship requirements are met.

Second, the IRA also makes it easier for CCUS projects to quality for 45Q credits by relaxing the annual thresholds of CO_2 captured that these facilities must satisfy. For example, electric generating facilities now only need to capture 18,750 tons of CO_2 annually to be qualified for the credits, down from 500,000 tons under previous legislations. The annual threshold for direct air capture reduces from

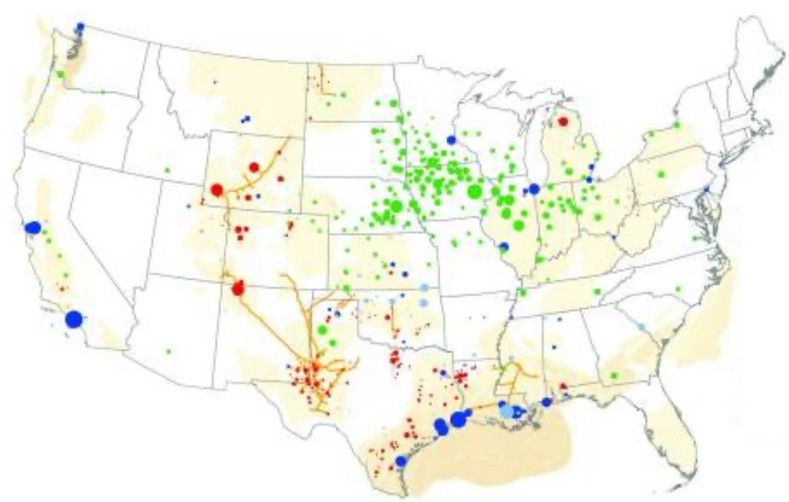
100,000 tons to merely 1,000 tons.

Third, monetization of these credits is made easier with additional options, such as selling any portion of the credits to third party for cash or direct payment from the Treasury under specific conditions.

A.2 **Existing CO_2 pipelines in the United States**

Figure 1 shows existing CO_2 pipelines in the United States up to 2018. Orange lines represent existing CO_2 pipelines. Beige areas represent saline storage potential. The dots represent potential sources of CO_2, with larger dots representing larger source and smaller dots representing smaller sources. The colors represent the potential source of CO_2: ammonia production (light blue); hydrogen production (dark blue); ethanol production (green); and natural gas processing (red).

Figure 1 Existing 5,012 miles of CO_2 pipelines in the United States and closeness to saline storage potential



Source: Edwards and Celia (2018).

Note: Pipelines were updated to 2018. Orange lines= existing CO_2 pipelines. Beige area = saline storage potential; Dots= sources of CO_2 (Light blue = ammonia; dark blue = hydrogen; green = ethanol; red = natural gas processing; Large dot = large source; small dot = small source).

A.3 **Relationships Between Pipeline Size, CO_2 Phase, and Compression Costs**

In addition to points made in the main text, our research highlights three additional takeaways related to the size of the flow and the phase in which CO_2 is transported. These findings, summarized in Table 4 and discussed in turn below, further reinforce the importance of network planning.[112] As above, we focus on the general cost curve pattern of CO_2 pipelines because actual costs are location-specific and depend on variables discussed above, i.e., cost of capital, equipment, labor, etc.

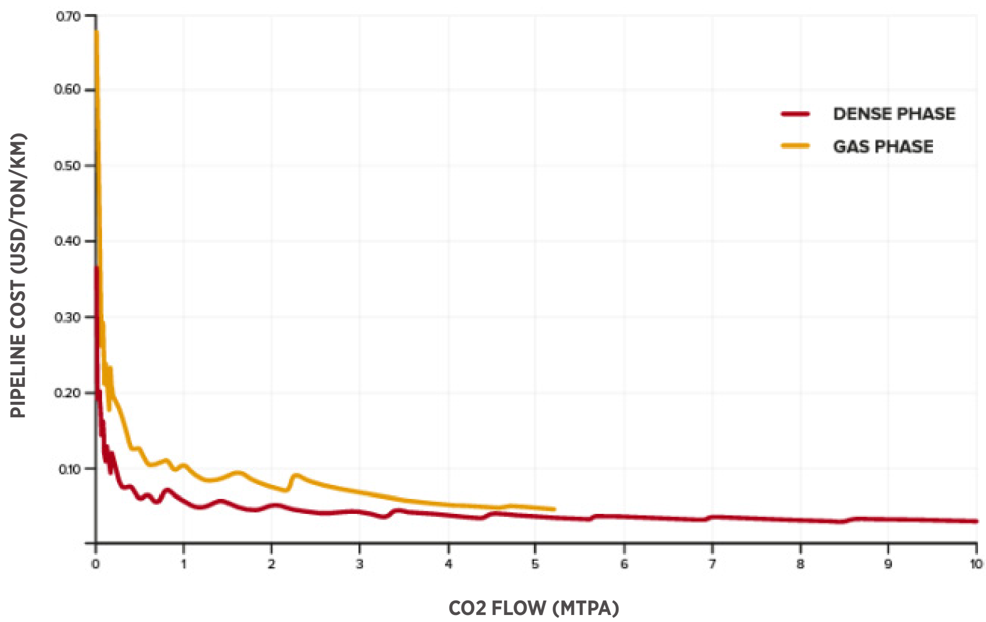
Table 4 Key takeaways on CO_2 pipeline costs relating to their capacity and phase

SALIENT POINT	IMPLICATION
Economies of scale are most pronounced at capacities up to 1 Mtpa, then start to level off, regardless of the phase of CO_2.	Give attention to limiting use of <1 Mtpa pipelines as much as possible. Facilitate pipelines that aggregate flows above 1 Mtpa.
Despite appearing cheaper on a standalone basis, dense-phase pipelines might be less economical than gas-phase pipelines, if one takes into consideration compression costs as well.	Costs must be evaluated as part of a system. See Box 1.
Gas-phase pipelines reach a capacity limit around 5 Mtpa using standard pipe diameters.	Beyond 5 Mtpa, use of gas-phase pipelines would require building two pipelines to transport the same quantity as a single dense-phase pipeline, which is not cost-effective.

Source: Global CCS Institute. 2020. "The Global Status of CCS: 2020." Australia. https://www.globalccsinstitute.com/resources/global-status-report/.

First, as shown in Figure A3.1, pipeline costs decline the most between 0 to 0.5 Mtpa and more gradually up until 1.0 Mtpa, regardless of CO_2 phase. Beyond 1.0 Mtpa, most of the economies of scale have been captured, and cost reductions from further scale increases are small.

Figure 2 Pipeline cost per USD/ton-km for dense- and gas-phase CO_2 pipelines



Source: Global CCS Institute (2021b).

Second, dense-phase pipelines might appear to be cheaper than gas-phase pipelines, but the higher compression costs associated with dense-phase pipelines can make their overall economics uncompetitive, especially at lower Mtpa values.

Currently, most existing CO_2 pipelines carry dense-phase CO_2.[113] In most cases, for the same Mtpa flow, dense-phase pipelines are indeed more economical per ton-km as they require smaller width (in terms of diameter) than gas-phase pipelines. But dense-phase pipelines also require higher compression (usually over 74 bars, the critical pressure of CO_2), resulting in higher compression costs. At lower source volume at individual capture sites (e.g., below 9 bars), the cost tradeoff between compression and pipeline installation might mean that gas-phase pipelines are more economically attractive overall.[114]

This point underscores the importance of taking total systems costs into consideration and the need for network planning when addressing CO_2 transport infrastructure. It is also important as we expect CO_2 capture sites, many in smaller volume, to proliferate under a net-zero future. We explore the relationship between compression costs and Mtpa value in greater depth in Box 1.[115]

Third, aside from the cost differences between gas and dense-phase pipelines, gas-phase pipelines reach a physical capacity limit around 5 Mtpa using standard pipe diameters. This detail matters to policymakers exploring the conversion of existing pipelines currently used to transport other materials. Policy guidelines and forecasting should consider that, beyond 5 Mtpa, it would be necessary to build two gas pipelines to transport the same quantity as a single dense-phase pipeline; doing so would likely be prohibitively costly in environmental, regulatory, and economical terms.

Box 1 CO_2 compression—costs of one versus two stages

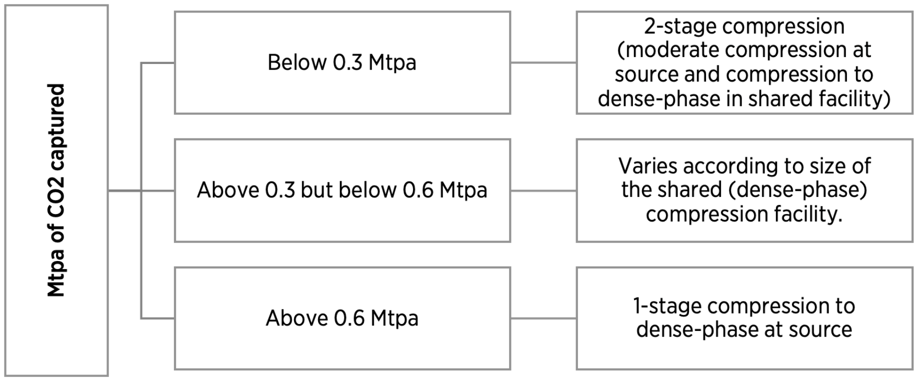
In a one-stage compression scenario, CO_2 is compressed at the capture facility and transported directly to its storage or utilization site. In a two-stage compression scenario, a capture site first moderately compresses CO_2 (to achieve, for example, 5-10 bar pressure), and then transports CO_2 in gas-phase pipelines to a shared compression facility. At the shared compression facility, flows from several capture sites are aggregated for compression to dense-phase (of up to 150 bar) before being transported to their CO_2 utilization or storage locations.

The cost-effectiveness of two-stage compression vis-a-vis one-stage compression must be analyzed in the context of systems in which the capacity of each compression site influences overall system costs. The Global CCS Institute has conducted such an analysis for shared facilities between 0.5-2 Mtpa.[116] Their analysis yields some helpful heuristics to evaluate one- versus two- stage compression costs, as summarized in Figure 3.

According to the Global CCS Institute, it is cost-effective for all sources of CO_2 with a flow rate of 0.3 Mtpa or lower to undergo two-stage compression. When the flow rate of point sources is above 0.6 Mtpa, one-stage compression is more cost-efficient and compression to dense-phase should occur directly at the point of capture.

When the flow rate of point sources is between 0.3 and 0.6 Mtpa, the difference between one and two-stage compression cost depends on the capacity of the dense-phase compression facility. Smaller compression facilities (0.5-1 Mtpa) justify two-stage compression only for the lower range of Mtpa source flows (0.3-0.4 Mtpa).

Figure 3 Two-stage compression is cost-effective for smaller capture facilities



Source: Authors' elaboration based on Global CCS Institute (2021b).

A.4 CO_2 Network Modeling in the Great Plains Institute and Net-Zero America Reports

As discussed in the main text, this brief focuses on understanding the salient characteristics and policies required for a CO_2 transport network infrastructure to achieve a net-zero United States through a national, multi-industry lens. Here, we provide more detail on two relatively comprehensive regional/national models discussed in the main text, Great Plains Institute (GPI) and Princeton's Net-Zero America (NZA), and compare their scope and modeling approaches. Table 5 is a summary of the two models.

While the models were published before the passage of the Inflation Reduction Act in 2022, which changes the economics of specific projects, comparing the models and their scenarios provides valuable insights affecting the development of CO_2 transport projects and their networks.

Table 5 Regional/national models for CO2 pipeline infrastructure and key characteristics

Report	***Transport Infrastructure for Carbon Capture and Storage: Whitepaper on Regional Infrastructure for Midcentury Decarbonization***, published by Great Plains Institute (GPI)	***Net-Zero America (NZA): Potential Pathways, Infrastructure, and Impacts***, published by Princeton University
Scope	Power and industrial facilities that qualify for 45Q in 21 Midwest and Gulf states†	Stationary emissions sources in all lower 48 U.S. states necessary to achieve net-zero by 2050
Network model	The Los Alamos National Laboratory's SimCCS model identifies optimal transport networks	Provides an "indicative/notional" network drawn by hand through main stationary emissions sources
Physical/ economic model	DOE/NETL 2018 CO_2 Transport Cost Model, integrated into the SimCCS model	DOE/NETL 2018 CO_2 Transport Cost Model (physical requirements, capital investments, O&M costs)
Scenarios	3	6 (including a reference case).

Source: Authors' elaboration based on the sources listed in the table.

Notes: Modeling was based on conditions before the passage of the Inflation Reduction Act. †Alabama, Arkansas, Colorado, Illinois, Indiana, Kansas, Kentucky, Louisiana, Michigan, Mississippi, Montana, North Dakota, Nebraska, New Mexico, Ohio, Oklahoma, South Dakota, Tennessee, Texas, Utah, Wyoming. ††EnergyPATHWAYS is a scenario analysis tool. †††The Regional Investment and Operations (RIO) platform is a linear optimization approach that develops a co-optimization of fuel and supply-side infrastructure decisions under different scenarios of energy demand and emissions constraints.

Great Plains Institute (GPI): CO_2 Pipeline Scenarios and Results

The GPI model aims to identify the regional CO_2 transport infrastructure that would serve existing facilities and allow participation by new facilities in 21 Midwest and Gulf states. The research covers three scenarios (renamed below for easier interpretation), two for near/medium term and one for mid-century:

1. **Scenario 1: Optimized scenario for the near/medium term** (i.e., best theoretical outcome for near-term opportunities, with limited consideration of capital constraints)
2. **Scenario 2: Constrained scenario for the near/medium term** (i.e., outcome considering capital constraints for all near-term opportunities)
3. **Scenario 3: Mid-century scenario** (i.e., considering all 45Q-eligible facilities within the scope and accounting for higher oil prices)

First, the GPI researchers identified 1,517 45Q-eligible facilities across the entire United States, of which 947 are located within the scope of the study (i.e., the 21 states). They further filtered down to 418 facilities as near/medium-term opportunities. Then, the researchers created the optimized pipeline network using the SimCCS 2.0 model, developed by Los Alamos National Laboratory, identifying the shortest feasible paths between all source and storage locations based on geographic details, right-of-way concerns, and existing infrastructure. Next, the researchers integrated the NETL CO_2 Transport Cost Model (as discussed in Section 3.1 in the main text) into SimCCS to generate transport cost estimates. Therefore, the researchers were able to produce granular estimates on costs based on specific input parameters (capital construction, operation, materials, maintenance, etc.).

Table 6 summarizes the number of facilities covered and the storage and transport assumptions behind the three GPI scenarios (renamed for easier interpretations):

Table 6 Comparison of Great Plains Institute (2020) scenarios

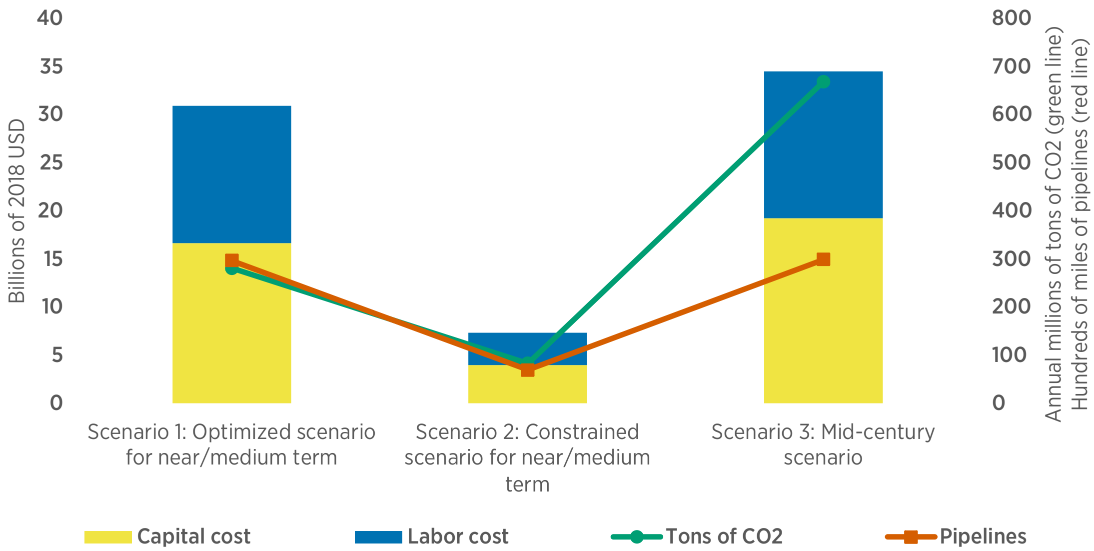
INDICATOR	SCENARIO 1: Optimized scenario for near/medium term	SCENARIO 2: Constrained scenario for near/medium term	SCENARIO 3: Mid-century scenario
Power/ industrial facilities covered	381	221	947
CO_2 captured and stored annually	281.2 million tons	83 million tons	669.1 million tons
Transport assumptions	Optimize for maximum capture and storage. Minimize for distance and land use. Requires capital investment.	Capital investment must be paid for by capture and storage under 45Q (pre-IRA level).	Same as Scenario 1.
Pipeline length	29,710 miles	6,923 miles	29,923 miles
Capital investment	$16.6 billion USD	$4.0 billion USD	$19.3 billion USD
Project labor investment	$14.3 billion USD	$3.4 billion USD	$15.3 billion USD
Annual operating & maintenance	$252 million USD	$58 million USD	$254 million USD
Storage	Deep saline geological formations: injection and storage costs <$5 USD/ton. Petroleum basins: oil prices of >$40 USD/barrel.		Same as other scenarios, but oil prices of > $60 USD/barrel.

Source: Authors' elaboration based on Great Plains Institute (2020).

Notes: 2018 USD. Modeling was based on conditions before the passage of the Inflation Reduction Act

Figure 4 summarizes scenario results. In Figure 4, the left vertical axis represents the total capital investment for each scenario, and the right vertical axis represents annual millions of tons of CO_2 stored, and hundreds of pipeline miles needed.

Figure 4 Comparison of Great Plains Institute (2020) scenario results



Source: Authors' elaboration based on Great Plains Institute (2020), pages 23, 25, and 27.

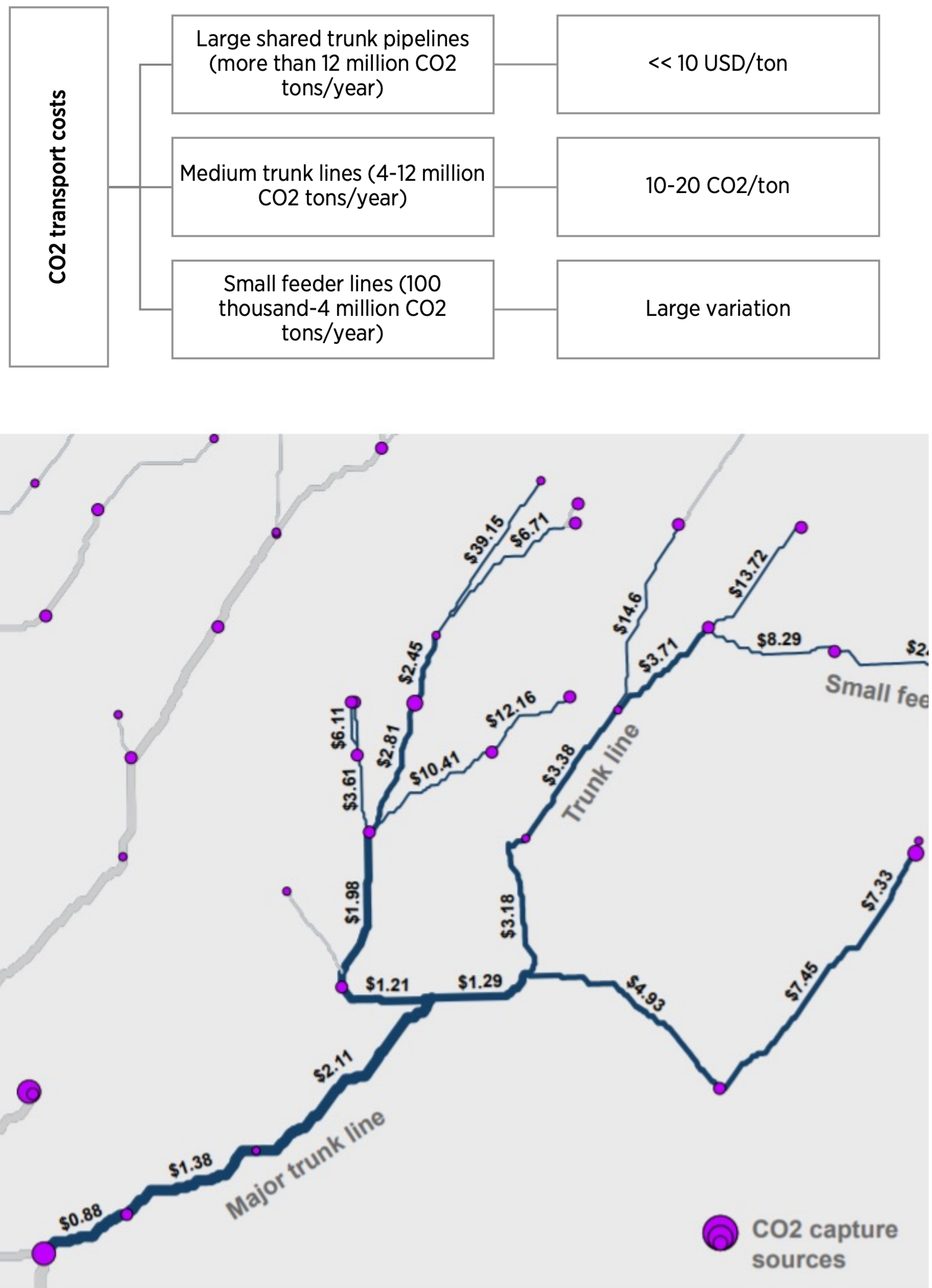
Notes: 2018 USD. Modeling was based on conditions before the passage of the Inflation Reduction Act.

As shown, the Mid-century scenario (i.e., Scenario 3) covers more than triple the facilities (and captures more than double the CO_2) compared to both the Optimized and Constrained Near/Medium term scenarios (i.e., Scenarios 1 and 2). Nevertheless, the mileage of pipelines and capital investment required are only slightly higher than the optimized scenario (i.e., Scenario 1). This result underscores the salience of economies of scale in pipeline transport.

On the other hand, the comparatively low tonnage of CO_2 transported under the Constrained Scenario for near/medium term (i.e., pipeline construction is paid for by the sale of CO_2) demonstrates that there was some immediate potential for CCUS capture under conditions and 45Q incentives before the passage of the IRA in 2022. And the comparison of Constrained Scenario with Scenario (1) demonstrates the difference that adequate financing can make to the deployment of transport, and therefore CCUS overall.

Specifically, GPI estimates that under 2020 conditions and Section 45Q, transport costs could not exceed $10-20 2018 USD/ton for CCUS to be cost-effective. Of course, the costs of individual pipelines depend on the factors discussed in Section 3 on Key Determinants of CO_2 Pipeline Costs. Figure 5 (top) summarizes the relative differences in costs. GPI categorizes pipelines in three groups: (1) large and shared trunk pipelines; (2) medium trunk pipelines; and (3) small feeder lines. Figure 5 (bottom) provides a visual example of transport costs within a portion of the network, in 2018 USD/ton.

Figure 5 Pipeline costs according to Great Plains Institute (2020).



Source: Source: Authors' elaboration based on Great Plains Institute (2020) (top) and Great Plains Institute (2020) (bottom). Notes: 2018 USD. Modeling was based on conditions before the passage of the Inflation Reduction Act.

Net-Zero America: CO_2 Pipeline Scenarios and Results

As compared to the GPI model, the modeling behind NZA has a much broader scope, in which CCUS is only one of six modeled “pillars” (the others being efficiency/electrification, clean electricity, clean fuels, non-CO_2 emissions, and land sinks). The CCUS-specific data in the NZA model are therefore relatively more limited. Nevertheless, considering the scarcity of nationwide research on CCUS transport infrastructure in the United States, NZA can offer important insights.

Unlike the “bottom-up” approach adopted by GPI researchers, the methodology in the NZA study is a “top-down” exercise. The process can be summarized as follows:

1. **Overall CCUS volume:** NZA researchers used the EnergyPATHWAYS and RIO models to create broad-bush transition scenarios and compiled the “required” CO_2 capture and storage quantity under each scenario to reach net-zero by 2050.
2. **CO_2 storage capacity and location:** NZA researchers identified the “base case” for CO_2 storage capacity across seven storage basins in the continental United States and created one notional cost curve for the entire model. This cost curve assumes that capacity charge for shared infrastructure is $15 USD per ton, while spur lines range from $5 to $35 USD per ton. The researchers explain that having one national cost curve is “simplistic and in reality, each of the regional blocks identified will have their own cost curves”.
3. **Downscaled CO_2 capture sources:** They then downscaled the projected annual flows of CO_2 captured in Step 1 by allocating them to point sources in three sectors, including thermal power plants (proportional to generation capacity), bioconversion facilities (proportional to biomass input rate), and cement/lime facilities (assume all facilities built after 2025 will incorporate CCUS technology). Therefore, the aggregated CO_2 volume is now distributed and mapped by point source in each geographical location.
4. **High-level pipeline structure:** Based on storage sites (identified in Step 2) and capture sites (identified in Step 3), the NZA researchers “drew notional transmission pipeline pathways by hand” to connect the storage and capture sites. Then, they used ArcGIS to optimize these pathways based on right-of-way corridors of existing infrastructure, while keeping the projection relatively notional and indicative, given the uncertainty involved in siting and capacity.

5. **Pipeline costs per catchment zone:** The researchers divided the continental United States map into 25 "transmission pipeline catchment zones" (23 projected to require CO_2 pipelines) and sized the transmission pipeline to satisfy the maximum annual flow within the catchment and additional inflows from upstream connected pipelines. Similar to GPI, the optimal pipeline diameter and capital costs are estimated using the DOE/NETL 2018 CO_2 Transport Cost Model; but, instead of bottom-up modelling, these estimates are only modeled in a per-zone basis.

6. **Spur line siting:** Using ArcGIS, the researchers located minimum distance spur pipelines connecting the CO_2 point sources to the transmission lines drawn in Step 5. These are divided into spur lines and sub-spurs. Cost estimates are modeled based on a regression of line lengths and CO_2 flow rate, a simplified version of the NETL model.

7. **Deployment schedule:** The researchers assume that the development and construction of the transmission network comes on stream five years before the facilities start their CCUS process. Additional assumptions were made on WACC and pipeline asset life.

Table 7 summarizes the amount of CO_2 stored and CO_2 pipelines required in 2050 under each scenario according to NZA, and Figure 6 provides a visual representation of the data. As shown in Table 7, all NZA scenarios except one (E+RE+) include subsurface sequestration. Only the E+ and E-B+ NZA scenarios include an estimate for pipeline construction and costs.

Figure 6 presents NZA pipeline infrastructure estimates. Note that E+ and E-B+ have very different CO_2 transport needs (dashed) but similar pipeline mileage (solid). Just as in the GPI model, NZA results demonstrate the economies of scale for CO_2 pipelines.

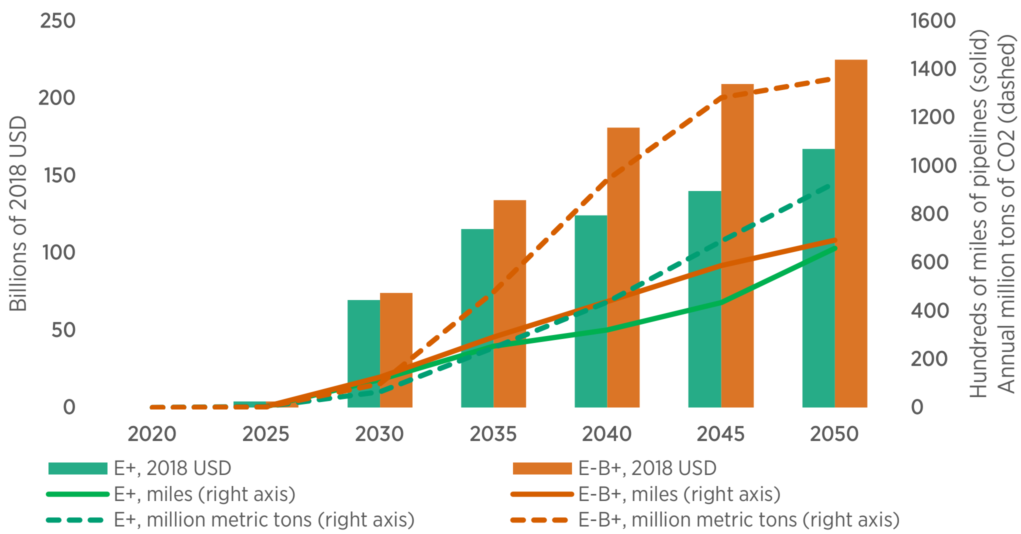
Table 7 Summary of scenarios in Net-Zero America

SCENARIO NAME	SCENARIO DEFINITION	Subsurface sequestration	Annual CO_2 stored in 2050 (Million tons)	Pipeline network estimated	CO_2 pipelines
E-B+	High biomass	✓	1,361	✓	69,100
E+	High electrification	✓	929	✓	65,800
E+RE-	Renewable constrained	✓	1,649	X	N/A
E-	Less-high electrification	✓	1,484	X	N/A
E+RE+	100% renewable	X	N/A	X	N/A
REF	Reference	✓	0.3	X	N/A

Source: Authors' elaboration based on Larson et al. 2021, pages 12-13, 71-72, 27, 57, and 87.

Notes: 2018 USD. Annual CO_2 storage (MMT). Pipeline length was converted from kilometers to miles for comparison with GPI model. Modeling was based on conditions before the passage of the Inflation Reduction Act

Figure 6 E+ (Green) and E-B+ (red) scenarios, Cumulative investment (bars, left axis); hundreds of miles of pipelines (solid line, right axis); annual million tons of CO_2 stored (dashed line, right axis).



Source: Authors' elaboration based on Larson et al. 2021.

Notes: 2018 USD. Modeling was based on conditions before the passage of the Inflation Reduction Act.

Comparing the Results from the Great Plains Institute and Net-Zero America

Table 8 presents the main results of the GPI and NZA reports in absolute terms. The main results shown are: (1) CO_2 stored (in Mpta); (2) pipeline lengths (hundreds of miles); (3) cumulative capital costs (in million USD, 2018); (4) operating and maintenance costs (in million USD); (5) capital costs per hundred miles of pipeline (in million USD, 2018); and (5) capital costs per million tons of CO_2 stored (in million USD, 2018).

As indicated, the cost estimates on a per-unit basis vary significantly between the two studies. The projected cost per mile of pipeline by NZA is 3.9 to 5.1 times higher than that of GPI, while the projected cost per ton of CO_2 by NZA is 5.7 to 6.2 times higher.

Table 8 Net-Zero America (E+ scenario = blue; E-B+ scenario = green) and Great Plains Institute (Mid-Century scenario) results, as well as their ratios

		RESULTS			COMPARISON OF RESULTS (NZA/GPI)	
Key metrics	**Unit**	**GPI (Scenario 3: Mid-century)**	**NZA (E+)**	**NZA (E-B+)**	**NZA (E+) / GPI (Mid-century)**	**NZA (E-B+) / GPI (Mid-century)**
CO_2 stored	million ton/year	669	929	1,361	1.4	2.0
Pipeline length	hundreds of miles	299	658	691	2.2	2.3
Cumulative capital cost	million, 2018 USD	19,261	167,114	224,560	8.7	11.7
Operating and maintenance cost	million 2018 USD	254	N/A	N/A	N/A	N/A
Capital cost per hundred mile of pipeline	million 2018 USD	64	254	325	3.9	5.1
Capital cost per million tons of CO_2 per year	million 2018 USD	29	180	165	6.2	5.7

Source: : Authors' elaboration based on Larson et al. 2021 and Great Plains Institute (2020).

Notes: Modeling was based on conditions before the passage of the Inflation Reduction Act.

In the main text, we highlighted the scope differences between the two studies, which partially explain the cost discrepancies in absolute terms. Obviously, the most apparent differences are the geographical scope and modeling approach. The GPI study is a more sophisticated exercise, where pipeline infrastructure is modeled at the plant-level for 15 sectors. Instead, NZA models pipeline infrastructure on a national level by catchment zones, and only include three sectors in their CCUS analyses, namely thermal power plants, bioconversion facilities, and cement/lime facilities.

The high-level nature of the NZA study is a likely design choice because the broader project focuses on more than CCUS. The methodology chosen--downscaling the overall CCUS target into specific sectors and regions--limits the granularity of the outputs. In fact, NZA researchers note these limitations in their study, stating that the network is "indicative and notional," and there is merit to developing a "more rigorous cost-optimized spatial and temporal sequences of CO_2 transport infrastructure."

Beyond the scope differences, a lack of detailed information precludes us from making further definitive conclusions on other potential sources of discrepancy. NZA does not provide operating and maintenance cost estimates. Hence, it is not possible to calculate the total cost (depreciated capital and operating costs) per ton-miles of CO_2 for NZA.

Additionally, while NZA discloses some investment-related assumptions (WACC, inflation, economic life of pipeline assets, etc.), GPI does not fully disclose these figures but only states that they "used default capital and return assumptions published in the NETL model." While they do make use of the same underlying cost model (i.e., DOE/NETL 2018 CO_2 Transport Cost Model), the researchers did not specify, out of the six pipeline cost formulae provided in the model, the one selected for their respective studies.

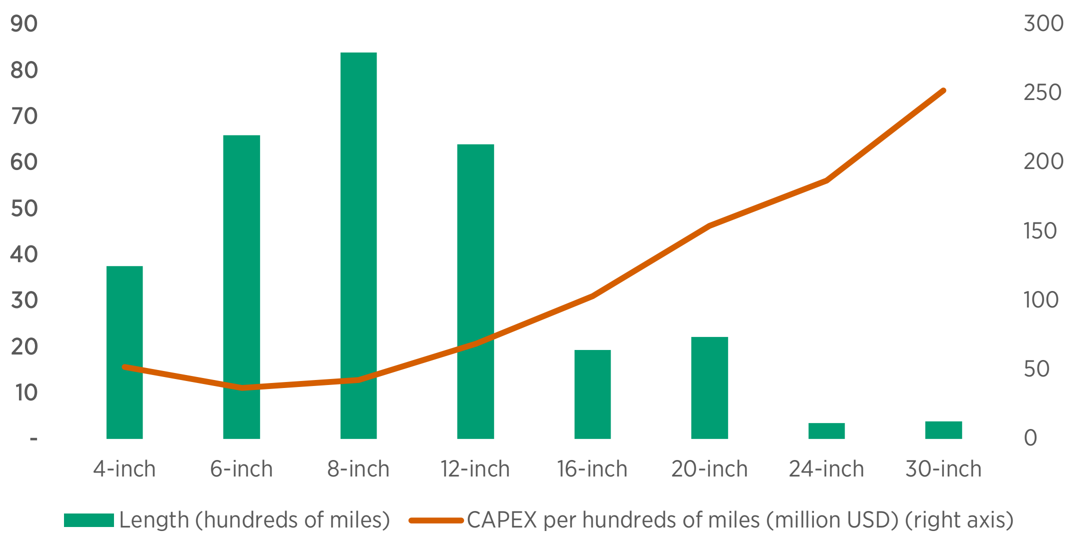
Nevertheless, one plausible hypothesis for the drastically different final estimates is the **difference in assumptions regarding pipeline diameter**. Specifically, pipeline diameters are projected to be much smaller in GPI than NZA, as presented in Table 9.

Table 9 Breakdown of pipeline types and their respective lengths and capital costs under GPI Mid-Century Scenario and NZA E+ Scenario

PIPELINE TYPE	Length (hundreds of miles)	CAPEX (million USD) Results	CAPEX per hundreds of miles (million USD)
GPI Mid-Century Scenario			
4-inch	37.40	1,937	51.79
6-inch	65.80	2,426	36.87
8-inch	83.76	3,561	42.51
12-inch	63.85	4,377	68.55
16-inch	19.23	1,986	103.28
20-inch	22.02	3,388	153.86
24-inch	3.41	637	186.80
30-inch	3.77	949	251.72
NZA E+ Scenario			
Trunk line (mostly 48-inch)	130.91	100,656	768.89
Spur line	526.85	66,458	126.14

The model behind the GPI simulates eight pipeline diameter options (including both trunk and spur lines), ranging from 4 to 30 inches. As shown in Figure 7, under the Mid-century Scenario, over 70 percent of total pipeline length is connected through pipelines of 6 to 12 inches (21,341 out of 29,923 miles). The report describes 24- and 30-inch pipelines as "super-sized trunk lines," and these only account for 2.3 percent of the total pipeline lengths modeled in this scenario.

Figure 7 Length (hundreds of miles, left axis) and unit cost (million USD per hundreds of miles, right axis) of transport pipelines by diameter in GPI's Mid-Century Scenario



NZA researchers took a different approach. They assumed the maximum diameter of trunk pipelines to be 48 inches. Based on the top-down approach described above, NZA's model optimizes for the maximum size (i.e., 48-inch), unless the capacity of the corridor in the catchment zone is too low to run the 48-inch pipelines. Therefore, in both E+ and E-B+ scenarios, 15 out of 23 catchment zones are assumed to build 48-inch pipelines; all but two catchment zones are assumed to build pipelines of 30 inches or above.

As for spur lines, NZA does not provide the diameter assumptions and instead only provides the projected total length. Nevertheless, a comparison of the per-mile capital cost between NZA and GPI (as shown in Table A4.5) reveals that NZA's spur lines are comparable to the assumptions for 16- to 20-inch pipelines in GPI. Therefore, NZA spur lines are significantly wider in diameter than the spur lines modeled in the GPI study.

As described in Section 3 of the main text, economies of scale play a crucial role in determining pipeline costs. Pipelines that are larger in diameter lead to higher flow rate, which means that in the long run they are more cost-effective because they can transport more CO_2 with the same infrastructure. However, as also discussed, larger-diameter pipelines mean higher upfront capital cost. Since NZA models most pipelines with diameters that almost quadruple those in the GPI study, their capital cost per mile is also understandably several times higher.

We compare the capital cost per ton-mile as well. This unit cost is expected to be lower for larger-diameter pipelines (i.e., under NZA's scenarios) if economies of scale are captured. NZA's cost per ton-mile also doubles that of GPI however, which indicates that their model does not reflect any economies of scale. Our hypothesis is that NZA's assumption of 48-inch pipelines is too aggressive given the expected amount of CO_2 they will transport, such that the incremental capital cost outweighs the cost efficiency from the additional capacity. In other words, the 48-inch capacity is almost always underutilized and results in a higher capital cost per ton-mile than necessary, and than compared to GPI's. This analysis again illustrates the importance of choosing the optimal diameter for CO_2 pipelines, among other baseline assumptions discussed in this brief, when estimating future costs and capacity planning.

To summarize, our review and comparison of the two models show, among other things, the difficulty in establishing a common cost estimate for the totality of the potential CCUS transport infrastructure network that may develop. Additional studies that can verify, challenge, and complement the existing estimates would be helpful to policymakers, business, and other stakeholders as they consider the roadmap to expand CCUS efforts to the scale required for a net-zero America by mid-century.

Endnotes

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