International Journal of Greenhouse Gas Control 109 (2021) 103367

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

The cost of CO_2 transport and storage in global integrated assessment modeling

Erin Smith[a], Jennifer Morris[a], Haroon Kheshgi[b], Gary Teletzke[c], Howard Herzog[a], Sergey Paltsev[a,*]

[a] Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge MA 02139, United States
[b] ExxonMobil Research and Engineering Company, 1545 Route 22 East, Annandale NJ 08801, United States
[c] ExxonMobil Upstream Research Company, 22777 Springwoods Village Parkway, Spring TX 77389, United States

ARTICLE INFO

Keywords:
CCS
CO_2 transport cost
CO_2 storage cost
integrated assessment model

ABSTRACT

This paper assesses the range of CO_2 transport and storage costs and evaluates their impact on economy-wide modeling results of decarbonization pathways. Much analytic work has been dedicated to evaluating the cost and performance of various CO_2 capture technologies, but less attention has been paid to evaluating the cost of CO_2 transport and storage. Many integrated assessment modeling studies assume a combined cost for CO_2 transport and storage that is uniform in all regions, commonly estimated at \$10/tCO_2. Realistically, the cost of CO_2 transport and storage is not fixed at \$10/tCO_2 and varies across geographic, geologic, and institutional settings. We surveyed the literature to identify key sources of variability in transport and storage costs and developed a method to quantify and incorporate these elements into a cost range. We find that onshore pipeline transport and storage costs vary from \$4 to 45/tCO_2 depending on key sources of variability including transport distance, scale (i.e. quantity of CO_2 transported and stored), monitoring assumptions, reservoir geology, and transport cost variability such as pipeline capital costs. Using the MIT Economic Projection and Policy Analysis (EPPA) model, we examined the impact of variability in transport and storage costs by applying a range of uniform costs in all regions in a future where global temperature rise is limited to 2°C. We then developed three modeling cases where transport and storage costs vary regionally. In these latter cases, global cumulative CO_2 captured and stored through 2100 ranges from 290 to 377 Gt CO_2, compared to 425 Gt CO_2 when costs are assumed to be uniformly \$10/t CO_2 in all regions. We conclude that the widely used assumption of \$10/tCO_2 for the transport and storage of CO_2 is reasonable in some regions, but not in others. Moreover, CCS deployment is more sensitive to transport and storage costs in some regions than others, particularly China. More analysis is needed to further quantify CO_2 transport and storage costs at a regional level.

1. Introduction

Deploying carbon capture and storage (CCS) at the scale needed to achieve global emissions reduction goals will require buildout of infrastructure to transport and store gigaton-scale levels of CO_2. In addition to uncertainty (which refers to how unknown or missing data can impact the precision of an estimate) there is a high level of variability in transport and storage costs – across geologic settings, locations, transport and storage technologies, and scales - that is hard to capture in macroeconomic models. Many well-documented Integrated Assessment Model (IAM) studies combine the cost of CO_2 transport and storage into a single estimate and report costs below \$15 per ton of CO_2 (tCO_2) for most CCS deployment scenarios, and some estimates report costs below \$5/tCO_2 (Herzog, 2011; McCoy and Rubin, 2008; Dahowski et al., 2011). After reviewing these and other studies, the IPCC Fifth Assessment Report (IPCC, 2014) stated that a common assumption for the cost of transport and storage of CO_2 is \$10/tCO_2.

This study's objectives are to (1) assess the range of CO_2 transport and storage costs in different regions of the world at a more granular level than a fixed cost of \$10/tCO_2 assumed in many studies; (2) consider different options for transportation (pipelines, shipping) and project networks (clustering), and (3) evaluate the impact of transport and storage costs on economy-wide modeling results of decarbonization pathways that include the CCS option.

---

* Corresponding author.
E-mail address: paltsev@mit.edu (S. Paltsev).

https://doi.org/10.1016/j.ijggc.2021.103367
Received 26 January 2021; Received in revised form 14 May 2021; Accepted 21 May 2021

One of the most impactful cost analyses published in recent years is Rubin et al. (2015), which summarized CO_2 transport and storage costs from several key studies and adjusted these estimates to a common basis for accurate comparison (IPCC, 2005; ZEP, 2011a; ZEP 2011b; GCCSI, 2011; Michael L USDOE, 2014a; USDOE, 2014b). In doing this work, Rubin et al. (2015) stressed the challenge of comparing cost estimates across studies because of inconsistent documentation of key metrics and underlying assumptions. In addition, we surveyed several well-documented estimates of CO_2 transport and storage cost have been released after Rubin et al. (2015) (IEA, 2020; USDOE, 2017, 2018; Grant et al., 2017; NPC, 2019; Abramson et al., 2020; Pale Blue Dot, 2016). Generally, there is still a great deal of variability and ambiguity in the literature in documenting key CO_2 transport and storage cost metrics, which makes comparison across studies difficult as Rubin et al. (2015) warned.

Different studies vary in their treatment and documentation of inflation rates and whether costs are reported in constant or current dollars (which exclude or include the effects of inflation, respectively). There is also variation in the year of currency used, and it is not always transparent what method or index is used to escalate costs to a particular year. Moreover, transport and storage costs are typically reported using one of several common metrics, each of which measures something different. Common metrics include: i) cost of CO_2 avoided ($\$/tCO_2$), which includes the total cost of CO_2 captured and stored and can only be reported as part of a complete CCS system; ii) levelized cost of transport or storage ($\$/tCO_2$), which measures the cost of transport or storage amortized over the life of the project; and iii) unitary transport cost per unit of distance or quantity transported.

Many studies also obscure the system boundary between CO_2 capture and transport, and between CO_2 transport and storage. This makes it difficult to accurately assess the magnitude of transport and storage costs individually. For instance, CO_2 conditioning is required to compress CO_2 prior to pipeline transport and studies vary in whether CO_2 conditioning is included as part of the capture or transport cost, and some studies do not distinguish this at all. There are also several important project assumptions – such as overall CO_2 quantity being transported or stored, time horizon of the project, utilization rate, etc. - that can have a sizeable impact on cost estimates but which are inconsistently documented across the literature. Finally, there is regional variation in the cost of capital, labor, materials, and other inputs that impact transport and storage cost assessments documented in a particular geography, as well as different regulatory structures incentivizing or disincentivizing parts of the CCS value chain.

Awareness of the above factors is critical for accurate comparison of CO_2 transport and storage costs across studies, though it is important to remember that different studies report CCS cost estimates with different objectives, scopes, and audiences in mind. Since there is often a tradeoff in detail vs. scope in many modeling analyses, it is important to identify the central question or objective in order to identify the appropriate analytical tool and interpret results accordingly. Bottom-up studies in the literature tend to report transport and storage costs tailored to a particular project or geography and are often focused on generating accurate, detailed cost estimates for a specific CCS scheme in a given region. By contrast, top-down studies typically seek to capture large-scale macroeconomic trends broadly to inform policy and decision-makers – these are typically the type of studies that employ IAMs or other macroeconomic models as an analytical tool. Our objective is to understand future decarbonization pathways that include CCS and the policy implications they present by characterizing CO_2 transport and storage costs in more detail than is currently assumed in many studies, such as those that use a uniform fixed cost of $\$10/tCO_2$ for transport and storage (IPCC, 2014; Rubin et al., 2015; IEAGHG, 2017; Morris et al., 2019).

2. CO_2 transport

2.1. *Transport options*

CO_2 pipelines are a mature technology and have been widely used globally for decades, with over 5000 miles of CO_2 pipelines in the United States in 2017 (Righetti, 2017). CO_2 pipelines in the United States are used primarily to transport CO_2 to oil fields for use in enhanced oil recovery. Data for the cost of transporting different quantities of CO_2 are limited, but natural gas pipelines are a useful analog by which to understand the cost components and variability underpinning CO_2 pipelines. Both depend largely on pipeline diameter and distance and differ little in land construction costs, though CO_2 pipelines may cost slightly more due to greater pipe thickness needed to transport CO_2 at higher pressure (Heddle et al., 2003). The feasibility of repurposing natural gas pipelines for CO_2 transport is not practical for transporting large quantities of CO_2 (e.g., 20 Mtpa) over long distances (100 miles or more). This is because CO_2 requires a higher pressure than natural gas to be kept in a liquid state for pipeline transport, and thus thicker pipelines are generally needed (NPC, 2019). Offshore pipelines exhibit many of the same cost components and variability as onshore pipelines but tend to be more expensive due to the more complicated offshore equipment required for construction on the ocean floor.

Shipping is a mature technology for liquefied natural gas (LNG) and liquefied petroleum gas (LPG) but is not widely used for CO_2 transport today. LPG tankers are a closer analog for CO_2 transport via ship than LNG tankers because liquefied CO_2 must be transported at elevated pressures like LPG, whereas LNG is transported at atmospheric pressure. LPG tankers can be repurposed for CO_2 or dual-purpose transport, but in general, tankers specifically designed for CO_2 transport can be better optimized for maximum capacity and investment cost (IEAGHG, 2020).

CO_2 can be transported via train or truck and may be economic over short distances and small CO_2 quantities (Sanchez et al., 2018; Psarras et al., 2020). While rail and truck transport may be important for small-scale transport in the early years of CCS expansion, it is not expected to play a major role in large-scale rollout of CCS. Pipelines and ships are expected to be much more cost effective in transporting megatons of CO_2 per year (Mtpa) due to economies of scale (NPC, 2019).

2.2. *Current status of CO_2 transport costs*

CO_2 transport costs vary due to transport method (i.e. pipelines vs. ships); whether CO_2 is transported onshore or offshore; scale (quantityof CO_2 transported); distance to CO_2 storage; regional variation; and the CO_2 source and whether or to what degree it is pressurized or purified prior to transport. Pipelines are generally the most cost-effective CO_2 transport option in most regions, though shipping can be cost effective for transporting CO_2 over long distances.

Shared CO_2 transport networks have significant potential to reduce costs through economies of scale (Pale Blue Dot, 2016; Friedmann et al., 2020). The cost and feasibility of CO_2 transport networks varies regionally and is interdependent with the development of CO_2 source clusters and storage hubs. There are several promising locations for CCS clusters and hubs globally that are being pursued that could facilitate a shared transport infrastructure, particularly in the United States, Europe, and China (IEA, 2020). In the United States, much analytic work has been dedicated to exploring potential trunk line networks and routes in the U.S. midcontinent and gulf coast, in addition to movement on federal legislation that would fast-track permitting for CO_2 pipelines (Abramson et al., 2020). Relatedly, in October 2019 amendments to the London Protocol were ratified by a sufficient number of participating parties that would allow onshore cross-border transport of CO_2 in Europe, which previously had faced regulatory hurdles (IEAGHG, 2020).

Several regions are investigating in CO_2 shipping for future scaled-up CCS operations, most notably the Northern Lights Project in Europe and JGC Corporation in Japan. The Northern Lights Project initially expects

Table 1
Capital cost factor range for onshore CO_2 pipelines in current 2019$/in-mi.

Source	Low	Mean	High
Heddle et al. (2003)	$18,195	$52,892	$87,588
USDOE (2018)	$40,052	$51,581	$83,881
NPC (2019)	$80,000	$115,000	$150,000

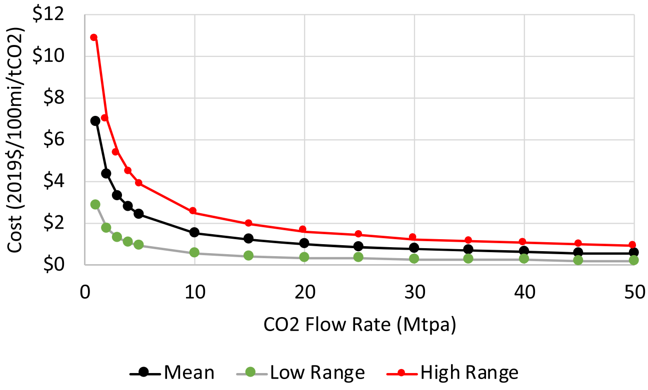


Fig. 1. Total CO_2 transport costs for a 100-mile onshore pipeline in the United States in 2019 current dollars. Low and high cost range reflect two standard deviations away from the mean and are based on the capital cost factors updated from Heddle et al. (2003) as visible in Table 1.

to transport up to 1.5 Mtpa CO_2 captured from two industrial plants in Norway by ship to temporary onshore storage, after which it will be transported by offshore pipeline for permanent storage in geologic formations in the North Sea. Eventually, the project envisions transporting CO_2 by ship from CCS hubs across Europe, with a targeted scale of 5 Mtpa CO_2 by 2030. In Japan, most CO_2 storage reservoirs are offshore and the JGC Corporation is wrapping up its demonstration phase for offshore CO_2 transport and storage in 2020, with projections to reuse existing offshore oil and gas infrastructure (JGC, 2019).

Because shipping is not widely used for CO_2 transport, we relied on published estimates of shipping costs for our analysis. IEAGHG (2020) estimates CO_2 shipping costs for four scenarios in Europe and reports a similar cost range as the Northern Lights Project. However, these estimates do not include the cost of CO_2 injection, leaving a degree of uncertainty with regard to the total cost. For this reason, we assume shipping costs reported by Northern Lights Project, which has a targeted combined cost range of €30–55/tCO_2 for CO_2 transport and storage by 2030 (Northern Lights Project, 2020).

2.3. CO_2 transport cost range

This section explains our method for calculating the CO_2 transport cost range for onshore CO_2 pipelines in the United States and how this range can be used to estimate costs for offshore pipelines and pipeline networks. For our analysis, we assume a pure stream of CO_2 that is compressed prior to transport. There are three key sources of variability in CO_2 transport cost estimates: 1) distance, 2) scale (i.e., quantityof CO_2 transported), and 3) underlying transport cost assumptions, particularly pipeline capital costs.

To explore the variability in CO_2 pipeline costs we used a variety of models, most notably Heddle et al. (2003), the NETL CO_2 Transport Cost Model (USDOE, 2018), and NPC (2019). Heddle et al. (2003) employs a pipeline capital cost factor in dollars per inch per mile. The inch refers to pipeline diameter and the mile refers to pipeline length. Pipeline construction costs include materials, labor, rights of way, and other miscellaneous costs (e.g. surveys, engineering, supervision, contingencies, etc.). CO_2 pipelines have been a mature technology for decades and after comparison with recent models like USDOE (2018) – which references Heddle et al. (2003) in its approach and also uses capital cost factors - we concluded Heddle et al. (2003)'s method to be simple, accurate, and consistent in estimating CO_2 transport costs in dollars per ton ($/t$CO_2$) for a given CO_2 flow rate and distance.

Heddle et al. (2003) used natural gas pipelines as an analog for estimating the cost of CO_2 transport via pipeline. Both face similar construction costs that are sensitive to distance and scale, though CO_2 pipelines may cost slightly more due to greater pipeline thickness needed for transporting CO_2 at higher pressures. Heddle et al. (2003) leveraged industry data on natural gas pipelines from 1989 to 1998 to chart the relationship between average CO_2 pipeline construction cost (in $/mile) as a function of CO_2 flow rate. Pipeline diameter depends on the CO_2 flow rate, so we were able to translate this into a relationship of average CO_2 pipeline construction cost (in $/mile) versus pipeline diameter.

We escalated costs from Heddle et al. (2003) to current 2019 dollars according to the Producer Price Index (PPI) normalized to 100 in the year 2000 (U.S. Bureau of Labor Statistics, 2020). Rubin et al. (2015) escalated transport and storage costs according to the Chemical Engineering Plant Cost Index (CEPCI) because these services are typically provided to power plants by organizations from the oil and gas industry. We opted to use the PPI because it tracked closely with CEPCI, which is no longer open source. We then followed Heddle's approach by using linear regression on mean pipeline construction costs (in $/mile) for a given pipeline diameter to calculate a capital cost factor of $52,892/in-mi for onshore CO_2 pipelines. We then built low and high capital cost factor estimates by using linear regression on pipeline construction costs (in $/mile) for a given pipeline diameter two standard deviations above and below the mean, yielding a range of $18,195/in-mi to $87,588/in-mi reported in Table 1. These capital cost factors include pipeline construction costs only - O&M costs were added separately as an O&M cost factor in dollars per year per mile ($/yr/mi). USDOE (2018) used O&M cost factors from Heddle et al. (2003). Finally, following Heddle et al. (2003)'s approach, we annualized construction costs using a capital charge rate of 15% per year and added this to the annual O&M cost. From there we were able to estimate the total cost of transporting any CO_2 quantity any distance (Fig. 1).

USDOE (2018) documents mean and high capital cost factors similar to the range we calculated using Heddle et al. (2003)'s approach. USDOE (2018) low, mean, and high values in Table 1 reflect capital cost factors based on a 100 mile 12-inch diameter pipeline and are calculated using three equations from Rui, McCoy, and Parker, respectively. All three equations use pipeline capital costs reported in O&GJ (1989), encompass the same cost components outlined in Appendix B, and calculate capital cost factors as a function of pipeline length and diameter. Grant et al. (2017) used Parker's equation (which corresponds to the high estimate listed in Table 1 for USDOE (2018)) to be conservative and err on the side of over-estimating CO_2 transport costs. NPC (2019) documents higher capital cost factors ranging from $80,000/in-mi to $150,000/in-mi across four major U.S. regions. Their mean value in Table 1 reflects the midpoint of this range. However, NPC (2019) reports a high range of $100,000/in-mi for three likely trunk line routes in the United States. Our calculated mean and high capital cost factors of $52,892 and $87,588, respectively, are similar to the mean and high capital cost factors documented in USDOE (2018) and those of likely U.S. trunk line routes reported in NPC (2019).

Offshore pipelines exhibit many of the same cost components and variability as onshore pipelines but tend to be more expensive. By contrast, pipeline networks are generally assumed to be less expensive due to infrastructure sharing and economies of scale. For simplicity, we assume multipliers of onshore pipeline costs to estimate higher-cost offshore pipelines and lower-cost pipeline networks based on figures reported in the literature. Some studies suggest offshore pipelines can cost 50 to 100% more than onshore pipelines (CO_2Europipe, 2011) while pipeline networks can reduce costs up to 75% (Zapantis et al., 2019).

Shipping is not widely employed today for CO_2 transport but is seriously being considered for future use as CCS scales up in Europe and Japan. We assume shipping costs based on current figures from the Northern Lights Project, which targets CO_2 transport and storage costs of 30 to 55€/tCO_2 ($35 to $64/t$CO_2$ USD) by 2030 for 5 Mtpa CO_2.

3. CO_2 storage

3.1. Storage options

The vast majority of CO_2 storage potential worldwide is in onshore and offshore saline aquifers (USGS, 2013). The cost of CO_2 storage is very site dependent because geologic characteristics vary from site to site and injection, labor, drilling, capital, and other costs vary regionally. Similar to offshore pipelines, offshore CO_2 storage is generally more expensive than onshore storage. For CO_2 storage in saline aquifers, various types of wells must be drilled (exploration, injection, and monitoring) which comprise a large share of the overall storage cost. The number of wells that must be drilled hinges on the scale of the project and a handful of key geologic parameters discussed in Section 3.2. In addition, many published CO_2 storage cost estimates of saline aquifers do not consider the cost of extracting, processing, and disposing of formation fluid to make way for injected CO_2, which is particularly an issue in closed onshore saline formations (Anderson et al., 2019). Such closed formations that require active pressure management present a tradeoff between CO_2 storage capacity and storage cost.

The same geologic parameters that shape the number of wells that must be drilled to inject a given quantityof CO_2 in saline aquifers also impact depleted oil and gas fields. Previous studies have suggested the cost of CO_2 storage in depleted oil and gas fields is lower than in saline aquifers because the oil and gas fields have already been surveyed and offer the potential to reuse existing infrastructure (ZEP, 2011a). However, uncertainty and costs associated with verifying infrastructure integrity and repurposing it for CCS applications may negate any cost savings, or it can increase the risk of CO_2 leakage through existing wells and thus require more monitoring, which also raises costs. These competing factors prevent us from distinguishing the difference in storage costs between saline aquifers and depleted oil and gas fields; therefore, in this study we approximate them as being the same.

Other geologic formations have potential to store CO_2. Unmineable coal seams have been investigated, but many questions still remain about whether they are a practical storage medium. Formations that are in the early stage of study include shale formations, basalt formations where CO_2 crystallizes into solid carbonate minerals (e.g., active project in Iceland (Gunnarsson et al., 2018)), and shallow offshore sedimentary formations. These alternative storage formations are outside the scope of this study.

3.2. Current status of CO_2 storage costs

CO_2 storage costs hinge on three major sources of variability: 1) geologic characteristics; 2) scale (i.e., amount of CO_2 stored); and 3) monitoring, financial, and other modeling assumptions. A handful of geologic parameters are primary determinants of whether a reservoir is favorable for CO_2 storage: permeability, thickness, depth, porosity, and lateral continuity (Michael L USDOE, 2014a; USDOE, 2017). These features dictate how much total CO_2 can be stored in a reservoir, the number of wells that must be drilled, and the degree to which pressure buildup must be managed, which adds extra costs. Some estimates suggest the cost of pressure management could double CO_2 storage costs (Anderson, 2017). Reservoirs with the lowest storage costs are permeable and thick, while reservoir depth can impact the cost of drilling injection and monitoring wells. The cost to drill injection and monitoring wells varies regionally and CO_2 storage costs are quite sensitive to assumptions around the number of injection and monitoring wells required.

Regulatory regimes and financial assumptions also impact the cost of CO_2 storage. In the United States, the 2018 expansion of the 45Q tax credit is expected to stimulate billions of dollars of investment in CCS by providing financial incentives for CO_2 stored permanently in saline reservoirs or via enhanced oil recovery (Bennett and Stanley, 2018). Different jurisdictions have different requirements regarding long-term liability of CO_2 storage and how long secure geologic storage must be monitored; for example, United States federal and California state protocols differ. This has the potential to raise storage costs and is not modeled in many studies, with the 2017 NETL CO_2 Saline Storage Cost Model (USDOE, 2017) being a notable exception. Relatedly, just as U.S. landowners receive royalty payments for oil and gas produced on their property, in the presence of a price on carbon or other CO_2 storage tax credits, it is unclear if or how royalty payments on stored CO_2 would be implemented and how this might impact CO_2 storage costs.

CO_2 storage costs typically decline as the scale of a storage project increases. As CCS deployment ramps up, CCS hubs - which are industrial centers that leverage a shared CO_2 transport and storage infrastructure – are expected to develop and reduce CO_2 transport and storage costs through economies of scale. Since 2017, investment plans have been announced for several potential CCS hubs, including five in the United States, four in China, and 12 across Europe (IEA, 2020). These dynamics are important to keep in mind when representing CO_2 storage costs in energy economic models and understanding their impact on decarbonization pathways.

3.3. CO_2 storage cost range

This section explains our method for calculating CO_2 storage costs for saline aquifers and depleted oil and gas fields in the United States. As discussed in Section 3.1, we assume storage costs are the same for saline aquifers and depleted oil and gas fields.

There are three key sources of variability in CO_2 storage cost estimates: 1) geologic characteristics, 2) scale, and 3) model assumptions regarding monitoring, finance, etc. Permeability, thickness, depth, porosity, and lateral continuity are among the geologic features most impactful in determining reservoir suitability for CO_2 storage. These parameters determine the total volume of CO_2 that can be injected into a reservoir (a matter of scale) as well as the maximum rate of CO_2 injection per injection well which, by extension, determines the number of injection wells required. In general, thick, permeable formations are optimal because they can store more total CO_2 and require fewer injection wells. Some studies including NPC (2019) assume a certain ratio of monitoring wells per injection well, as well as assumptions about finance costs. We explored several models with various strengths and limitations in capturing these key sources of variability.

- Heddle et al. (2003). Heddle's model captures several geologic parameters in great detail including their impact on CO_2 injection rate per well and required number of injection wells. However, the costs underpinning this model reflect outdated drilling technology that we concluded was not suitable for our analysis.
- IECM (2015). IECM is an open source model maintained by Carnegie Mellon University under contract to the US Department of Energy that allows users to adjust a variety of geologic parameters and modeling assumptions for various regions in the United States to calculate an overall cost of CO_2 storage.
- USDOE (2017). NETL manages the CO_2 Saline Storage Cost Model, a large, open source model with detailed geologic monitoring capabilities that was last updated in 2017. Grant et al. (2017) used this model to report CO_2 storage costs for 4 U.S. formations with a range of geologic properties. By default, USDOE (2017) assumes a flat cap on the CO_2 injection rate per well and rigorous monitoring requirements. For these reasons, we believe this model reports estimates on the high end of the CO_2 storage cost range.

Table 2
Reservoir Properties from Michael L Szulczewski et al. (2012) and Grant et al. (2017).

Formation	Permeability (mD) * Thickness (m)	Depth (m)	Mean Storage Capacity (Gt CO_2)	Storage Capacity Standard Deviation (Gt CO_2)
Potomac	1,200,000	1,000	4	2
Frio	800,000	1,000	18	8
Woodbine*	106,680	1,676	24	
Black Warrior River	100,000	1,000	31	12
Mt. Simon	40,000	2,000	88	27
Madison	36,000	3,000	5	2
Fox Hills	20,000	1,000	6	2
Navajo-Nugget	20,000	3,000	5	2
Morrison	14,000	2,000	17	5
Red River*	6,300	2,743	72	
Paluxy	4,500	2,000	2	0.5
Cedar Keys	4,000	2,000	87	22
St. Peter	2,000	2,000	1.6	0.4

Using the USDOE (2017) model with the parameter values described above, we calculated the CO_2 storage cost for all 13 reservoirs in Table 2 for four different scales of CO_2 transport and storage projects (in Mtpa) to reflect varying levels of CCS deployment.

Table 3
U.S. storage cost range (2019$/t$CO_2$) under base monitoring assumptions.

Rate Mtpa CO_2	Low	Mean	High
1	$9.74	$16.47	$23.20
3.2	$5.25	$8.00	$10.75
6	$4.36	$6.73	$9.09
15	$4.05	$6.24	$8.44

Table 4
U.S storage cost range (2019$/t$CO_2$) under extra monitoring assumptions.

Rate Mtpa CO_2	Mean	Mean with Extra Monitoring	Extra Monitoring-Only Costs
1	$16.47	$28.14	$11.67
3.2	$8.00	$15.14	$7.14
6	$6.73	$12.67	$5.95
15	$6.24	$11.49	$5.25

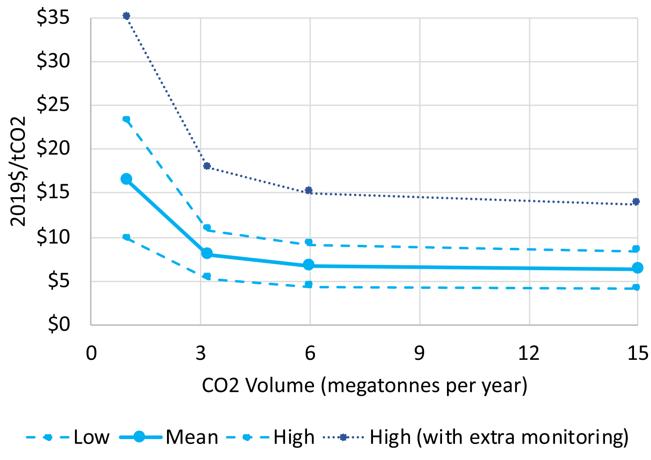


Fig. 2. U.S. CO_2 storage cost range in current 2019$/t$CO_2$.

- NPC (2019). Uses a modified version of USDOE (2017) that reduces the ratio of monitoring wells per injection well, reduces the number of 3D seismic studies, and focuses on the lowest cost (<$15–20/t depending on region) storage formations. The study calculated CO_2 storage costs using volume-weighted averages across several U.S. regions, reporting a national average CO_2 storage cost of $8/t$CO_2$.

For our analysis, we used a modified version of USDOE (2017) in line with NPC (2019) assumptions because 1) the USDOE (2017) and IECM (2015) models were similar in methodology and produced similar estimates of storage cost and number of injection and monitoring wells, and 2) to be consistent with NPC (2019), which we assess to be the most accurate reported estimate of CO_2 storage costs, as well as the most recent. Below, we outline our approach to quantifying the three key elements of variability in CO_2 storage costs.

We selected 13 U.S. reservoirs with a range of reservoir properties to serve as a proxy for geologic variability that storage project developers are likely to encounter globally (Table 2). Eleven of these reservoirs are from Michael L Szulczewski et al. (2012) and two from the Grant et al. (2017). These reservoirs have a combined CO_2 storage capacity of 360 Gt out of an estimated 500 to 4000 Gt of onshore storage capacity in the United States (Kearns et al., 2017). We used permeability, thickness, and depth values reported in Michael L Szulczewski et al. (2012) and Grant et al. (2017). For reservoir pressure we assumed hydrostatic pressure, which is a function of depth. The rest of the parameters were from the USDOE (2017) database. Where a particular reservoir was not included in the USDOE (2017) database, we used the closest analog in the same basin or region. The reservoirs in Table 2 are ranked in order from most to least favorable as determined by the product of permeability and thickness.

- 1 Mtpa - roughly equivalent to one demonstration-scale CO_2 transport and storage project.
- 3.2 Mtpa – reflects a handful of CO_2 transport and storage projects and is the same scale used in Grant et al. (2017) and NPC (2019).
- 6 Mtpa - reflects moderate levels of CCS deployment and is roughly twice the level assumed in Grant et al. (2017) and NPC (2019), and is slightly higher than the Northern Lights Project target of 5 Mtpa CO_2.
- 15 Mtpa - reflects large-scale rollout of CCS encompassing numerous CO_2 clusters, hubs, and shared transport networks globally.

One quirk of the USDOE (2017) model is that it capped cumulative CO_2 injected into each reservoir at levels significantly below 15 Mtpa CO_2. As a result, we extrapolated our storage costs for 15 Mtpa by calculating the cost difference per MtCO_2 between 1 and 3.2 Mtpa CO_2, and 3.2 and 6 Mtpa CO_2, to approximate a rate of cost decline with scale for each reservoir. We applied this rate of cost decline to estimate CO_2 storage costs for 15 Mtpa CO_2.

By default, USDOE (2017) assumes stringent monitoring requirements that we determined to reflect the high end of the CO_2 storage cost range and which we refer to as "extra" monitoring assumptions. For our analysis, we reduced the monitoring and finance assumptions in USDOE (2017) to be in line with those used in NPC (2019) by adjusting the ratio of monitoring to injection wells from 9:1 to 2:1; reducing the number of 3D seismic studies from 16 to 6; and assuming self-insurance rather than a trust fund for debt financing. We then used the model to calculate the per-ton cost for four different CO_2 injection rates in 13 reservoirs under two sets of monitoring assumptions which we refer to as "base" monitoring assumptions (e.g. NPC (2019) assumptions) and "extra" monitoring assumptions (e.g. USDOE (2017) default assumptions).

We calculated the mean and standard deviation in CO_2 storage costs across the 13 reservoirs in Table 2, weighted by storage capacity, for four CO_2 rates and under both sets of monitoring and finance assumptions. The USDOE (2017) model did not solve for two of the smallest and least desirable reservoirs (St. Peter and Paluxy), so these costs were excluded from the mean and standard deviation calculations.

After calculating the mean and standard deviation in storage cost for

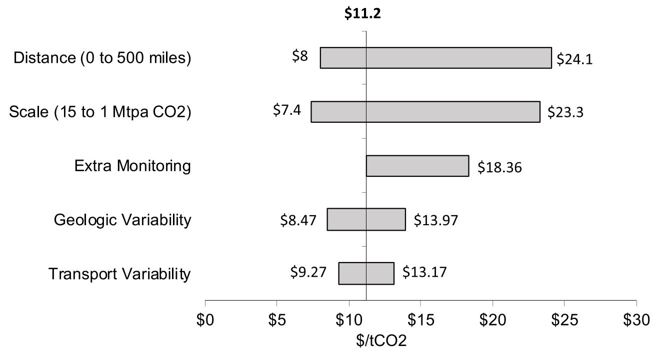


Fig. 3. Sensitivity of CO_2 transport, storage and monitoring costs around the base case of 3.2 Mtpa CO_2 being transported 100 miles.

Table 5
CO_2 transport and storage costs in current 2019$/t$CO_2$ for various combinations of scale, transport distance, and monitoring assumptions in the United States.

CO_2 Scale and Distance	Low	Mean	High	High (with extra monitoring)
1 Mtpa, 0 miles	$9.7	$16.5	$23.2	$34.9
1 Mtpa, 100 miles	$12.6	$23.3	$34.0	$45.7
1 Mtpa, 500 miles	$24.1	$50.6	$77.2	$88.9
3.2 Mtpa, 0 miles	$5.3	$8.0	$10.7	$17.9
3.2 Mtpa, 100 miles	$6.5	$11.2	$15.9	$23.1
3.2 Mtpa, 500 miles	$11.6	$24.1	$36.6	$43.8
6 Mtpa, 0 miles	$4.4	$6.7	$9.1	$15.0
6 Mtpa, 100 miles	$5.2	$9.0	$12.7	$18.6
6 Mtpa, 500 miles	$8.7	$17.9	$27.1	$33.0
15 Mtpa, 0 miles	$4.0	$6.2	$8.4	$13.7
15 Mtpa, 100 miles	$4.5	$7.4	$10.4	$15.6
15 Mtpa, 500 miles	$6.3	$12.2	$18.2	$23.4

Table 6
Definition of the CO_2 transport and storage modeling cost cases.

	Scale Mtpa CO_2	Transport Distance (miles)	Regional Variation?	$T + S$ Cost ($/t$CO_2$)
Reference Case	N/A	N/A	No	$10
Base Case	3.2	100	Yes	Table 7
CCS Networks & Clusters	15	100	Yes	Appendix D
Low Cost EU	3.2	100	Yes	Same as Base Case but EU assigned to Medium cost tier – see Table 7

each CO_2 rate, we used the national average cost estimate of $8/t$CO_2$ to store 3.2 Mtpa CO_2 reported in NPC (2019) as the anchor for calculating our storage cost range. We did this by calculating a ratio between the NPC (2019) and our mean capacity-weighted storage cost for 3.2 Mtpa CO_2 under base monitoring assumptions, resulting in a ratio of 1.36. We then applied this ratio to our mean capacity-weighted storage costs for 1 and 6 Mtpa CO_2 to bring our estimated cost for each CO_2 rate in line with NPC (2019). As discussed above, we then calculated the costs for 15 Mtpa by extrapolation. Finally, similar to our CO_2 transport cost range, we applied two standard deviations below and above our NPC-adjusted, capacity-weighted mean storage cost to calculate our low- and high-cost range for each CO_2 rate under base monitoring assumptions (Table 3). See Appendix A for more detail on our calculations.

Next, we examined CO_2 storage costs under extra monitoring assumptions. We applied the ratio of 1.36 directly to the capacity-weighted mean cost we calculated under USDOE (2017) default monitoring assumptions to adjust them in line with the NPC figures (Table 4).

Table 7
Regional inputs for CO_2 transport and storage costs for the Base Case. Costs are in current 2019$/t$CO_2$.

	Tier 1 - Low Cost	Tier 2 - Medium Cost	Tier 3 - High Cost	Tier 4 - Shipping Cost
Transport Cost ($/t$CO_2$)	$3.22	$5.17	N/A	N/A
Storage Cost ($/t$CO_2$)	$8.00	$10.75	N/A	N/A
Total Cost ($/t$CO_2$)	$11.22	$15.92	$25.86	$35.8
Assumptions	Mean value for 3.2 Mtpa CO_2, 100 miles from Table 5	High value for 3.2 Mtpa CO_2, 100 miles from Table 5	Midpoint between Medium Cost and Shipping tiers	Northern Lights Project, Low Range
EPPA Regions	USA; Middle East; Russia; Canada; Mexico	China; Australia; Brazil; Indonesia; Other Latin America; Other Eurasia; Dynamic Asia; Other East Asia	Africa; India	Europe; Japan; Korea

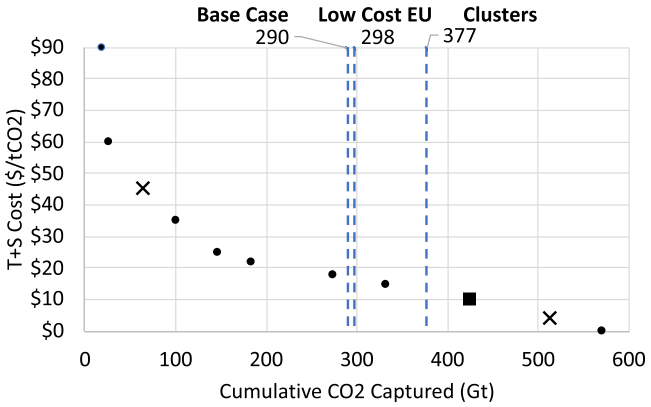


Fig. 4. Cumulative global CO_2 captured and stored (2020–2100) under a scenario that limits warming to 2 °C. Points reflect cases where transport and storage costs are uniform in all regions (*Reference Case* is reflected by the square; our cost range of $4 to $45/t$CO_2$ is reflected by x's). Vertical lines reflect cases where transport and storage costs vary by EPPA region.

See Appendix A for more detail on our calculations. As can be seen in Fig. 2, CO_2 storage cost declines rapidly with scale and then level off after about 5–6 Mtpa.

4. Combined CO_2 transport and storage cost range

Once we calculated the CO_2 transport and storage cost ranges separately, we compiled them into a combined CO_2 transport and storage cost range. It is important to flag that these costs are reflective of onshore CO_2 pipeline transport and onshore geologic storage (in saline aquifers and depleted oil and gas fields) in the United States. We explore applying these costs to other regions in the next section.

Our estimates capture five key sources of variability impacting transport and storage costs as discussed in Sections 2.3 and 3.3, and listed in order from largest to smallest impact on combined transport and storage costs: 1) transport distance, 2) scale (i.e. quantity of CO_2 transported and stored), 3) extra monitoring assumptions, 4) geologic variability, and 5) transport variability. Fig. 3 shows the sensitivity range of CO_2 transport and storage costs for each of these sources of variability. See Appendix B for summary of $T + S$ cost components.

Table 5 shows the cost of CO_2 transport and storage for various

Table 8
Cumulative Gt CO_2 captured and stored (2020–2100) by EPPA region for different transport and storage costs assumptions when warming is limited to 2C.

Cumulative Gt CO_2 captured and stored by case (2020–2100)		USA, Tier 1	China, Tier 2	India, Tier 3	EU, Tier 4	Other Regions	Total
Reference	\$10/tCO_2	29	174	72	16	134	425
Uniform $T + S$ Costs	\$4/tCO_2	38	213	75	21	166	513
	\$45/tCO_2	12	1	31	6	16	65
	\$90/tCO_2	6	0	1	6	5	18
Regional Cases	Base Case	28	103	61	6	92	290
	CCS Networks & Clusters	30	173	62	6	106	377
	Low Cost EU	28	103	61	14	92	298

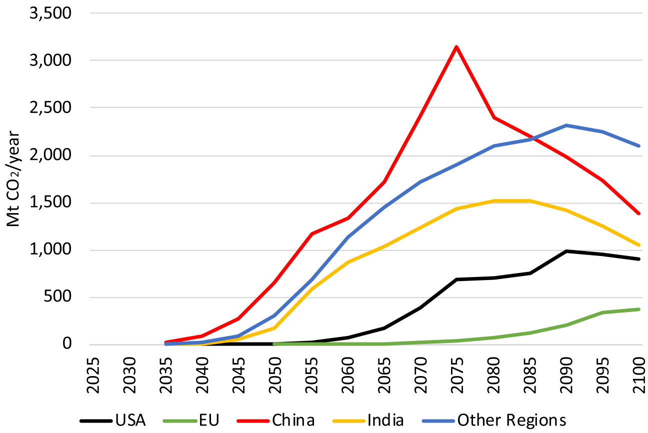


Fig. 5. CO_2 captured and stored in the *Base Case* under a scenario that limits warming to 2 °C, by EPPA region.

combinations of scale, transport distance, monitoring requirements, and low and high cost assumptions. For our modeling exercise, we identified three transport distances (0, 100, and 500 miles) reflecting various assumptions about how far CO_2 must be transported from the point of capture to a secure geologic reservoir. The overall CO_2 transport and storage cost ranges from a low of \$4/tCO_2 to a high of \$88.9/tCO_2. Note that the \$88.9/tCO_2 is incurred for transporting a very small amount of CO_2 (1 Mtpa) over a long distance (500 miles) and assumes extra monitoring requirements for CO_2 storage. Such a project would not likely be developed. A cost of \$45/tCO_2 is a more reasonable high bound because this reflects transport and storage projects of more realistic scope (1 Mtpa CO_2 over 100 miles, or 3.2 Mtpa CO_2 over 500 miles).

5. Modeling cases

Our modeling cases are summarized in Table 6. These cases were assessed using the MIT Economic Projection and Policy Analysis (EPPA) model but could be applied to other integrated assessment models. Because many analyses used in IAMs like EPPA assume a fixed CO_2 transport and storage cost of \$10/tCO_2 for all regions, regardless of the underlying quantity of CO_2 being transported and stored and other underlying assumptions, we called this our reference case.

As described in the previous section, our Base Case uses a cost of \$11.2/tCO_2 for transporting 3.2 Mtpa of CO_2 100 miles for onshore storage in the United States. To complete the base case, we then assign the remaining 17 EPPA regions to one of four cost tiers: low, medium, and high cost assumptions for onshore CO_2 pipeline transport and storage, and one tier assuming shipping and offshore storage. Because the United States has multiple active CCS projects, is an oil and gas producer, has a low cost of capital, and has a large CO_2 storage capacity, we assumed the U.S. Base Case cost of \$11.2/tCO_2 reflects the low end of the CO_2 transport and storage cost range.

To assign the EPPA regions into cost tiers, we first separated regions we believe would use CO_2 shipping: Europe, Japan, and Korea. We ranked the remaining 14 EPPA regions based on 1) 2015 oil and gas production, 2) cost of capital, 3) available years of CO_2 storage, and 4) maturity and extent of oil and gas infrastructure (see Appendix D). We expect these three factors are useful proxies for the cost of transporting and storing CO_2 in each region. This method was useful but had limitations because it indicated some regions were favorable that we expect to have high transport and storage costs, and vice versa. This approach was still useful in guiding our sorting and we qualitatively sorted each EPPA region into tiers outlined in Table 7. As mentioned above, the low-cost tier uses the U.S. base case cost. The medium-cost tier uses the high cost assumptions for transporting 3.2 Mtpa CO_2 over 100 miles for storage without extra monitoring (see Table 5). The high cost tier is the midpoint between the medium-cost and shipping tiers.

We examined two additional modeling cases, one that assumes low transport and storage costs from economies of scale of CCS networks and clusters (see Appendix D), and another that assumes Europe has Medium Cost transport and storage costs. The latter case is identical to the base case, except Europe is assigned to Tier 2 instead of Tier 4.

6. Results and discussion

Using the EPPA model, we examined the impact of transport and storage cost variability under a carbon constrained future when global temperature rise is limited to 2 °C by applying an escalating, globally uniform, price of carbon emissions as did Morris et al. (2020). The results are shown in Fig. 4. Table 8 shows details for four key regions, one from each of the cost tiers defined in Table 7.

We first ran a series of "uniform cost" cases where transport and storage costs were fixed in all regions ranging from \$0 to \$90/t$CO_{2,}$ including the previous "reference case" assumption of \$10/t$CO_{2.}$ These are shown by the dots in Fig. 4, with the *Reference Case* indicated by a black square. The *Reference Case* results in 425 Gt CO_2 captured and stored cumulatively by 2100 – identical to the level found in Morris et al. (2020). The values corresponding to our range of variability of cost of \$4 to \$45/tCO_2 from Section 4 are 513 to 65 Gt CO_2, respectively.

Under our *Base Case* assumptions outlined in Table 7, 290 Gt CO_2 is captured and stored cumulatively by 2100 - a reduction of 32% from the *Reference Case* (see Table 8). Europe faces the highest transport and storage costs in the *Base Case* of ~\$35/tCO_2 because it is assumed to employ shipping and offshore storage. This is much higher than \$10/tCO_2 assumed in the *Reference Case* and reduces cumulative CO_2 captured and stored in Europe from 16 to 6 Gt CO_2 by 2100 (a reduction of over 60%). Large-scale ramp-up of natural gas plants equipped with CCS is delayed in Europe until 2070 (see Fig. 5), reducing cumulative electricity generated from these sources by over 50% compared to the reference case. India is in the next highest cost tier of ~\$25.86/tCO_2 and, under a 2 °C scenario, witnesses a 27% increase in nuclear power generation and a 16% reduction in power generation from coal with CCS due to higher transport and storage costs than in the reference case. This is accompanied by a reduction of 10 Gt in cumulative CO_2 stored and captured by 2100. The significantly higher transport and storage costs in these regions in the *Base Case* reduces CCS deployment in the power sector.

China is in the medium transport and storage cost tier of ~\$15.92/tCO_2 in the *Base Case* – only moderately higher than the *Reference Case* of \$10/t$CO_{2.}$ Electricity generation from coal with CCS is cut by 40% in

China compared to the *Reference Case*, much of which is replaced by nuclear power. This results in roughly 70 fewer Gt CO_2 cumulatively stored between 2020 and 2100, with a peak in 2075 in annual CO_2 captured (see Fig. 5). This is noteworthy given the transport and storage costs increased only moderately compared to the reference case and suggests CCS deployment in China may be more sensitive to CCS costs than was previously understood. In China, other power generation options such as nuclear have lower or similar capital costs to coal with CCS such that moderate increases in transport and storage cost make CCS uncompetitive. The United States is in the low-cost tier of $11.2/t$CO_2$. Because U.S. transport and storage costs are only slightly higher than in the *Reference Case*, the results do not differ much.

We also examined a case where we assume low transport and storage costs due to the economies of scale achieved by rollout of shared CO_2 transport networks and CCS clusters (Appendix D). In this *Clusters Case*, 377 Gt CO_2 are captured and stored cumulatively by the end of the century – a 30% increase from the *Base Case*. In the *Clusters Case,* we assume identical (in the case of Europe) or very similar (in the case of India and China) transport and storage costs as the *Base Case*, so the results are very similar to the *Base Case* in these regions. The United States sees approximately a 25% reduction in transport and storage costs of compared to the reference case (~$7.4/t$CO_2$), but this does not produce noticeable changes in the U.S. electricity profile other than a slight increase (14%) in electricity generation from coal plants with CCS.

We also examined a case where Europe experiences low transport and storage costs – either because it employs pipelines instead of ships, starts storing CO_2 onshore, or the Northern Lights Project sees rapid cost declines. Under such *Low Cost EU* assumptions, Europe is assigned to the medium cost tier of ~$15.92/t$CO_2$ – moderately higher than the *Reference Case* but below *Base Case* assumption of ~$35/t$CO_2$. When we assume Europe has low transport and storage costs, an additional 8 Gt CO_2 is cumulatively captured and stored globally compared to the *Base Case*, driven by a doubling in the amount of electricity generated from natural gas plants with CCS in Europe. Under these assumptions, slightly less (2 Gt) CO_2 is stored cumulatively by 2100 in Europe compared to the *Reference Case*. See Appendix E for snapshots of annual CO_2 captured and stored in 2050 and 2075 in four key regions across the cases.

7. Conclusions

We estimate a practical cost range of $4 to $45/t$CO_2$ for the transport and storage of CO_2 via pipeline. This range represents the range that could be expected across geographic, geologic, and institutional settings. These costs depend on five key sources of variability: transport distance; scale; extra monitoring assumptions; geologic characteristics; and transport cost variability (primarily pipeline capital costs). For the combined cost of transporting CO_2 via ship for offshore storage, we used the low range of the most recent estimates from the Northern Lights Project of €30–55/tCO_2 ($35 to $64/t$CO_2$ USD). We use estimates of cost variability to estimate expected regional differences in transport and storage cost.

In our reference case, where transport and storage costs are assumed to be $10/t$CO_2$ uniformly across all regions, results generated using the MIT Economic Projection and Policy Analysis (EPPA) model give 425 Gt CO_2 captured and stored cumulatively from 2020 through 2100. When uniform transport and storage costs are assumed, the model-estimated cumulative CO_2 captured and stored decreases with increasing assumed cost.

Our base case, which captures regional variability by assigning our best estimate of CO_2 transport and storage costs to each of the 18 EPPA regions, results in 290 Gt CO_2 captured and stored cumulatively by 2100. CCS transport networks and storage clusters increase global capacity to capture and store CO_2, with 30% more CO_2 captured and stored cumulatively by 2100 compared to the *Base Case*. Incorporating lower transport and storage costs in Europe – which could occur if projected shipping and storage costs from the Northern Lights Project decline or Europe pursues pipelines instead of ships - results in an additional 8 Gt CO_2 captured and stored cumulatively by 2100 in Europe compared to the *Base Case*.

The frequently used value of $10/t$CO_2$ for transport and storage costs is a reasonable assumption in some regions (i.e. the United States, Middle East, Russia, Canada, and Mexico) but not in others (i.e. Europe, Japan, China, Africa, India, etc.). This assumption has a large impact on CCS deployment in regions such as China that have power generation alternatives with low or similar capital costs, making CCS competitiveness more sensitive to increases in transport and storage cost than other regions.

Several transport and storage options should be taken into account when modeling large-scale deployment of CCS in decarbonization pathways. Pipelines are still expected to be the main method of transporting CO_2, and these costs can increase or decrease depending whether the pipeline is assumed to be onshore or offshore or is part of a shared transport infrastructure. Shipping can be cost effective over long distances in regions with limited onshore CO_2 storage capacity, such as in Japan, or that have regulatory barriers to onshore CO_2 transport and storage, such as is seen in Europe (IEAGHG 2020).

Cost data are scarce, there is still a significant amount of uncertainty and variability in available CO_2 transport and storage costs, and more analysis is needed to quantify the cost ranges. Deploying CCS at the scale needed to achieve global emissions reduction goals will require buildout of infrastructure to transport and store gigaton-scale levels of CO_2. Qualitatively it is known that CCS transport networks and storage hubs can significantly reduce CO_2 transport and storage costs, and that these will develop in different locations at different paces. It is also known that CO_2 transport and storage costs vary regionally and CCS deployment will be more sensitive to these costs in some regions than others. In addition, regulatory regimes can enable or create barriers for certain CO_2 transport and storage options and can impose or remove significant costs accordingly. More work is needed to quantify the impact of these factors on CO_2 transport and storage costs, especially at the regional level.

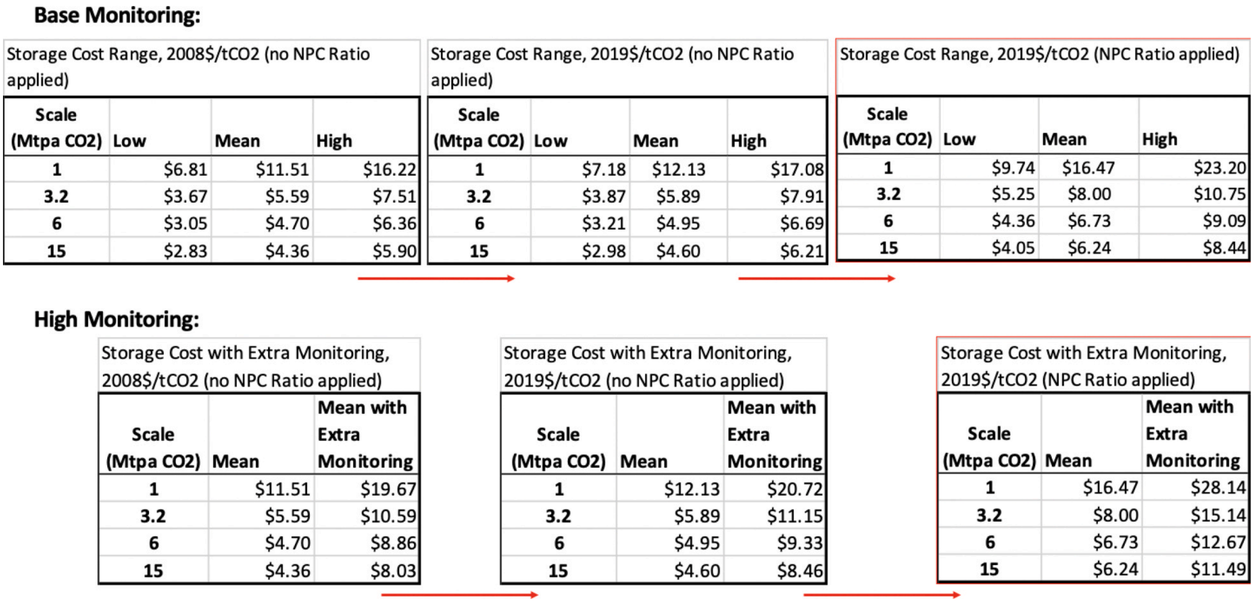
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The study is supported by an international consortium of government, industry and foundation sponsors of the MIT Joint Program on the Science and Policy of Global Change (see the list at: https://globalchange.mit.edu/sponsors) and by ExxonMobil through its membership in MIT Energy Initiative.

Appendix A



Base Monitoring:

Storage Cost Range, 2008$/tCO2 (no NPC Ratio applied)

Scale (Mtpa CO2)	Low	Mean	High
1	$6.81	$11.51	$16.22
3.2	$3.67	$5.59	$7.51
6	$3.05	$4.70	$6.36
15	$2.83	$4.36	$5.90

Storage Cost Range, 2019$/tCO2 (no NPC Ratio applied)

Scale (Mtpa CO2)	Low	Mean	High
1	$7.18	$12.13	$17.08
3.2	$3.87	$5.89	$7.91
6	$3.21	$4.95	$6.69
15	$2.98	$4.60	$6.21

Storage Cost Range, 2019$/tCO2 (NPC Ratio applied)

Scale (Mtpa CO2)	Low	Mean	High
1	$9.74	$16.47	$23.20
3.2	$5.25	$8.00	$10.75
6	$4.36	$6.73	$9.09
15	$4.05	$6.24	$8.44

High Monitoring:

Storage Cost with Extra Monitoring, 2008$/tCO2 (no NPC Ratio applied)

Scale (Mtpa CO2)	Mean	Mean with Extra Monitoring
1	$11.51	$19.67
3.2	$5.59	$10.59
6	$4.70	$8.86
15	$4.36	$8.03

Storage Cost with Extra Monitoring, 2019$/tCO2 (no NPC Ratio applied)

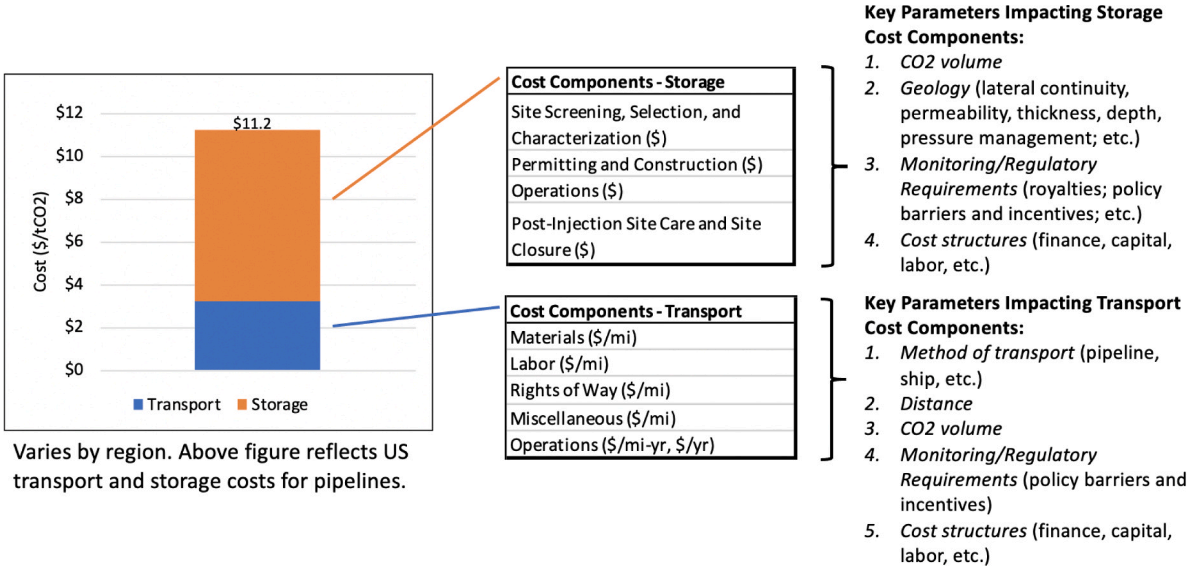
Scale (Mtpa CO2)	Mean	Mean with Extra Monitoring
1	$12.13	$20.72
3.2	$5.89	$11.15
6	$4.95	$9.33
15	$4.60	$8.46

Storage Cost with Extra Monitoring, 2019$/tCO2 (NPC Ratio applied)

Scale (Mtpa CO2)	Mean	Mean with Extra Monitoring
1	$16.47	$28.14
3.2	$8.00	$15.14
6	$6.73	$12.67
15	$6.24	$11.49

A.1. CO_2 storage cost range under base (top row) and high (bottom row) monitoring assumptions
Costs were first escalated from 2008 current dollars to 2019 current dollars. A ratio of 1.36 was calculated by dividing the NPC average storage cost ($8/t$CO_2$) by the capacity-weighted mean storage cost for 3.2 Mtpa in 2019 dollars (aka: $5.89). The ratio of 1.36 was then applied to the capacity weighted mean storage cost for 1 and 6 MTPA CO_2 for the Base monitoring assumptions, and then to the capacity-weighted High monitoring assumption storage cost for 1 and 6 Mtpa.

Appendix B



Varies by region. Above figure reflects US transport and storage costs for pipelines.

Cost Components - Storage
Site Screening, Selection, and Characterization ($)
Permitting and Construction ($)
Operations ($)
Post-Injection Site Care and Site Closure ($)

Cost Components - Transport
Materials ($/mi)
Labor ($/mi)
Rights of Way ($/mi)
Miscellaneous ($/mi)
Operations ($/mi-yr, $/yr)

Key Parameters Impacting Storage Cost Components:

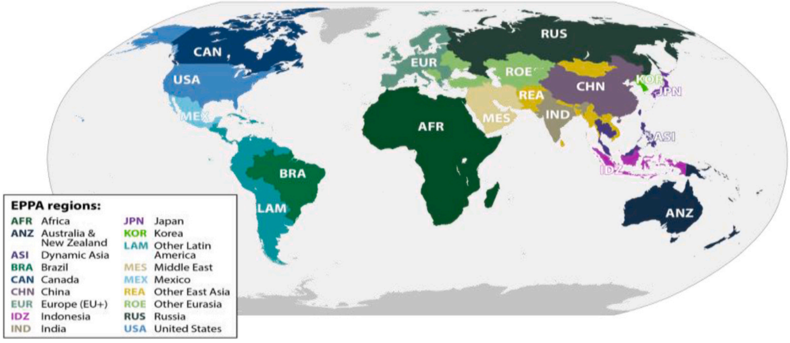
1. *CO2 volume*
2. *Geology* (lateral continuity, permeability, thickness, depth, pressure management; etc.)
3. *Monitoring/Regulatory Requirements* (royalties; policy barriers and incentives; etc.)
4. *Cost structures* (finance, capital, labor, etc.)

Key Parameters Impacting Transport Cost Components:

1. *Method of transport* (pipeline, ship, etc.)
2. *Distance*
3. *CO2 volume*
4. *Monitoring/Regulatory Requirements* (policy barriers and incentives)
5. *Cost structures* (finance, capital, labor, etc.)

B.1. Summary of CO_2 transport and storage cost components.

Appendix C



C.1. EPPA region description and characteristics.

2015 oil and gas production is drawn from BP (2019) Statistical Review of Global Energy. Capital cost scaling factors are drawn from Morris et al. (2019). Years to store CO_2 are calculated based on 2015 CO_2 emissions (Reilly et al., 2018) and the low estimate of onshore CO_2 storage capacity from Kearns et al. (2017).

Appendix D

D.1

Breakdown of CO_2 transport and storage cost tiers for CCS Networks and Clusters Case.

	Tier 1 - Low Cost	Tier 2 - Medium Cost	Tier 3 - High Cost	Tier 4 - Shipping Cost
Transport Cost ($/t$CO_2$)	$1.19	$1.94	N/A	N/A
Storage Cost ($/t$CO_2$)	$6.24	$8.44	N/A	N/A
Total Cost ($/t$CO_2$)	**$7.44**	**$10.38**	**$23.09**	**$35.8**
Assumptions	Mean value for 15 Mtpa CO_2, 100 miles from Table 5	High value for 15 Mtpa CO_2, 100 miles from Table 5	Midpoint between Medium Cost and Shipping tiers	Northern Lights Project, Low Range
EPPA Regions	USA; Middle East; Russia; Canada; Mexico	China; Australia; Brazil; Indonesia; Other Latin America; Other Eurasia; Dynamic Asia; Other East Asia	Africa; India	Europe; Japan; Korea

Appendix E

E.1

Snapshot of Mt CO_2/year Captured and Stored in 2050 and 2075.

Mt CO_2/year captured and stored in 2050		USA	EU	China	India	Other Regions	Total
Reference	$10/t$CO_2$	14	19	2017	443	466	2959
Uniform $T + S$ Costs	$4/t$CO_2$	18	24	2636	554	1133	4365
	$45/t$CO_2$	6	2	0.5	27	15	50
	$90/t$CO_2$	2	2	0	1	3	8
Regional Cases	Base Case	14	2	654	181	302	1152
	CCS Networks & Clusters	14	2	1972	224	417	2629
	Low Cost EU	14	16	655	181	301	1166
Mt CO_2/year captured and stored in 2075		USA	EU	China	India	Other Regions	Total
Reference	$10/t$CO_2$	693	358	4242	1584	2912	9789
Uniform $T + S$ Costs	$4/t$CO_2$	945	504	4377	1638	3590	11,053
	$45/t$CO_2$	100	42	7	904	231	1284
	$90/t$CO_2$	44	42	3	17	47	154
Regional Cases	Base Case	691	42	3143	1437	1905	7218
	CCS Networks & Clusters	751	42	4230	1440	2267	8731
	Low Cost EU	691	274	3149	1439	1905	7458

References

Abramson, Elizabeth, Dane McFarlane, Jeff Brown. "Whitepaper on regional infrastructure for midcentury decarbonization." Great Plains Institute. June 2020.

Anderson, Steven T., 2017. "Cost Implications of Uncertainty in CO_2 Storage Resource Estimates: a Review". Nat Resources Res 26 (2), 137–159.

Anderson, Steven T., Jahediesfanjani, Hossein, 2019. "Estimating the Pressure-Limited Dynamic Capacity and Costs of Basin-Scale CO_2 Storage in a Saline Formation". Int J Greenhouse Gas Control 88, 156–167. September 1.

Bennett, Simon, Stanley, Tristan, 2018. "US budget bill may help carbon capture get back on track". Int Energy Agency. 12.

CO2Europipe, "Towards a Transport Infrastructure for Large-Scale CCS in Europe: WP3.3 Report – Legal, Financial, and Organizational Aspects of CO2 Pipeline Infrastructure", May 2011.

Dahowski, R.T., Davidson, C., Dooley, J., 2011. Comparing large scale CCS deployment potential in the USA and China: a detailed analysis based on country-specific CO_2 transport and storage cost curves. Energy Procedia 4, 2732–2739.

Friedmann, S Julio, Zapantis, Alex, Page, Brad, Consoli, Chris, Fan, Zhiyuan, Havercroft, Ian, Liu, Harry, 2020. "Net-zero and geospheric return: actions today for 2030 and beyond". Columbia SIPA Center on Global Energy Policy; Global CCS Institute 55. September.

GCCSI. "Economic Assessment of Carbon Capture and Storage Technologies: 2011 Update", 2011.

Grant, Tim, David Morgan, Kristin Gerdes. "Quality Guidelines for Energy System Studies: carbon Dioxide Transport and Storage Costs in NETL Studies". U.S. Department of Energy Office of Fossil Energy. National Energy Technology Laboratory (NETL), November 2017.

Gunnarsson, Ingvi, Aradóttir, Edda S., Oelkers, Eric H., Clark, Deirdre E., Arnarson, Magnús Þór, Sigfússon, Bergur, Snæbjörnsdóttir, Sandra Ó., 2018. "The Rapid and Cost-Effective Capture and Subsurface Mineral Storage of Carbon and Sulfur at the CarbFix2 Site". Int J Greenhouse Gas Control 79, 117–126.

Heddle, Gemma, Howard Herzog, Michael Klett. "The Economics of CO2 Storage". Massachusetts Institute of Technology Laboratory for Energy and the Environment, MIT LFEE 2003-003 RP (2003): 115.

Herzog, H., 2011. Scaling up carbon dioxide capture and storage: from megatons to gigatons. Energy Economics 33, 594–604.

IEA., 2020. "CCS in Clean Energy Transitions: special Report on Carbon Capture Utilisation and Storage". Energy Technol Perspect.

IEAGHG. "Effects of Plant Location on the Costs of CO2 Capture". IEAGHG Technical Report. United Kingdom: IEA Greenhouse Gas R&D Programme, August 2017.

IEAGHG. "The status and challenges of CO2 shipping infrastructures". IEAGHG Technical Report 2020-10. July 2020.

IECM. Integrated Environmental Control Model (IECM) Version 11.4. Carnegie Mellon University. 2015. https://www.cmu.edu/epp/iecm/index.html.

IPCC, 2014. In: *Climate Change 2014: Mitigation of Climate Change*. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2005. Intergovernmental Panel on Climate Ce. *Special Report on Carbon Dioxide Capture and Storage*. Cambridge University Press.

JGC Corporation. "CO2 transport demonstration." Japan CCS Forum 2019. June 12, 2019.

Kearns, Jordan, Teletzke, Gary, Palmer, Jeffrey, Thomann, Hans, Kheshgi, Haroon, Chen, Yen-Heng Henry, Paltsev, Sergey, Herzog, Howard, 2017. "Developing a Consistent Database for Regional Geologic CO_2 Storage Capacity Worldwide". Energy Procedia 114, 4697–4709.

McCoy, S.T., Rubin, E.S., 2008. An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage. Int J Greenhouse Gas Control 2, 219–229.

Morris, J., Farrell, J., Kheshgi, H., Thomann, H., Chen, Y.H., Paltsev, S., Herzog, H., 2019. Representing the costs of low-carbon power generation in multi-regional multi-sector energy-economic models. Int J Greenhouse Gas Control 87, 170–187.

Morris, J., Kheshgi, H., Paltsev, S., Herzog, H., 2020. Scenarios for the deployment of carbon capture and storage in the power sector in a portfolio of mitigation options. Climate Change Econ.

Northern Lights Project. "Northern Lights: a European CO2 Transport and Storage Network". February 24, 2020.

NPC. "Meeting the dual challenge: a roadmap to at-scale deployment of carbon capture, use, and storage". 2019.

Pale Blue Dot Energy, Axis Well Technology. "Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource: a Summary of Results from the Strategic UK CO2 Storage Appraisal Project", April 2016.

Psarras, Peter, He, Jiajun, Pilorgé, Hélène, McQueen, Noah, Jensen-Fellows, Alexander, Kian, Kourosh, Wilcox, Jennifer, 2020. "Cost Analysis of Carbon Capture and Sequestration from U.S. Natural Gas-Fired Power Plants". Environ. Sci. Technol. 54 (10), 6272–6280.

Reilly, John, Ronald Prinn, Henry Chen, Andrei Sokolov, Xiang Gao, Adam Schlosser, Jennifer Morris, "Food, water, energy, climate outlook perspectives from 2018". MIT Joint Program on the Science and Policy of global Change. 2018.

Righetti, Tara K., 2017. "Siting Carbon Dioxide Pipelines". Oil Gas Natural Resources Energy J 3 (4), 70.

Rubin, Edward S., Davison, John E., Howard, Howard J., July 3, 2015. "The Cost of CO_2 Capture and Storage". Int J Greenhouse Gas Control 40, 378–400.

Sanchez, Daniel L., Nils Johnson, Sean T. McCoy, Peter A. Turner, Katharine J. Mach. "Near-Term Deployment of Carbon Capture and Sequestration from Biorefineries in the United States". *Proceedings of the National Academy of Sciences*, 115, no. 19 (May 8, 2018): 4875–80.

Szulczewski, Michael L, Christopher W MacMinn, Howard J Herzog, Ruben Juanes. "Supporting Information for: the Lifetime of Carbon Capture and Storage as a Climate-Change Mitigation Technology". 2012, 93.

U.S. Bureau of Labor Statistics. "Producer Price Index (PPI) for commodities in the United States from 1990 to 2019". January 2020.

USDOE, 2014a. FE/NETL CO2 Saline Storage Cost Model: model Description and Baseline Results, Report No. DOE/NETL-2014/1659. US Dept of Energy, National Energy Technology Laboratory, Pittsburgh, PA.

USDOE, 2014b. FE/NETL CO2 Transport Cost Model: description and User's Manual, Report No. DOE/NETL-2014/1660. US Dept of Energy, National Energy Technology Laboratory, Pittsburgh, PA.

USDOE, 2017. FE/NETL CO2 Saline Storage Cost Model: description and User's Manual, Report No. DOE/NETL-2018/1873. US Dept of Energy, National Energy Technology Laboratory, Pittsburgh, PA.

USDOE, 2018. FE/NETL CO2 Transport Cost Model: description and User's Manual, Report No. DOE/NETL-2018/1877. US Dept of Energy, National Energy Technology Laboratory, Pittsburgh, PA.

USGS 2013. National assessment of geologic carbon dioxide storage resources – Results. Ver. 1.1; 2013.

Zapantis, Alex, Townsend, Alex, Rassool, Dominic, 2019. "Policy Priorities to Incentivise Large Scale Deployment of CCS". Thought Leadership Report. Global CCS Institute. April.

ZEP, 2011a. The costs of CO2 storage: post-demonstration CCS in the EU. European Technology Platform for Zero Emission Fossil Fuel Power Plants. Brussels, Belgium.

ZEP, 2011b. The cost of CO2 transport: post-demonstration CCS in the EU. European Technology Platform for Zero Emission Fossil Fuel Power Plants. Brussels, Belgium.