Original Research Article

GREENHOUSE GASES SCIENCE AND TECHNOLOGY

Developing a roadmap for carbon capture, and storage in Oklahoma by assessing the viability of stacked storage

Marcos W. Miranda, Carbon Solutions LLC, Okemos, Michigan, USA and Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, Columbus, Ohio, USA
Jonathan D. Ogland-Hand, Carbon Solutions LLC, Okemos, Michigan, USA
Jeffrey M. Bielicki, Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, Columbus, Ohio, USA and John Glenn College of Public Affairs, The Ohio State University, Columbus, Ohio, USA
Rouzbeh G. Moghanloo and Jamal DaneshFar, University of Oklahoma, Norman, Oklahoma, USA
Richard S. Middleton, Carbon Solutions LLC, Okemos, Michigan, USA

Abstract: The Intergovernmental Panel on Climate Change concludes that CO_2 capture and storage (CCS) is critical for climate-stabilizing energy transitions. In CCS, captured CO_2 is sequestered in saline aquifers within sedimentary basins. The CO_2 storage capacity and the rate of injection are functions of the geology of the saline aquifer, which is uncertain. To minimize impacts of this uncertainty, CCS projects could include backup plans, such as co-locating geologic CO_2 storage (GCS) sites with or near existing CO_2-enhanced oil recovery (CO_2-EOR) operations. These "stacked storage" projects could hedge against uncertainty in the saline formation performance because captured CO_2 could be injected into either location in the event of unexpected events (e.g., the injectivity decreases). Here, we investigate the possibility and ramifications of developing CCS networks in Oklahoma that are amendable to stacked storage. We find that stacked storage is possible in Oklahoma but the counties with the lowest-cost saline storage resources do not have existing CO_2-EOR operations. At the systems level, we find it is slightly more expensive (e.g., \$1/tCO_2 to \$5/tCO_2) to site GCS in counties with CO_2-EOR projects. This increased expense is largely due to increased CO_2 transportation costs because hundreds of km of additional pipeline is required to capture CO_2 from the lowest-cost sources. Overall, our results suggest that it is optimal to build more pipelines and avoid injecting CO_2 in some of

Correspondence to: Carbon Solutions LLC, Okemos, MI, USA.
E-mail: miranda.116@osu.edu; marcos.miranda@carbonsolutionsllc.com
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the lowest-cost saline storage resources, to enable capturing CO_2 from the least-cost sources. © 2023 Society of Chemical Industry and John Wiley & Sons, Ltd.

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Keywords: CCS; SCO_2T^{PRO}; $SimCCS^{PRO}$; site-screening; stacked storage; stacked storage

Introduction

Background and motivation

Pathways that limit climate warming to 1.5 or 2°C involve deep and, in most cases, immediate GHG emission reductions in all economic sectors.[1] CO_2 capture and storage (CCS) is consistently among the portfolio of technologies and processes included in these pathways. In CCS, CO_2 that would otherwise be emitted is instead captured and geologically stored in saline formations underground. The AR6 synthesis report projects a median average of 664 billion tons or gigatons of CO_2 (664 $GtCO_2$) will need to be injected and stored by 2100 across 97 different emission reduction pathways modeled.[2]

The primary constraint historically limiting the deployment of CCS is a lack of financial incentives. Despite the need for CCS deployment to reach climate mitigation targets, there is no natural market for geologically stored CO_2 because it has no inherent or intrinsic market value at the scale required for climate targets. But this is changing, at least in the United States, with the passage of the Inflation Reduction Act (IRA), which enhanced transferrable tax credits that can be easily monetized. Under the IRA, sequestered CO_2 is worth \$60 or \$85/tCO_2, depending on if it is utilized or permanently sequestered in subsurface resources, respectively. As such, there is now a financial incentive in the United States for companies to incur the cost of CCS. This is timely since the operational capacity of CCS projects being planned has increased by 44% since 2021.[3]

As the financial hurdles are being addressed, one of the primary challenges now limiting the deployment of CCS is inherent uncertainty in the geology of the subsurface. Even after a potential geologic CO_2 storage (GCS) site is thoroughly characterized within a saline aquifer, which requires substantial time and investment, the CO_2 injectivity and capacity remain uncertain until at-scale CO_2 injection begins.[4] This uncertainty could be problematic for CCS operations as the CO_2 capture process might have to stop, meaning the facility emitting the CO_2 must also stop capturing, if CO_2 cannot be injected into the subsurface as planned. Consequently, CO_2 storage site plans typically include backup CO_2 injection wells.[5]

In addition to backup CO_2 injection wells, another option for addressing the uncertainty in the subsurface is stacked storage. In stacked storage systems, CO_2 is injected in either GCS or CO_2-enhanced oil recovery (CO_2-EOR) processes.[6] These stacked storage systems are defined by co-locating GCS in saline aquifers topped by a nonpermeable cap rock with depleted oil fields.[7] CO_2-EOR is a method by which CO_2 is used to repressurize and increase mobility in depleted oil fields to extract remaining oil. In contrast, GCS involves permanently storing CO_2 in deep saline aquifers or depleted oil fields.[8] Currently, in the United States, CO_2-EOR processes sequester approximately 70 million tons of CO_2 annually (70 $MtCO_2$/year), but 70% of this comes from underground mined sources of CO_2.[9] If CCS systems were to consider stacked storage, when unforeseen complications with the storage site occur, the captured CO_2 could be diverted to the CO_2-EOR process, thereby allowing CO_2 capture to continue uninterrupted and reducing reliance on mined sources of CO_2.

Literature review and research gap

Previously, stacked storage systems have been explored as a means for expanding on and financing GCS efforts because oil production is profitable.[6,7] But with the passage of the IRA, oil profit is no longer needed to financially justify GCS. Consequentially, a primary driver for developing stacked storage projects could be protecting against uncertainty in reservoir capacity and injectivity or jumpstarting geologic sequestration before transitioning away from hydrocarbon production. If complications arise with geologic CO_2 injection, in situations where either the capacity or injectivity are lower than expected, CO_2 could be diverted for use in co-located CO_2-EOR operations. In this way, stacked storage systems could be the first step in developing regional CCS systems by allowing flexibility in geologic CO_2 injection locations. In other words, stacked storage presents a unique opportunity to explore and improve upon CO_2 injection by hedging against uncertainty in underground reservoir parameters.

Despite the opportunity stacked storage may present to initial CCS networks, to our knowledge, no one has yet to quantitatively investigate how the integration of stacked storage in CCS decision making affects CCS network deployment. For example, prior work in CCS network deployment has considered depleted oil fields,[10] or using stacked storage as part of a CCS network within a limited region,[11] but did not examine how CCS pipeline deployment changes in response to prioritizing stacked storage and if there exist optimal combinations of stacked storage and geologic CO_2 storage. The closest study to consider multiple options for sequestering CO_2 in the design of regional CCS networks was focused on subsurface geothermal resources, highlighting potential co-benefits from GCS and CO_2 plume geothermal energy production.[12]

There are currently many open questions related to designing CCS networks that incorporate stacked storage such as, how does prioritizing stacked storage change the required CO_2 pipeline network? Yet no previous work explores what CCS networks would look like if they were to prioritize stacked storage development. For example, previous work in the field of stacked storage has indicated that captured CO_2 will be used for both CO_2-EOR operations and injection into saline formations13. Other work demonstrates that stacked storage has the life cycle potential to reduce greenhouse gases depending on injection procedures at the CO_2-EOR project.[14] Perhaps most closely related to work on CCS networks, is the SECARB Cranfield project which successfully injected captured CO_2 into a saline formation that was underlying a future CO_2-EOR project and demonstrated the feasibility of stacked storage through repurposing of wells.[15,16] In the field of CCS deployment, prior work has highlighted that increasing CCS deployment will require substantial investments in CO_2 pipeline infrastructure but does not quite examine how technologies such as stacked storage might directly affect this deployment.[17]

Contribution and scope of paper

In this study, we build upon the previous stacked storage work that demonstrates that stacked storage is feasible and can reduce CO_2 emissions, by considering how planning for stacked storage could influence CCS network development. This is novel because we are the first to study the effects (e.g., changes to pipeline, sources of CO_2 deployed for capture) that prioritizing stacked storage has on CCS network development. Specifically, we are the first to identify what costs (capture, transport, or storage) of a CCS network change the most when stacked storage is prioritized and identify, through a case study, key locations that could be targeted for future stacked storage exploration.

In addition to studying the development of a CCS network that considers stacked storage for the first time, we are also the first to focus on the state of Oklahoma as a case study. Oklahoma presents a unique opportunity for this investigation because there are already numerous CO_2-EOR projects in the state, and it has some of the best saline aquifer resources for GCS in the country. Oklahoma could become a leader in developing and expanding CCS efforts by deploying these stacked storage systems, but this has yet to be investigated. This work looks to support a roadmap for CCS development in states like Oklahoma by investigating how CCS networks may develop if existing CO_2-EOR projects were to play a role in determining site selection.

Methods

As suggested in Fig. 1, our methodology consists of applying preexisting tools to generate and use data within the *SimCCS*^{PRO} framework over three tasks:

1. Applying county-level geology data to the Sequestration of CO_2 tool (SCO_2T^{PRO}) software to estimate the cost and capacity of GCS for both the Simpson and Arbuckle formations. These are the two primary sedimentary basin saline formations that are targets for GCS in Oklahoma. The section on applying SCO_2T^{PRO} provides more details on SCO_2T^{PRO} and how it was applied.
2. Using the CO_2 national capture opportunities and readiness database (CO_2NCORD) to determine how much CO_2 is available for capture across Oklahoma, the cost of capturing that CO_2, and the location of all individual CO_2-emitting facilities. The section on applying CO_2NCORD describes CO_2NCORD in more detail and how we applied it for this study.

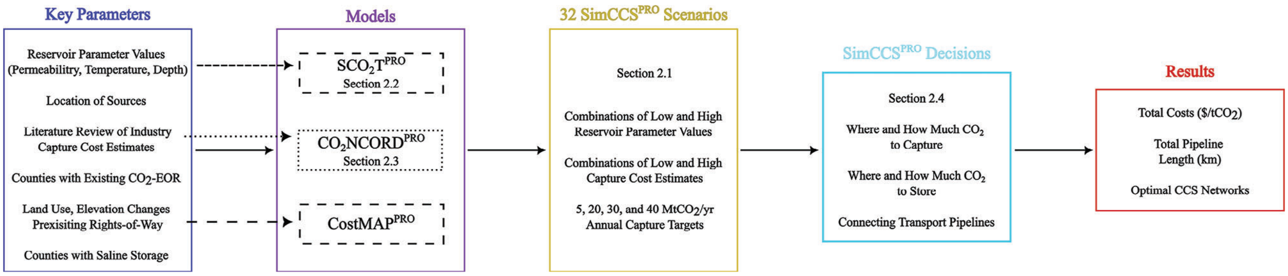

Figure 1. Overview of *SimCCS^{PRO}* workflow and key parameters for model inputs.

CO_2NCORD has absorbed an earlier working version of the database that was called NICO_2LE.

3. Parameterizing the scalable infrastructure model for carbon capture and storage (*SimCCS^{PRO}*) with the data from SCO_2T^{PRO} and CO_2NCORD across a range of scenarios to determine the average cost of the CCS network, the deployed sources of CO_2, counties for GCS, and pipelines networks. The section on running *SimCCS^{PRO}* provides more details on our scenarios modeled and the assumptions behind those scenarios.

Construction of scenarios

In this study, we use *SimCCS^{PRO}* to run a total of 32 distinct scenarios. Each of these scenarios involve a series of key parameters, such as reservoir parameters and capture costs, that are fed into SCO_2T^{PRO} and CO_2NCORD^{PRO}, respectively, to generate inputs for *SimCCS^{PRO}*. We first create two different sets of scenarios differentiating which counties could geologically store CO_2. In the first set of scenarios, CO_2 could be stored in any county with a saline aquifer resource that could be used for geologic CO_2 storage, including but not limited to those counties that have existing CO_2-EOR operations. This set of scenarios will enable us to understand if there is an optimal combination of injection locations that include both stacked storage and geologic CO_2 storage. In the second set of scenarios, CO_2 could only be stored in saline aquifer resources located in counties that also have existing CO_2-EOR operations. This set of scenarios examines how CCS networks deploy when stacked storage is the sole focus of CO_2 storage efforts in Oklahoma. By comparing the results of these two scenarios, we can better learn what are the ramifications of developing CCS networks amenable to stacked storage because stacked storage operations would only occur in counties that have both CO_2-EOR operations and geologic CO_2 saline-storage resources. Counties with CO_2-EOR operations were determined based on data from the state's CO_2 catalogue.

In both of the county sets, we have four scenarios for every combination of CO_2 storage (high and low reservoir properties; applying SCO_2T^{PRO} section) and CO_2 capture (high and low capture cost; applying CO_2NCORD section). These combinations provide a more careful look at different combinations of costs and storage options that will help determine optimal CCS networks. By using combinations of low and high estimates for capture costs and reservoir properties, this work can develop an understanding of how networks might be deployed in the future given different innovations in technologies or future criteria for CCS efforts.

It is important to note that tax credits that are available for permanently storing or utilizing captured CO_2 have not been applied to any of the costs associated with this analysis. That is to say, these are unsubsidized costs for CCS networks that are presented here. We made this decision because tax credits can change with time as policies are updated. As such, by focusing exclusively on costs, our findings will still be applicable as future policies are enacted.

Finally, for each set of counties and for each combination of storage and capture costs, we have four scenarios with annual CO_2 capture targets of 5, 15, 30, and 40 MtCO_2/year, with 40 MtCO_2/year representing the maximum available capturable emissions. As a result, these four capture targets represent a range of possible capture rates across the state. These different scenarios are laid out in Table 1 for clarity.

Applying SCO_2T^{PRO}

SCO_2T^{PRO} replicates full-physics dynamic reservoir simulations via reduced order models to estimate the capacity and cost of GCS given geologic parameters of saline aquifers.[18,19] In this study, we applied two sets of geologic parameters: scenarios using high (optimistic)

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Table 1. Listing of scenarios run through *SimCCS* for this analysis.

County's available for geologic CO_2 storage	Reservoir properties	Capture costs	Capture targets ($MtCO_2$/year)
All counties with saline aquifer available for geologic CO_2 storage	High	High	5, 15, 30, 40
	High	Low	5, 15, 30, 40
	Low	High	5, 15, 30, 40
	Low	Low	5, 15, 30, 40
Only counties with existing CO_2-EOR projects are available for geologic CO_2 storage	High	High	5, 15, 30, 40
	High	Low	5, 15, 30, 40
	Low	High	5, 15, 30, 40
	Low	Low	5, 15, 30, 40

reservoir parameters and scenarios using low (pessimistic) reservoir parameters, as key parameters for the model. These data were developed at the county-level resolution and were collected from open-hole logs analyzed at Oklahoma University.[20] There is inherent uncertainty in the geospatial variability of subsurface properties and our prior work demonstrates that holding everything else constant, the cost of CO_2 storage largely decreases with increasing reservoir depth, thickness, permeability, and geothermal temperature gradient.[19] More specifically, this prior work indicates that because fewer wells are required and more CO_2 can be injected in those wells that deploy, injection costs decrease with depth up until certain depths, whereafter the depth has less effect on costs. Additionally, this work finds that when not considering brine treatment, increasing geothermal gradient has almost negligible impact on injection costs. Finally, this work demonstrates that temperature and pressure affect CO_2 density inversely but that the overriding impact of CO_2 density ultimately indicates that storage injection rates and capacities rise as depth increases. As such, the geospatial cost of CO_2 storage estimated with these two sets of reservoir parameters is expected to capture the range of possible costs across Oklahoma counties.

Applying CO_2NCORD

CO_2NCORD applies CO_2 capture cost technoeconomic models and data from peer-reviewed literature to national-scale databases of CO_2 emitters to estimate the amount of capturable CO_2 from each facility and the cost of capturing that CO_2.[21] The key parameters for CO_2NCORD are the capture costs that are informed by various literature sources.[22–33] As CO_2 capture has yet to be deployed at scale, there is also industry dependent uncertainty on the cost of CO_2 capture. As a result, we used CO_2NCORD to generate low and high capture cost estimates for sources of CO_2 across Oklahoma.

There are a total of 140 sources that are included in this analysis across industries including chemical manufacturing, oil and gas extraction, electric power plants, and waste management. No exclusions were made based off emissions, capturable CO_2, or source type and we only considered a single stream of CO_2 for each source. In total, these sources emit approximately 40 million tons of capturable CO_2 ($MtCO_2$) each year. The ranges of capture costs used for this study are shown in Fig. 2.

Running *SimCCS^{PRO}*

SimCCS^{PRO} is an engineering-economic geospatial mixed-integer linear optimization that connects point sources of CO_2 with point GCS locations via pipelines.[34] *SimCCS^{PRO}* has been extensively used to design CCS networks in part due to its robust pipeline routing capabilities that provide more accurate routing costs.[35] *SimCCS^{PRO}* utilizes the site injection costs provided by SCO_2T, the capture costs provided by CO_2NCORD, and a weighted cost surface generated by CostMAP that accounts for changes in parameters such as population density, land use, and pre-existing rights-of-way. The location of sources and sinks and the weighed cost surface are used to generate a candidate pipeline network, using Delaunay Triangles, from which the optimal pipeline network will be created. For each of the 32 scenarios, *SimCCS^{PRO}* has an objective function that seeks to minimize total costs for the CCS network by deciding which sources of CO_2 to capture from and how much, which sink locations to inject CO_2 and how much, and the least cost pipeline network to connect these sources and sinks. The decisions that are then made by *SimCCS^{PRO}* outputs optimal CCS networks, reporting total costs ($/tCO_2$), costs for capture, transport, and storage ($/tCO_2$) as well as the total pipeline lengths (in kms). The individua sinks and sources deployed for each scenario are also provided.

The final key parameters for *SimCCS^{PRO}* relate to project lifetime and financing assumptions. Across every scenario and for the three models—*SimCCS^{PRO}*,

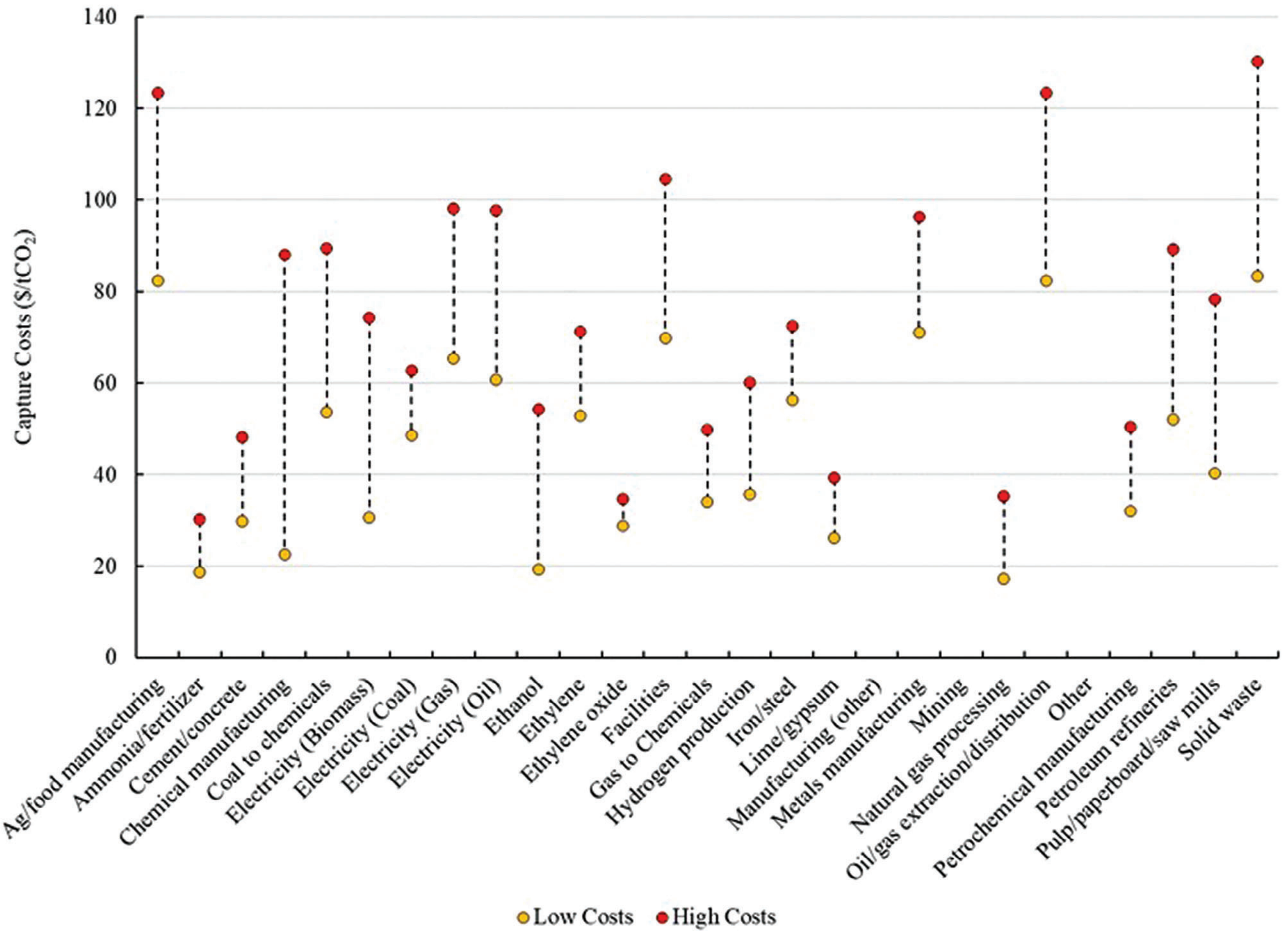

Figure 2. Range of capture costs for point-source emissions of CO_2 in Oklahoma.

CO_2NCORD, and SCO_2T^{PRO}—we assumed an interest rate of 8%.[36] Further, the project length was assumed to be 30 years. Lastly, CO_2 pipeline infrastructure currently exists in Oklahoma with a maximum transport capacity of approximately 0.3 $MtCO_2$ per year. Given that this capacity is small in comparison to the amount of CO_2 emitted in Oklahoma, we did not consider it within our analysis.

Results

Potential for stacked geologic CO_2 storage and CO_2-EOR in Oklahoma

Figure 3 shows the geospatial cost of GCS across Oklahoma for both the Arbuckle and Simpson formations. In Fig. 3, counties with existing CO_2-EOR projects are specified with large triangles. As can be seen, the Arbuckle and Simpson saline formations underlie some counties that have existing CO_2-EOR projects, which suggests stacked storage could be an option in Oklahoma. An estimated 36.4 $GtCO_2$ can be geologically stored in the Arbuckle formation under high reservoir parameters according to the SCO_2T^{PRO} model and dataset, and approximately 33% of this capacity underlies counties with existing CO_2-EOR operations (Table 2). Similarly, an estimated 39.2 $GtCO_2$ could be geologically stored in the Simpson formation under high reservoir parameter assumptions, with approximately 33% of this capacity underlying counties with existing CO_2-EOR projects. These percentages reduce to only about 28% in the low reservoir parameter assumption scenarios. Overall, these results suggest that (a) not only could stacked storage be an option in Oklahoma, but (b) even when limiting saline storage an order of magnitude more saline storage capacity exists than the maximum potential ~1.2 $GtCO_2$ of capturable CO_2 emissions.

While Fig. 3 and Table 2 demonstrate there is geospatial overlap between the Simpson and Arbuckle formations and CO_2-EOR counties, they also suggest

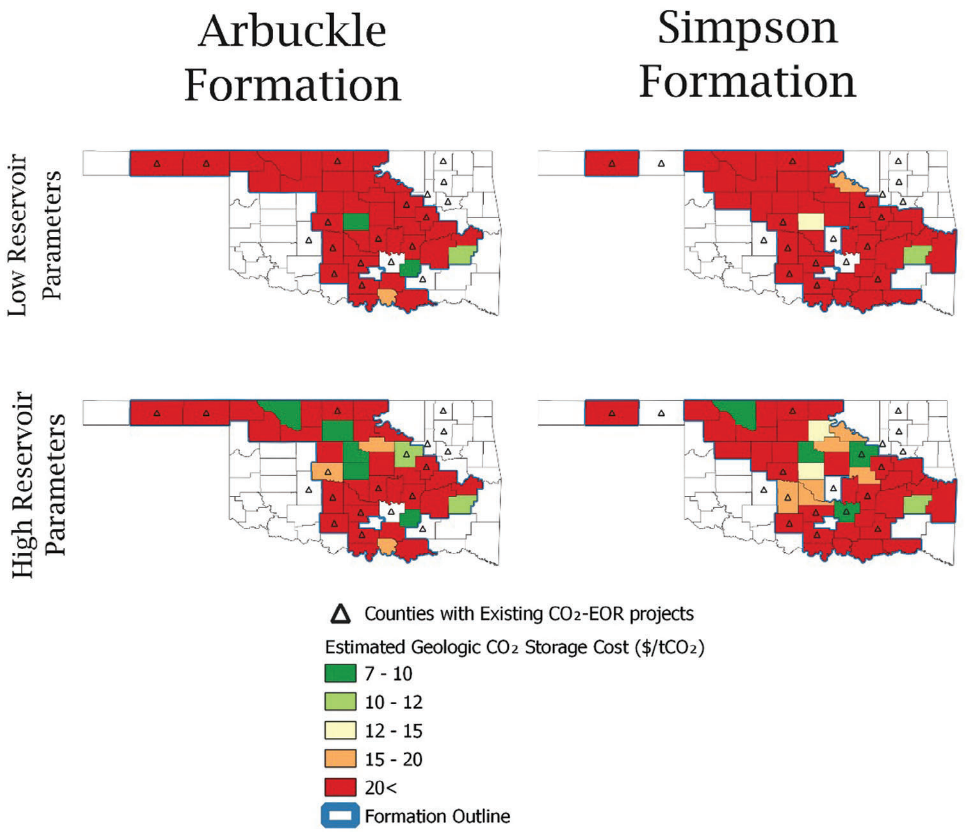

Figure 3. Estimated geologic CO_2 storage costs for the Arbuckle and Simpson saline formations in Oklahoma.

Table 2. Total geologic CO_2 storage capacity and mean storage cost across the Simpson and Arbuckle formations in Oklahoma for high and low reservoir parameter scenarios.

	Geologic CO_2 storage across all counties in OK	Geologic CO_2 storage across counties with existing CO_2-EOR projects
Arbuckle High	36.4 $GtCO_2$ $39/$tCO_2$	12.1 $GtCO_2$ (33% of total) $40/$tCO_2$
Arbuckle Low	26.8 $GtCO_2$ $81/$tCO_2$	9.0 $GtCO_2$ (33% of total) $147/$tCO_2$
Simpson High	39.2 $GtCO_2$ $43/$tCO_2$	11.1 $GtCO_2$ (28% of total) $48/$tCO_2$
Simpson Low	28.3 $GtCO_2$ $75/$tCO_2$	8.1 $GtCO_2$ (28% of total) $98/$tCO_2$

that the counties with the lowest cost saline storage resources (<$10/$tCO_2$) do not have CO_2-EOR operations. For example, the mean cost of storing CO_2 in saline aquifers is between $1/$tCO_2$ and $66/$tCO_2$ greater when only counties with CO_2-EOR projects are considered (Table 1). A cumulative distribution function curve for storage capacity and GCS cost estimates for the different cases considered can be found in the Supporting Information.

Average cost of CO_2 capture, transportation, and geologic CO_2 storage systems

We compare the *SimCCS^{PRO}* estimated average cost of each CCS system, as a function of CO_2 capture target for all scenarios modeled (Fig. 4). Scenarios in which GCS in saline aquifers is restricted to counties with CO_2-EOR operations are shown with triangles. The average cost is higher in these scenarios compared to scenarios in which GCS can occur in any county (circles). For example, with low estimated GCS costs and high capture costs, the average cost of the CCS system for 5 $MtCO_2$/year is $51/$tCO_2$ when all counties are available but is $56/$tCO_2$ when only counties with existing CO_2-EOR projects are considered. When the

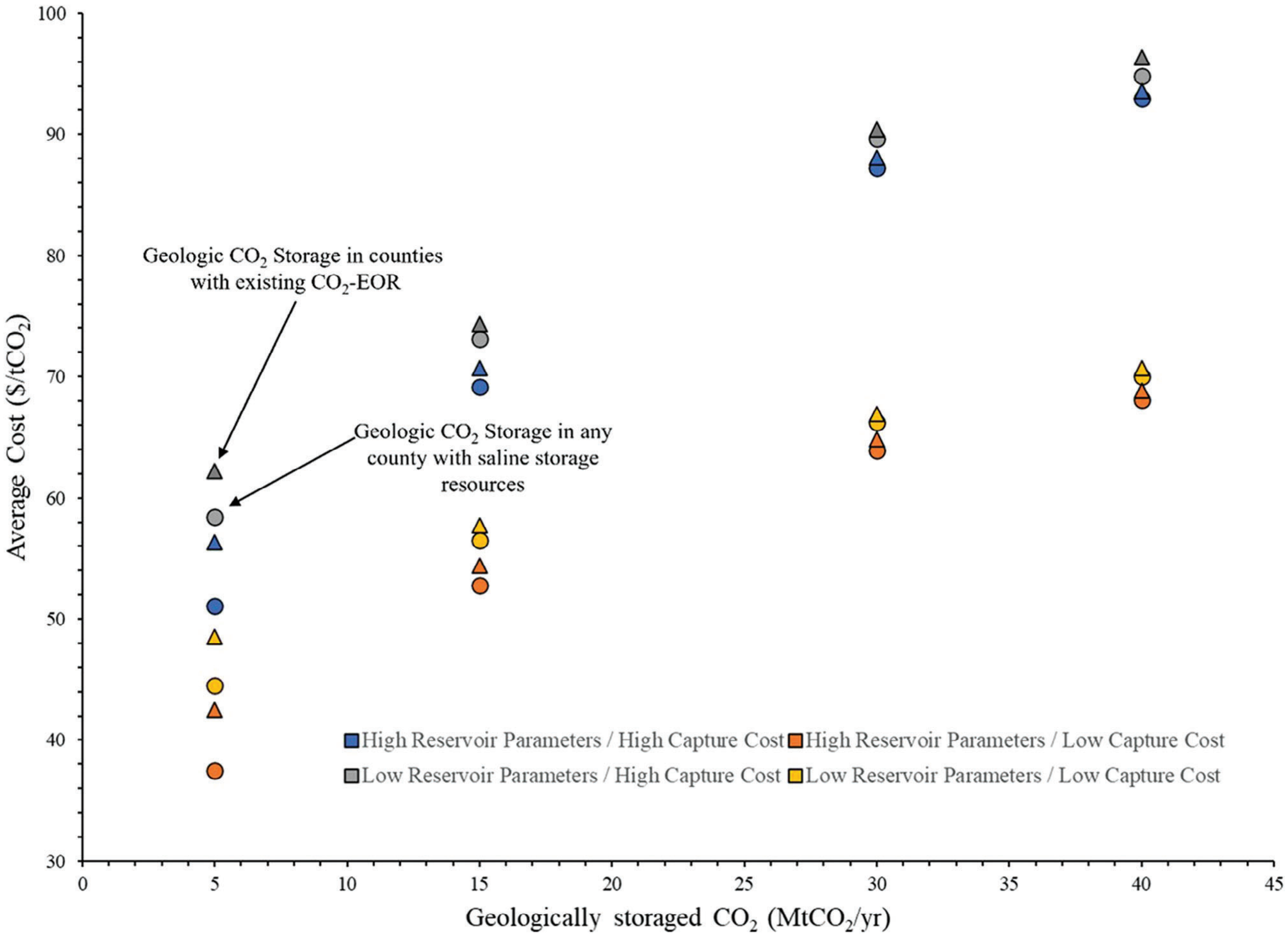

Figure 4. Average cost of the CCS network when geologic CO_2 storage can occur in (circles) any county with saline storage resources and (triangles) only in counties with existing CO_2-EOR projects.

CO_2 capture rate is 40 $MtCO_2$/year, the difference in average costs decreases, but is still higher when only counties with CO_2-EOR projects are considered ($94/$tCO_2$ compared to $93/$tCO_2$). These results suggest that only considering GCS where existing CO_2-EOR projects exist is likely to be more expensive than when not restricting where storage can occur.

Figure 5 shows the breakdown of the average costs shown in Fig. 4. This breakdown demonstrates that capture costs comprise most of the average cost, especially at the highest capture target of 40 $MtCO_2$/year. In contrast, estimated GCS is generally the smallest fraction of the average cost and tends to be smaller for higher amounts of CO_2 being captured, transported, and stored. For example, in the 40 $MtCO_2$/year capture target scenario, the cost of CO_2 capture contributes up to $80/$tCO_2$ of the average cost, but the cost of storage is less than $10/$tCO_2$.

While Fig. 3 demonstrates that CO_2-EOR operations generally do not occur in the counties with lowest-cost saline storage resources, and Fig. 4 demonstrates that limiting saline storage to counties with CO_2-EOR operations does increase the average cost of the CCS system, Fig. 5 suggests this increase in total cost is driven by an increase in transportation cost. In fact, Fig. 5 shows that CO_2 storage cost is generally smaller when GCS can only occur in counties with EOR-operations. For example, in the top left subplot, for a capture target of 5 $MtCO_2$/year, the cost of CO_2 storage contributes $10/$tCO_2$ to the total cost of CCS under a low reservoir parameter and high capture cost scenario (grey). But the cost drops to approximately $7/$tCO_2$ when we consider GCS in counties with CO_2-EOR operations (grey-striped bars). In contrast, in this same scenario, the cost of CO_2 transportation increases by over $5/$tCO_2$ when GCS can only occur in counties with CO_2-EOR operations. This might be

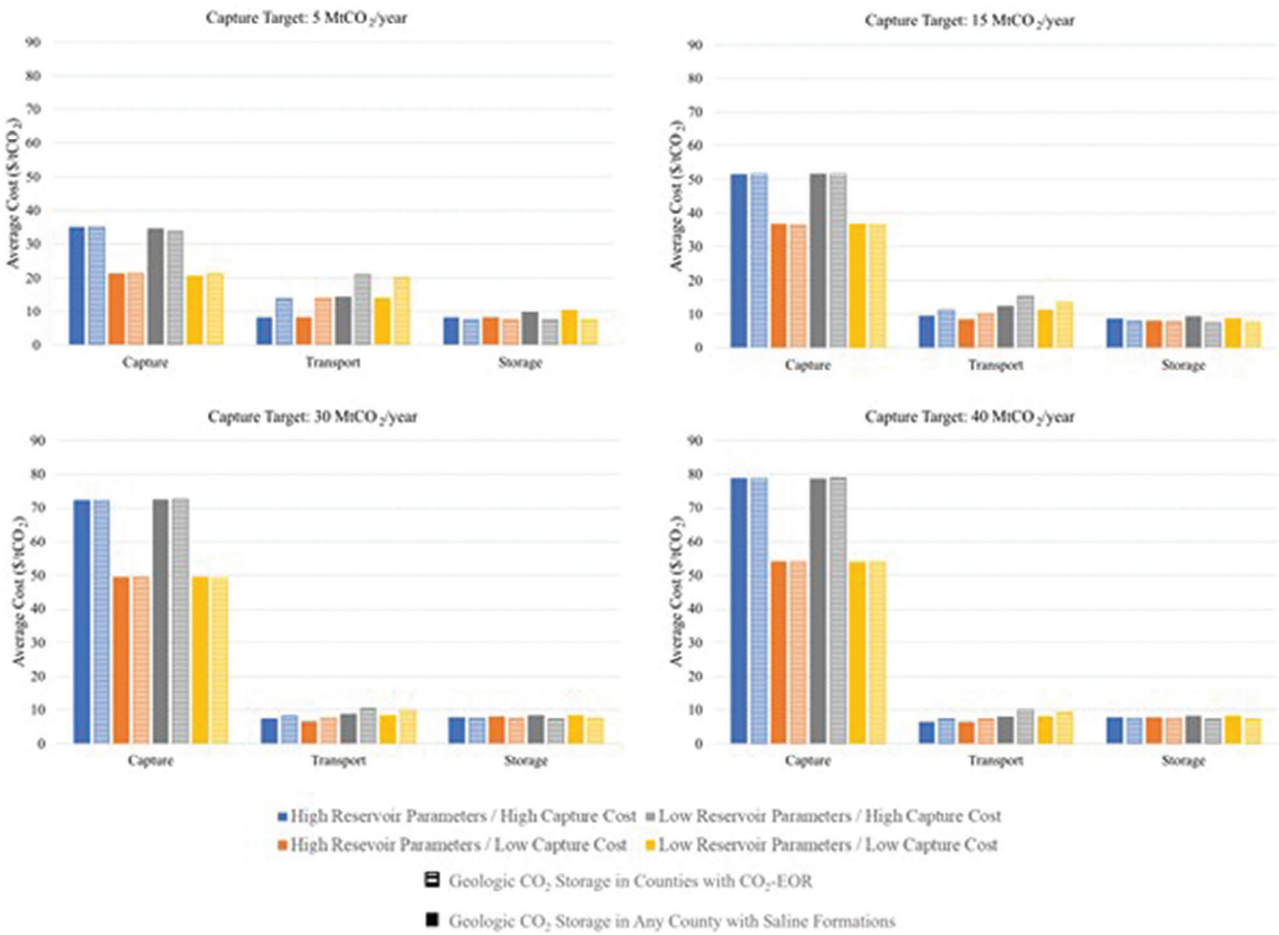

Figure 5. Breakdown of average cost for each capture target and combination of scenarios.

explained by the fact that the current CCS infrastructure in Oklahoma is set up for CO_2-EOR and not the capture and storage of anthropogenic sources of CO_2.

CO_2 Transportation pipeline lengths and deployed networks

As transportation cost is largely a function of the length of CO_2 pipeline deployed, if the CO_2 volume transported stays constant, this result suggests that limiting GCS to counties with CO_2-EOR operations will result in longer CO_2 transportation networks. To quantify this suggestion, Fig. 6 shows distributions of the increase in pipeline lengths between scenarios in which GCS could occur in any county with saline aquifers and when GCS could only occur in saline aquifers located in counties with CO_2-EOR operations. The distributions are across the different scenarios of CO_2 capture cost and reservoir parameters.

Figure 6 shows that for each capture target there is an increase in pipeline length, indicating that pipeline networks will be longer if GCS is limited to only those counties with existing CO_2-EOR projects. For example, the median increase in pipeline length is 250 km at a capture target of 5 $MtCO_2$/year, 225 km at 15 $MtCO_2$/year, 200 km at 30 $MtCO_2$/year, and 175 km at 40 $MtCO_2$/year. These results suggest that at a minimum, across all scenarios modeled, at least ~140 km of additional pipeline will be required if GCS can only occur in counties with CO_2-EOR operations.

In addition to requiring more pipelines, restricting GCS to counties with CO_2-EOR operations also changes the shape of the deployed pipeline network. For example, Fig. 7 shows the deployed pipeline network from a scenario that most clearly illustrated how the pipeline network changes when limiting GCS. While there are segments of the pipeline network that are consistent across both scenarios shown, limiting GCS to saline aquifers in counties with CO_2-EOR

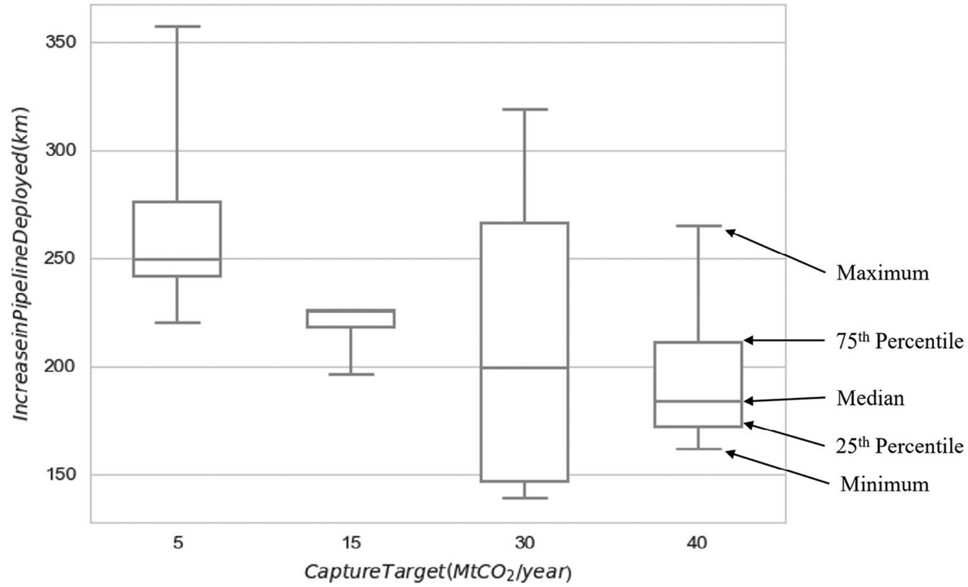

Figure 6. Distribution of the increase in pipeline deployed for between scenarios in which CO_2 can be injected in any county with geologic CO_2 storage and only counties with geologic CO_2 storage resources with CO_2-EOR operations. Distributions are across all scenarios of geologic parameters and CO_2 capture costs.

operations generally results in one large, interconnected network that runs through the central part of Oklahoma. In contrast, multiple smaller networks are deployed when GCS is not limited.

Counties deployed for geologic CO_2 storage

Regardless of what counties are available for GCS, Fig. 7 suggests the counties with the least-expensive CO_2 storage resources are not always deployed. For example, there is one county in north central Oklahoma with a CO_2 storage cost of less than \$10/tCO_2 (colored green) that is not deployed in either scenario shown in Fig. 7. To better understand if this observation applies to other county resources, in Fig. 8 we examine the rates at which each county was deployed across the different scenarios. Specifically, we compare county deployment for when GCS can occur in saline resources without limitation (16 scenarios; Fig. 8A) and county deployment across all 32 scenarios in this analysis (Fig. 8B). The top five counties deployed across all scenarios are Pontotoc (100%), Grady (63%), Canadian (50%), Coal (50%), and Creek (50%). When we focus on just the 16 scenarios where GCS can occur in any county with saline aquifer resources, the deployment shifts as follows: Pontotoc (100%), Grady (69%), Canadian (69%), Coal (100%), and Creek (50%). These deployment percentages imply that even if stacked storage was not prioritized, these five counties would still be utilized for GCS. Further, when comparing Figs 7 and 8, we observe that there are multiple counties that are consistently deployed that have expensive (>\$20/tCO_2) GCS costs. Overall, these results suggest that the cost of the GCS resource is not the primary factor driving the development of the CCS network.

Capturing CO_2 from the same sources of CO_2

Figure 7 shows that many of the sources of CO_2 selected for CO_2 capture are the same across the two scenarios. These results, as well as capture costs in Figure 5, do not change nearly as much between scenarios as do transportation and storage cost, suggesting that CO_2 sources drive the development of CCS networks. In other words, either the increase in transportation cost or the increase in capture cost is always more than the savings in accessing cheaper storage.

To investigate the impact of CO_2 sources on optimal CCS network decision-making, Fig. 9 shows cost curves for point source CO_2 capture when capture costs are high (16 of the 32 scenarios). The cost curves for all available CO_2 capture are shown in blue, the

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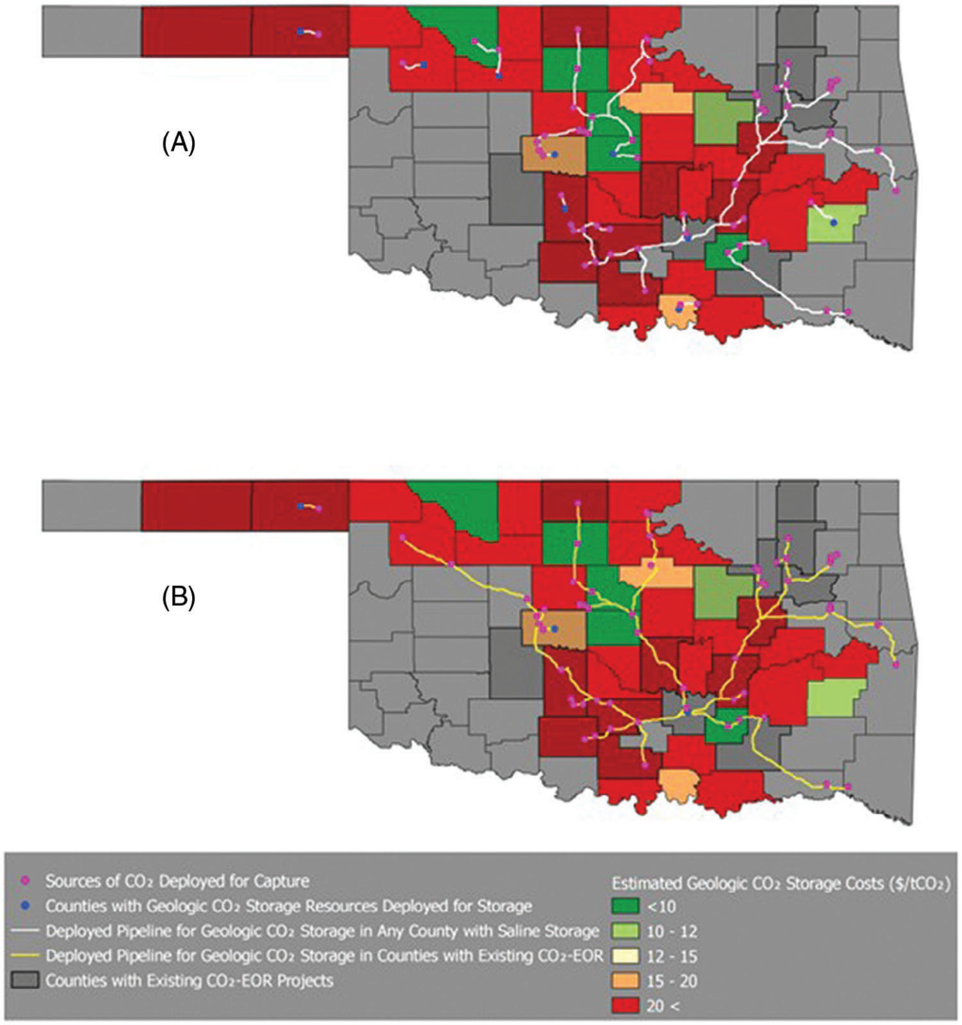

Figure 7. Comparison of pipeline network deployment between (A) scenarios in which CO_2 can only be geologically stored in counties with CO_2-EOR operations, and (B) and scenarios in which CO_2 can be stored in any county with geologic CO_2 storage resources. These results are from the high reservoir parameter and high capture costs scenario.

corresponding cost curves of CO_2 sources that are deployed when CO_2 can be injected in any county with saline storage resources are shown in orange, and only in saline storage resources located in CO_2-EOR counties are show in green. These cost curves are organized independent of order of deployment and are instead reordered from lowest to highest cost, for only deployed point sources. The other 16 corresponding curves when low capture costs are used, are included in the Supporting Information.

In each scenario the shapes of all three supply curves are very similar, indicating that (a) most of the same sources of CO_2 are captured across scenarios, and (b) these sources are generally deployed in the least-cost order. In other words, generally, our results suggest that it is the least-cost option to build more pipelines and even avoid injecting CO_2 in the least-cost saline storage resources if it enables capturing CO_2 from the least-cost sources.

Discussion

This analysis explores the outcome of intentionally developing CCS networks in Oklahoma that are amenable to stacked storage, as an approach to hedge against uncertainty in saline storage resources. Stacked

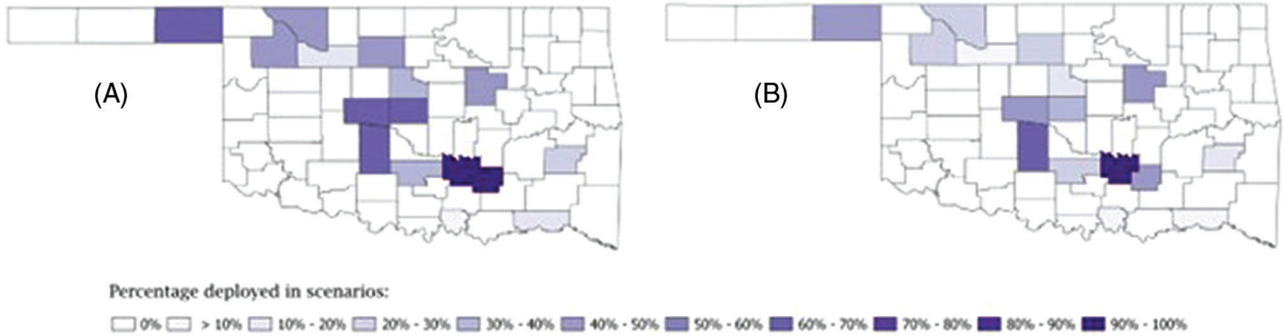

Figure 8. Percentage deployment of each county across (A) scenarios where geologic CO_2 storage occurs in any county with saline storage resources (only 16 scenarios) and (B) any scenario we that we conducted in this analysis (all 32 scenarios).

storage provides both values and costs to any CCS network, with the primary benefit being that stacked storage can serve as a backup option that enables CCS networks to hedge against uncertainty. Yet quantifying this value can be challenging and at the time remains somewhat uncertain. For example, the value of having backup CO_2 storage, should complications arise, will require input from CCS or CO_2-EOR operators and is dependent on the individual and project. There is no current concrete value that has been universally assigned to quantify the value that stacked storage would provide across different projects. Therefore, this analysis focuses on establishing the costs of intentionally developing CCS networks amenable to stacked storage, which can be quantified with a model. As a result, our findings suggest that the primary outcome of intentionally developing CCS networks amenable to stacked storage are twofold: an increase in the amount of pipeline deployed and a small increase in the \$t/CO_2 cost, driven by the larger amounts of pipeline needed.

The implications may be far reaching if longer transportation networks result in an increased opportunity for community pushback. Longer transportation networks will require project development across more land. If that change results in needing to secure right-of-way access from additional stakeholders, the project may then have additional opportunities for failure, such as the "not in my backyard" mentality.[37] While previous work has indicated that communities have "a neutral" reaction to CO_2 transport pipelines, and are generally indifferent to pipeline development, even when it occurs close to places of residence,[38] there has only been a limited number of CCS projects deployed to date. As such, designing CCS networks in Oklahoma by prioritizing stacked storage, may come at the expense of increasing uncertainty of community acceptance. This said, existing CO_2-EOR projects in Oklahoma have already gained community acceptance/support and their infrastructure could be leveraged in support of CCS systems.[39]

Additionally, our findings also demonstrate the importance of system-wide considerations in the development of CCS networks. The implication could be of particular importance when considering what counties to target for CO_2 storage development. Our results demonstrate that only considering the cost of CO_2 storage resources is insufficient because in comparison the cost of CO_2 sources has a larger impact on the development of CCS networks. This suggests it is possible that the location and cost of newly constructed sources of CO_2, or even those facilities developed with CO_2 capture from the start, may have a larger influence than the geology when deciding where CO_2 is geologically stored in Oklahoma. A further implication is that stacked storage locations that exist closer to least cost sources are consistently deployed, as evidenced by Pontotoc County that features in each of the 32 scenarios we consider. This can be further investigated through future scenario assessments that vary locations of sources, to better understand if this implication holds true.

There are caveats to our findings, which are listed below. These were beyond the scope of this study but could be areas of future work.

- We do not consider the possibility for induced seismicity, despite a history of induced seismicity in Oklahoma that has been attributed to both hydraulic fracturing and wastewater injection.[40] Most simply,

Greenhouse. Gas. Sci. Technol. **13**:763–779 (2023); DOI: 10.1002/ghg.2244

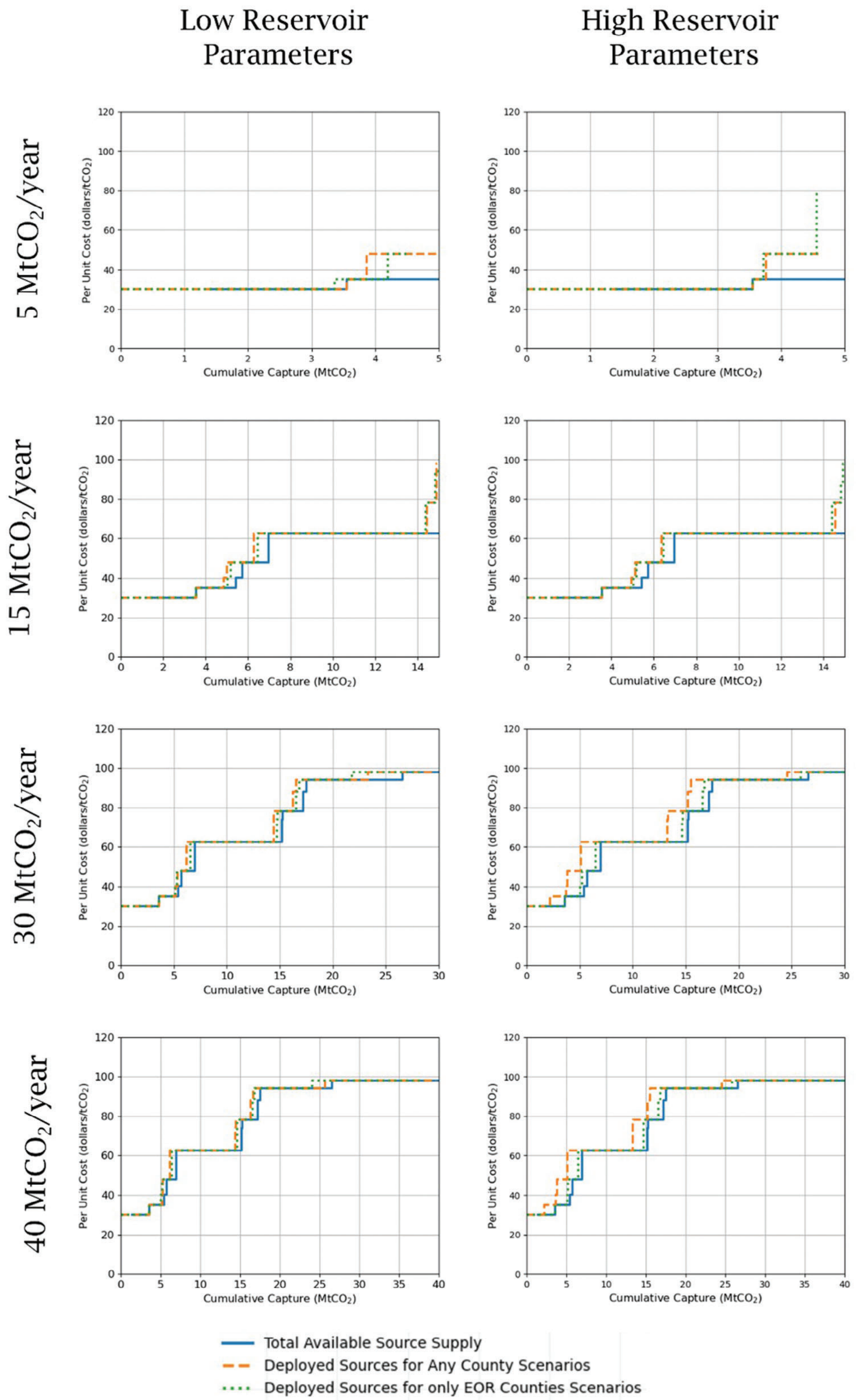

Figure 9. Supply curves for capturing CO_2 for the high capture costs scenario.

induced seismicity could be incorporated in our study by removing the counties that have previously experienced seismic events from the options of available locations for CO_2 storage. Considering our findings, it is most likely that adjusting our study to consider induced seismicity would result in very minimal increases in cost because CO_2 would be captured from the same sources, but more pipelines would be deployed to transport the captured CO_2 to the remaining counties.

- We assumed GCS occurred at the center of each county and did not consider finer resolutions. It is thus possible that we over- or underestimate the amount of pipeline needed compared to what would be estimated with more fine-resolution data on the location of CO_2-EOR projects. This could reduce the amount of additional pipeline needed for CCS networks amenable to stacked storage if the existing CO_2-EOR projects were on the perimeter of counties or closely located to the cheapest sources of CO_2.
- We did not consider any transportation of CO_2 across state borders. For example, Texas borders Oklahoma and has many existing CO_2-EOR projects, sources of CO_2, and vast resources for GCS in saline formations. Future work could explore the development of these inter-state networks and the impacts on stacked storage deployment. Overall, our findings show that increasing the number of locations for CO_2 storage generally results in multiple smaller independent CCS networks. From this perspective, it is possible that incorporating other states (e.g., Texas) could have minimal impacts on the CCS networks deployed in Oklahoma.
- We did not consider issues associated with acquiring rights-of-way to CO_2 pipelines, legal aspect of pore space rights for CO_2 storage, and potential societal challenges/acceptance of laying out CO_2 pipeline.

Conclusions

In this study, we investigate the potential for stacked storage in Oklahoma and the ramifications it may have for state-wide CCS networks. We find that:

1. There are between 55 to 75 $GtCO_2$ of saline storage capacity in Oklahoma, approximately a third of which is in counties that also have CO_2-EOR operations (Table 2). The capacity for saline storage in counties with CO_2-EOR operations is over an order of magnitude greater than 30 years' worth of current Oklahoma emissions (40 $MtCO_2$/year $\times$ 30 years $=$ 1.2 $GtCO_2$). While there is ample potential for stacked storage in Oklahoma, we also find that the counties with the lowest cost saline storage do not have CO_2-EOR operations (Fig. 3, Table 2).
2. A mixed strategy is optimal for CCS networks, in which saline storage can occur in counties with and without CO_2-EOR operations. As such developing CCS networks that could exclusively be amenable for stacked storage slightly increases the average cost of the system (i.e., \$1/tCO_2 to \$5/tCO_2; Fig. 4). This increase is a result of increases in transportation cost, not increases in capture cost or storage cost (Fig. 5).
3. The cost and geospatial distribution of CO_2 sources drives the development of CCS networks in Oklahoma more than the geology: the cost of CO_2 transportation increases when saline storage can only occur in counties that have CO_2-EOR operations because more pipelines (i.e., $\sim$140 to $\sim$360 km; Fig. 6) are deployed to connect the lowest-cost sources of CO_2 to the available GCS resources (Fig. 7). Further, across all our scenarios, the counties with higher-cost GCS resources were deployed more often than other counties with lower-cost resources (Fig. 8).

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Conflict of Interest

Marcos Miranda, Jonathan Ogland-Hand, and Richard Middleton are employed by Carbon Solutions LLC, a commercial entity, and Jeffrey Bielicki declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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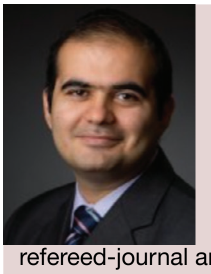
Marcos Miranda is a research scientist at Carbon Solutions LLC. He most recently graduated from The Ohio State University with a PhD in civil engineering focusing on evaluating the deployment of carbon capture and storage networks in Oklahoma and the Gulf Coast and conducting a life cycle assessment of a processes for recovering rare earth elements from coal mine drainage.

Jonathan Ogland-Hand is the director of energy systems analysis at Carbon Solutions LLC. He holds a PhD in environmental science, a BS in mechanical engineering, and was a postdoctoral researcher for 2 years in the earth science department at ETH Zurich in Switzerland.

Dr. Bielicki is an associate professor at Ohio State University and conducts research on issues where energy and environmental systems and policy interact. He directs the OSU EmPOWERment Program and is research lead for Sustainable Energy at the OSU Sustainability Institute.



Rouzbeh G.Moghanloo is currently an associate professor and the graduate liaison for natural gas engineering and management program at the Mewbourne school of petroleum and geological engineering at The University of Oklahoma. Dr. Moghanloo is author and co-author of 120 refereed-journal and conference articles and the editor of a multiauthor volume. Rouzbeh is a professional member of SPE and ACS and recipient of 2018 SPE Mid-Continent Regional Reservoir Description and Dynamics Award and 2016 ACS-PRF award. Dr. Moghanloo received his PhD in petroleum engineering from The University of Texas at Austin and his Bachelor and Master of Science degrees, both in chemical engineering, from Amirkabir University of Technology. His research interests span over applied topics such as enhanced oil recovery, geological storage of CO_2,

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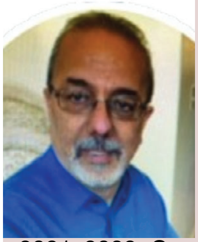
asphaltene deposition, to basic research on modeling of multiphase flow and particulate flow systems. He has also served as technical advisor for several companies. Rouzbeh is a member of several associations including SPE and ACS and holds three patents and serves as an associate editor for Elsevier's *Journal of Natural Gas Science and Engineering*.



Jamal DaneshFar, P.E., principal engineer, worked over 30 years as a production, completion, and reservoir engineer in the United States and overseas. Project coordinator for Carbon Utilization and Storage Partnership (CUSP-DOE funding program) in Oklahoma during 2021–2022. Graduated with master's degree in mathematics from University of Central Oklahoma (UCO) and master's degree in petroleum engineering from University of Oklahoma (OU). Currently, working on kinetic reaction of CO_2 injection into saline formation as part of PhD candidacy at University of Oklahoma.

Dr. Richard Middleton is CEO of Carbon Solutions, a mission-driven, fast-growing business focusing on low-carbon energy Research & Development and Software & Services. Previously, he was a manager and senior scientist at Los Alamos National Laboratory (LANL) for more than a decade. He has been ranked as the United States' third-most productive CCS researcher (1997–2017) as well as LANL's most-published Earth science first-author from 2010 to 2018. He is the lead developer of *SimCCS*, a research- and industry-leading decision support framework for understanding how, where, and when CCS infrastructure could and should be deployed.