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Author(s): Velasco Lozano, Moises
Ma, Zhiwei
Pawar, Rajesh J.
Chen, Bailian

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CO_2 Transport Infrastructure Outlook in the United States

Moises Velasco-Lozano, Martin Ma, Rajesh Pawar, and Bailian Chen

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Disclaimer

Moises Velasco-Lozano: Methodology, Formal Analysis, Running Simulations, Writing – Original Draft

Martin Ma: Methodology, Supervision, Writing – Reviewing and Editing

Rajesh Pawar: Supervision, Reviewing

Bailian Chen*: Methodology, Supervision, Writing – Reviewing and Editing

*Corresponding contact: bailianchen@lanl.gov, 505-667-1926

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Content

1 Introduction

Carbon capture and storage (CCS) represents one of the most important methods to mitigate anthropogenic carbon emissions at a large scale, playing a key role in meeting climate change targets (Bui et al., 2018) and for net-zero CO_2 by 2050 scenarios in the United States (Browning et al., 2023). This technology involves capturing CO_2 emissions from industrial processes, transporting them via pipelines, trucks, rails, or ships, and ultimately storing them in underground geological sites, such as saline aquifers or depleted oil reservoirs. Thus, to encourage carbon reduction initiatives, the U.S. Congress enacted the Bipartisan Budget Act in 2018, reforming the 45Q tax credit to benefit operators storing CO_2 in geologic formations (Jones and Sherlock, 2021). Additionally, the 2022 Inflation Reduction Act further expanded these incentives, providing additional support for CCS initiatives (Hackett and Kuehn, 2023).

Although numerous studies describe the importance of optimal CO_2 transportation to support the decision-making of CCS projects aligned with the objective of net-zero emissions by 2050 (Abramson and Christensen, 2021; Chen and Pawar, 2023; Greig and Pascale, 2021), further efforts are required to optimize the transport infrastructure for national-scale CCS deployment. Therefore, in this study, we examine three nationwide scenarios with the *SimCCS*$^{3.0}$ tool (Ma et al., 2022, 2023, 2024) along with a novel geospatial splitting approach developed by Velasco-Lozano et al. (Velasco-Lozano et al., 2024a, 2024b). We present optimized pipeline networks that meet the dynamic evolution of annual capture amounts, describing the required total pipeline lengths at each stage as a function of the pipeline diameters. Thus, the cases presented demonstrate the feasibility of CO_2 pipeline infrastructure for large-scale CCS projects.

2 CO_2 emitters and geological storage resources

2.1 CO_2 emitter sources

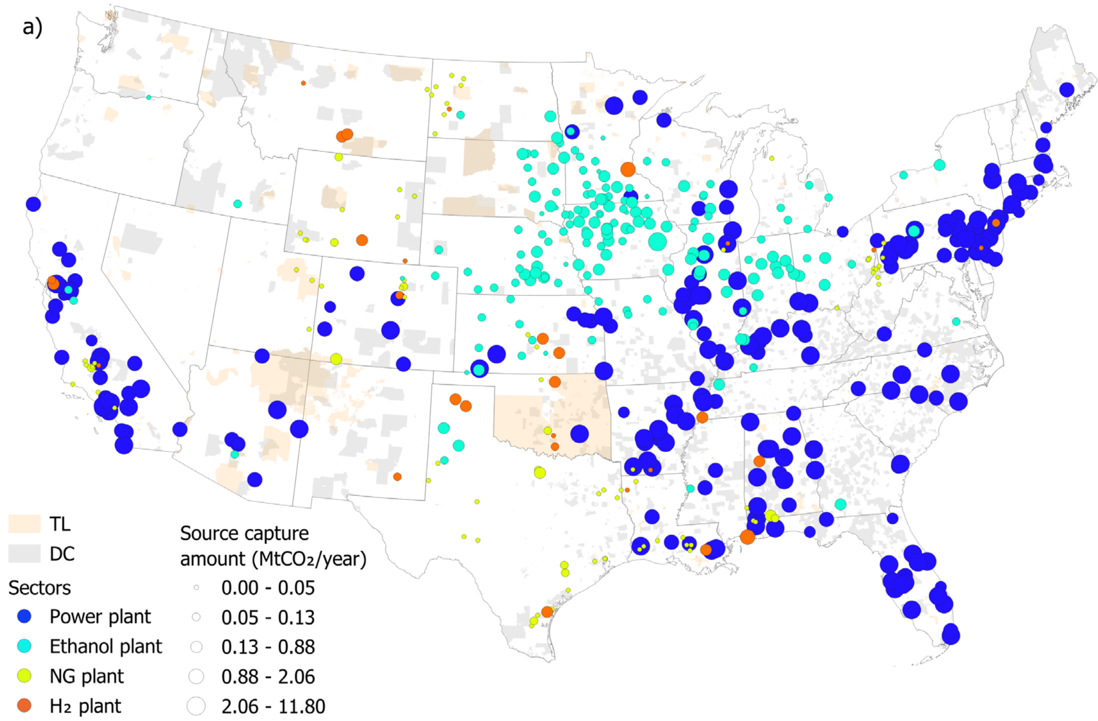
All the scenarios listed below include CO_2 capture from point sources across the lower 48 US states from the power sector, ethanol refineries, natural gas (NG) processing plants, and hydrogen used in refineries. The scenarios were leveraged from existing modeling for the U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM) by OnLocation, Inc. (OnLocation, 2024), sponsored by FECM. The first two scenarios are from the Long-Term Strategy (LTS) analysis (The United States Department of State and the United States Executive Office of the President, 2021) while the third case was developed as part of the Stanford Energy Modeling Forum EMF27 (Stanford, 2024), an inter-model comparison of net zero pathways.

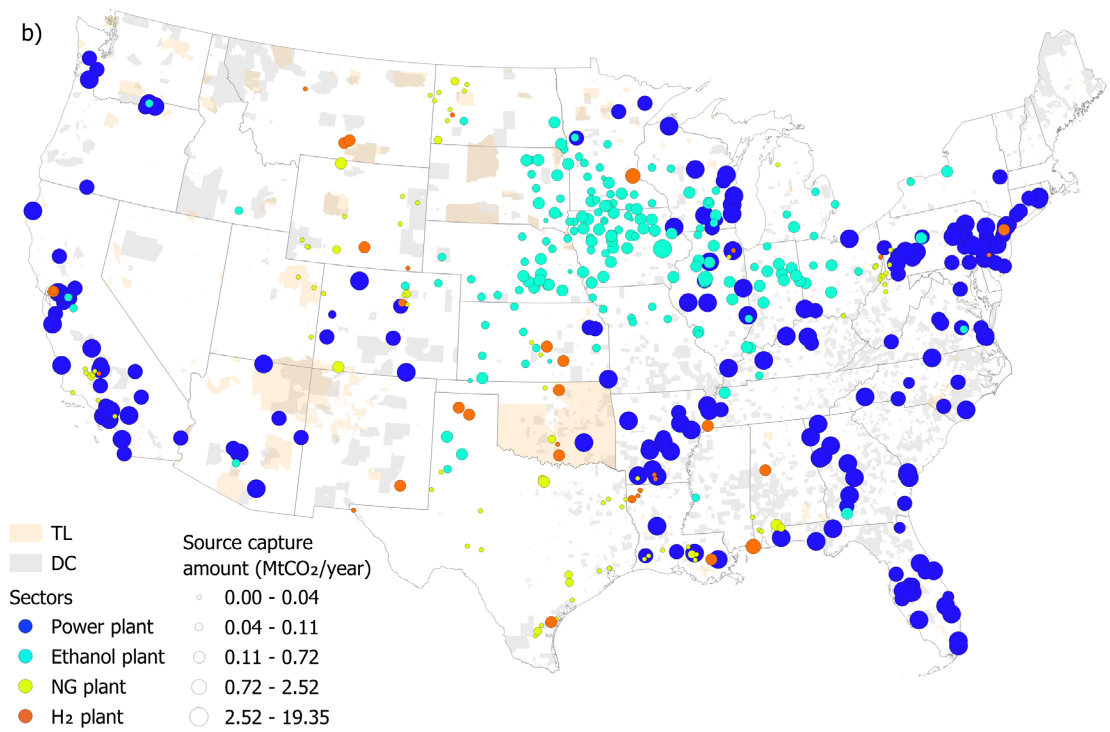
High-Removal scenario. In the LTS, this Higher Removals/Lower Technology scenario assumes that advanced technologies are available only in the power sector and therefore higher removals of CO_2 land use, land use change, and forestry (LULUCF) sink and carbon dioxide removal (CDR) technologies are necessary to achieve net zero GHG emissions by 2050. The High-Removal scenario leads to sequestering CO_2 captured from 608-point sources (power, ethanol, natural gas, and hydrogen) across the United States (Figure 1a). The objective in this scenario is to maximize CO_2 capture, employing standard technologies only in ethanol, natural gas, and hydrogen plants. The capture amount from each source is expressed in million metric tons (Mt) of CO_2 per year. In addition, the majority of the captured emissions are from power plants. In this scenario, most ethanol plants with capture are located in the midwestern region of the United States, whereas natural gas processing plants with capture are mainly situated in Texas and the Intermountain West region.

Low-Removal scenario. This LTS scenario assumed that advanced technologies are available in all energy sectors and hence lower removals are needed to achieve net zero emissions. In Figure 1b we show the location of the multiple CO_2 sectors for the low-removal scenario, where the objective is to sequester CO_2 captured from 555 sources. Here, low CO_2 removal indicates the use of advanced technology (more efficient technologies that reduce emissions at the source through fuel switching and electrification) in all sectors, resulting in a lower removal and need for CO_2 capture. In this scenario, the main difference from the High-Removal scenario is the absence of capture from power plants in the states of Mississippi and Alabama. However, there is some additional capture from power plants located in the Upper-Pacific region compared to the other two scenarios modeled in this study.

Net-Zero scenario. This scenario incorporates CO_2 capture from cement plants, new and existing capacity (OnLocation, 2021), and hydrogen plants modeled by OnLocation Inc. (OnLocation, 2024) using its hydrogen market module[1]. Additionally, CO_2 removal through direct air capture is planned to begin in 2034. Figure 1c shows the distribution of the CO_2 source emitters. The objective in this scenario is to sequester CO_2 captured from a total of 952 sources from five different sectors. It is important to mention that in all three scenarios described in this study, we account for disadvantaged communities (DC) and tribal lands (TL), inclusive of all Federally Recognized Tribes, consistent with the Administrations Justice40 Initiative (Energy, 2024).

[1]Hydrogen market module is a software module developed by OnLocation, Inc. that models the hydrogen market within the National Energy Modeling System (NEMS), allowing for detailed analysis of hydrogen production, storage, transportation, and end-use across different technology and policy scenarios, including estimations of costs and volumes across various sectors like industrial, commercial, and transportation.


a)
TL
DC
Sectors
Power plant
Ethanol plant
NG plant
H₂ plant
Source capture amount (MtCO₂/year)
0.00 - 0.05
0.05 - 0.13
0.13 - 0.88
0.88 - 2.06
2.06 - 11.80


b)
TL
DC
Sectors
Power plant
Ethanol plant
NG plant
H₂ plant
Source capture amount (MtCO₂/year)
0.00 - 0.04
0.04 - 0.11
0.11 - 0.72
0.72 - 2.52
2.52 - 19.35

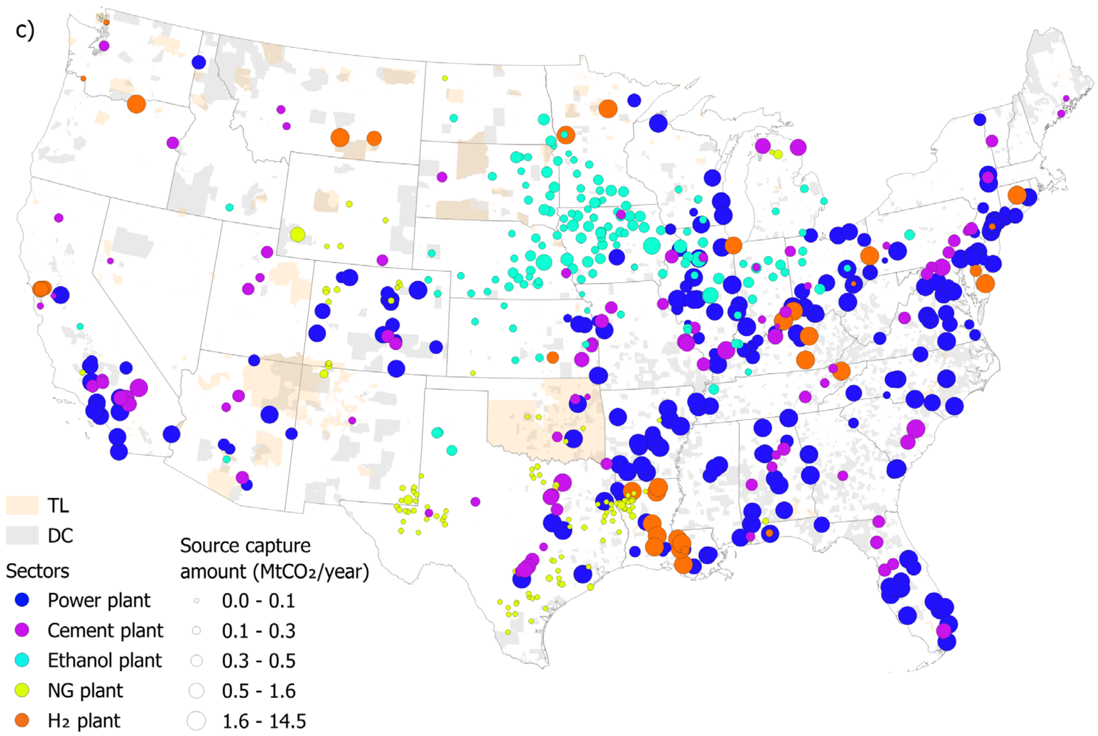


Figure 1. Maps of the CO_2 sources for the a) High-Removal scenario b) Low-Removal scenario, and c) Net-Zero scenario modeled. The size and color of each circle represent the potential CO_2 capture amount and sector, respectively. The gray and pale pink backgrounds indicate TL and DC, respectively

Figure 2 depicts the dynamic evolution of the CO_2 capture target for the High-Removal, Low-Removal, and Net-Zero scenarios. The maximum CO_2 to be captured from these three scenarios are 559.4, 671.5, and 557.5 $MtCO_2$/year, respectively.

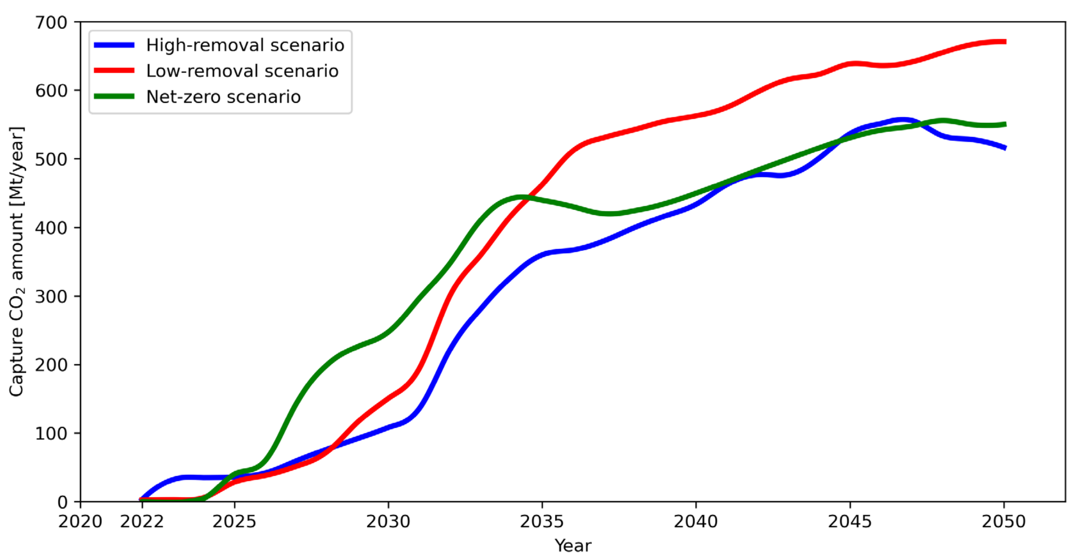


Figure 2. CO_2 dynamic capture target amounts for all three scenarios modeled.

2.2 CO_2 storage resources

Geologic storage sites are fundamental for the safe injection and long-term containment of captured CO_2, where their location and storage capacity represent key features for the decision-making deployment of CCS infrastructure. In this work, we used 314 geologic formations across the lower 48 states of the U.S. as potential CO_2 storage sites (NETL, 2015; Morgan et al., 2023). Figure 3 presents a map of the available sedimentary basins for storing captured CO_2 emissions in all three scenarios modeled. In this figure, dark brown regions indicate the existence of overlapped basins in the same areas.

The database of the 314 formations includes the individual areal extent, depth to the top of the storage formation, thickness, permeability, porosity, temperature, and hydrostatic pressure. Thus, with this information, the estimation of the storage resource and costs used in the pipeline network modeling was obtained through the storage module SCO_2T in the unified SimCCS platform. The results generated are comparable to those produced by the FECM/NETL CO_2 Saline Storage Cost Model (CO_2_S_COM) (Morgan, 2024).

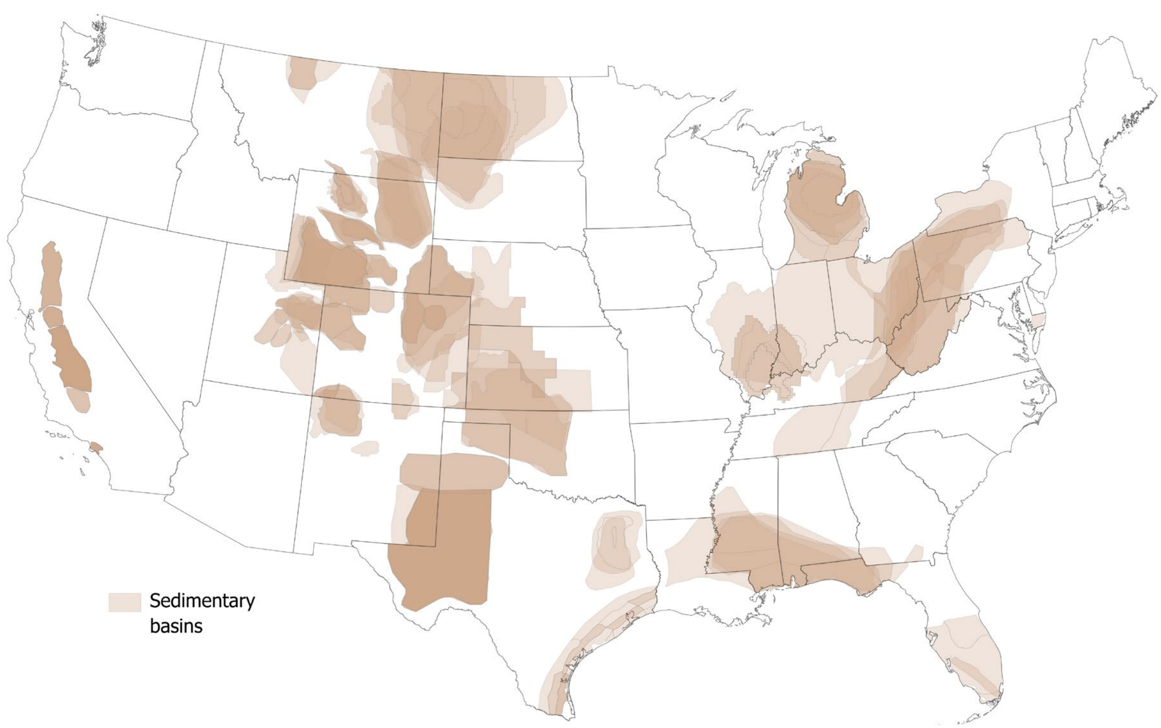


Figure 3. Map of the 314 geologic formations for potential CO_2 storage in the 48 lower states in the United States based on the National Carbon Sequestration Database and Geographic Information System (NETL, 2015) and other data resources (Morgan et al., 2024). Dark brown regions indicate the existence of overlapped basins in the same areas.

In conventional CO_2 pipeline network modeling, the centroids of geologic storage formations are assumed to be sink locations (Chen et al., 2022; Shih et al., 2023). However, this simple approach might lead to inefficient routes because some basins extend hundreds of square miles. Therefore, to overcome this limitation, we developed and implemented a novel geospatial splitting approach to partition large basins into multiple sub-basins (Velasco-Lozano et al., 2024a, 2024b) This results in optimal networks between CO_2 sources and storage sites in multistage nationwide CCS transport.

This new approach enables an improved distribution of the total storage capacity within each basin, providing additional sink locations and accounting for physical, geographic, and demographic constraints. As a result, in this study, we used a total of 2,535 sub-basins (Figure 4) derived from the original 314 geologic formations to optimize the pipeline network designs in all scenarios analyzed.

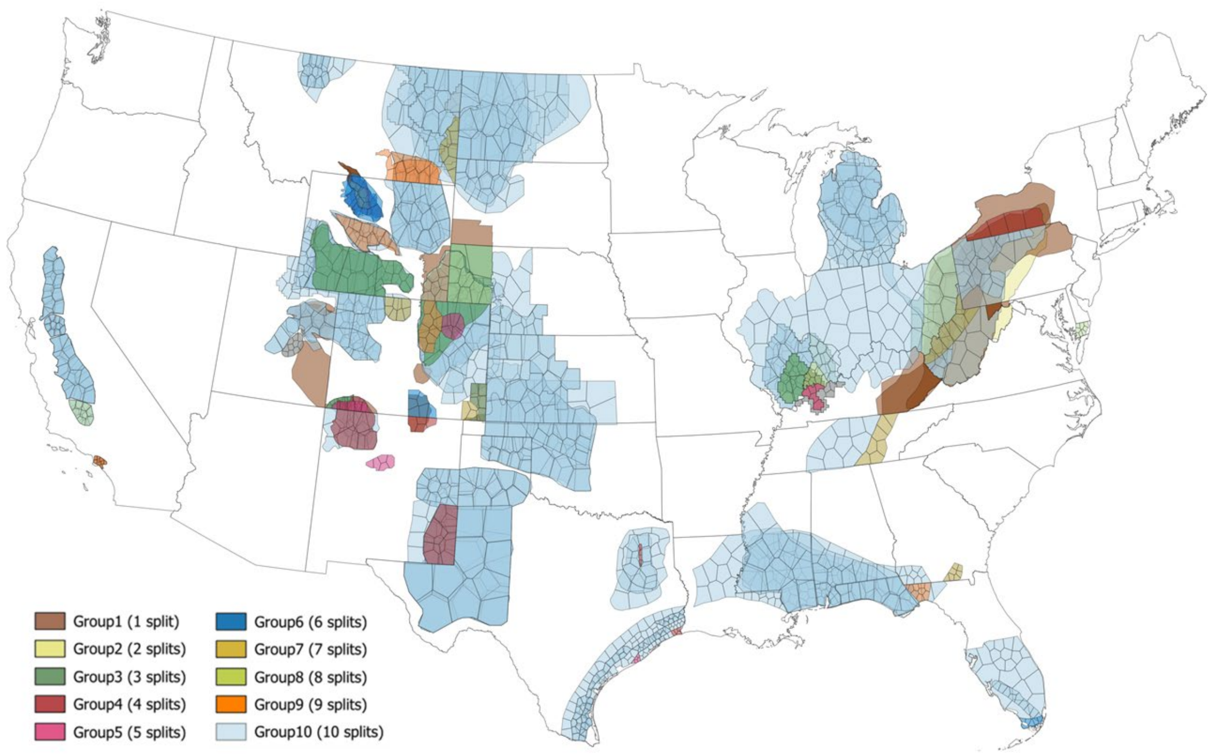


Figure 4. Map of 2,535 sub-basins for improved CO_2 storage based on the geospatial splitting approach developed by Velasco-Lozano et al. (2024a; 2024b). Groups indicate the number of splits in the original sedimentary basin.

3 CO_2 pipeline infrastructure modeling

In all cases presented next, we used the 2,535 sub-basins obtained from the newly developed geospatial splitting approach, providing multiple potential storage sites to facilitate the source-sink connectivity during the optimization process with *SimCCS*$^{3.0}$ (Ma et al., 2022, 2023, 2024)

3.1 High-Removal scenario

As previously described, this scenario demands a high level of CO_2 removal because of the use of standard technology in all sectors, except power. Figure 5 shows the CO_2 pipeline network by 2035 obtained with *SimCCS*$^{3.0}$ and using the split basins. In this scenario, a total pipeline length of 20,375 miles resulted to meet the transport of the CO_2 emissions from the sources to the sinks. Notably, a short infrastructure is observed in Texas and Louisiana. In addition, Figure 5 shows the CO_2 transportation infrastructure by 2050. In this case, the total pipeline length is 24,081 miles, reflecting an increase of 3,706 miles compared to 2035. As a result, new pipelines are designed mainly in the states of South Carolina, Pennsylvania, Utah, New Mexico, and Arizona. Thus, to meet the target CO_2 capture by 2035, 85% of the total required pipeline infrastructure needs to be completed. This is primarily driven because the U.S. aims to achieve a carbon-free power sector by 2035, as a significant portion of emissions come from the power sector. In the results shown in the next maps we merged DC and TL (blue-grey regions) to facilitate the visualization of the pipeline networks.

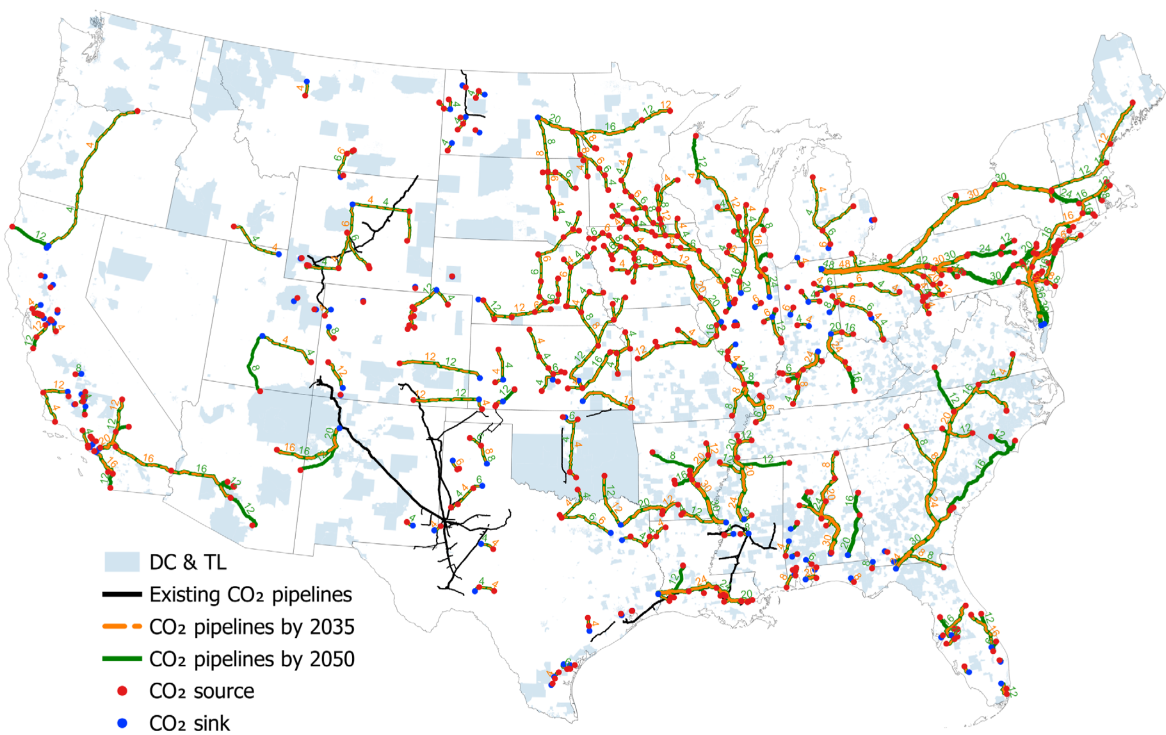


Figure 5. CO_2 pipeline networks by 2035 and 2050 for High-Removal scenario. The numbers shown along the pipelines represent the optimized pipeline diameters.

3.2 Low-Removal scenario

Figure 6 illustrates the simulated pipeline network by 2035 in the low-removal scenario, which uses advanced technology in all sectors. As a result, the number of sources (555) is smaller than the high-removal scenario modeled in this study. In this map below, we observe that the major trunklines are concentrated in the midwestern region, southeastern region, and western regions of the United States because of the numerous existing CO_2 sources. In Figure 6 we also present the total pipeline length of 23,781 miles needed by 2050 to properly meet the capture amount objectives in this scenario. The difference between the 2035 and 2050 pipeline lengths is relatively small (1,628 miles), however, new pipelines are required in South Carolina and the Mid-Atlantic region. A key highlight of this scenario is that approximately 93% of the total infrastructure must be operational by 2035. This reveals the urgent need to accelerate CCS deployments to achieve net-zero targets, as significant pipeline construction will be necessary within a short timeframe of about 10 years to align with projected CO_2 capture amounts.

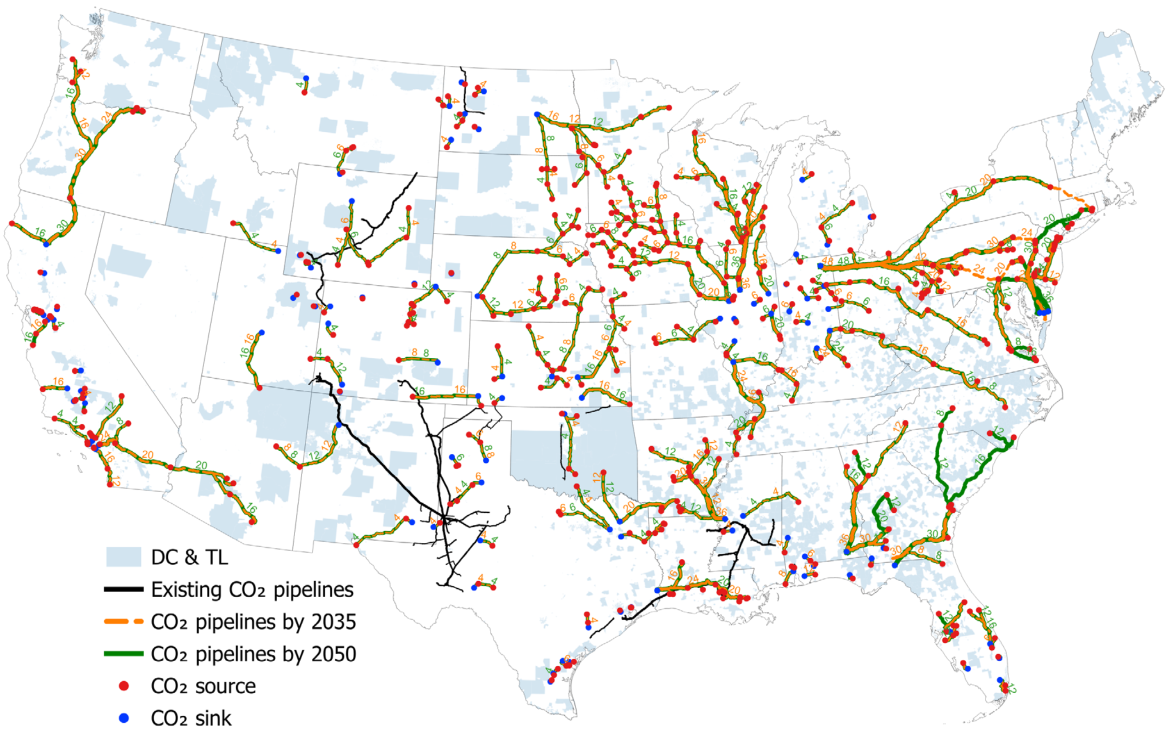


Figure 6. CO_2 pipeline networks by 2035 and 2050 for Low-Removal scenario.

3.3 Net-Zero scenario

Figure 7 illustrates the pipeline network of 25,031 miles required to meet the target capture amount of 440 $MtCO_2$/year by 2035 in the Net-Zero scenario, again according to the simulation result from *SimCCS*. As observed, most of the pipeline infrastructure is in the central and eastern regions of the United States due to the high density of CO_2 source emitters. Thus, the availability of multiple sinks facilitates effective connectivity among these sources, particularly evident in Indiana and Illinois. Additionally, shorter pipelines with smaller diameters are observed in Texas. The total pipeline infrastructure by 2050 for this Net-Zero scenario is shown in Figure 7. In this scenario, 27,438 miles are needed for CO_2 transportation—an increase of 2,407 miles compared to the infrastructure in 2035. Here notable differences are observed in the required pipelines in the states of Louisiana, South Carolina, and Minnesota. According to the results, 91% of the total pipelines must be constructed by 2035 to effectively meet the dynamic target capture amounts. Once more, this indicates that significant progress needs be made within the next 10 years to align with the net-zero objectives.

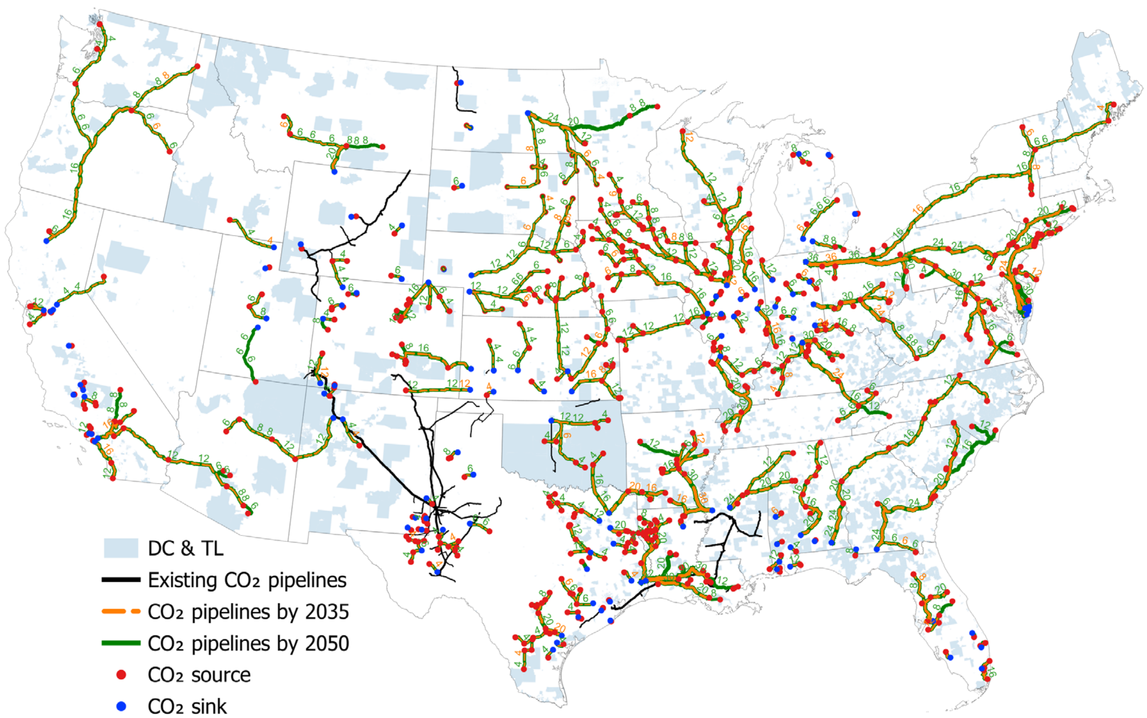


Figure 7. CO_2 pipeline networks by 2035 and 2050 for Net-Zero scenario.

4 Summary and conclusions

Table 1 summarizes the total pipeline lengths for all three scenarios modeled in this study, comparing projections for 2035 and 2050. The Net-Zero scenario exhibits the longest pipeline length, primarily due to the higher number of CO_2 sources compared to the other scenarios. In all cases, over 85% of the pipeline infrastructure needs to be completed to meet the target of a carbon-free power sector by 2035, highlighting the urgent need for accelerated CCS deployment on a national scale.

Table 1. Summary of total pipeline lengths by 2035 and 2050 for all three scenarios modeled.

	High-Removal scenario		Low-Removal scenario		Net-Zero scenario	
Year	2035	2050	2035	2050	2035	2050
Total pipeline length [miles]	20,375	24,081	22,153	23,781	25,031	27,438

Additionally, Figure 8 evaluates the CO_2 transport infrastructure for 2035 and 2050 across the three modeled scenarios. The total pipeline lengths illustrate the necessary diameters to effectively meet transportation requirements, with primary pipeline sizes of 4”-24” being used in all scenarios.

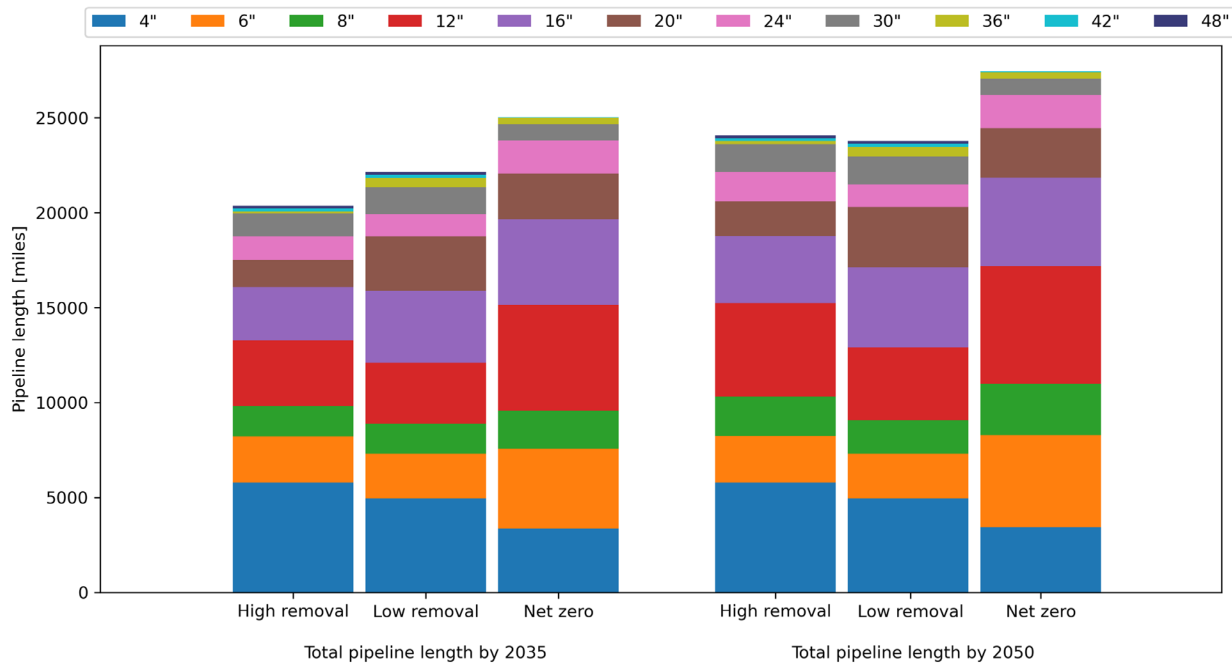


Figure 8. Comparison of total pipeline lengths by 2035 and 2050 for all three scenarios modeled. In each scenario, the required pipeline diameters are indicated in different colors to meet the CO_2 transportation objectives.

The key takeaways from this study are as follows:

- Between 23,781 and 27,438 miles of new pipelines will need to be constructed to capture and store CO_2 emissions as outlined in the three scenarios presented.
- The infrastructure design indicates that at least 85% of the total pipeline length must be completed by 2035. Comprehensive planning is essential for nationwide scenarios to achieve net-zero objectives, with a greater number of trunklines required in the Eastern, Midwestern, and Western regions of the U.S. to facilitate the transport of captured CO_2.
- The pipeline networks generated using *SimCCS$^{3.0}$* reflect the need for large-scale infrastructure capable of efficiently capturing, transporting, and storing CO_2 from multiple sources to available storage sites.

5 Acknowledgments

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