National Industrial Sector Decarbonization

EXTENT OF CARBON CAPTURE OPPORTUNITIES AND NETWORK OPTIMIZATION ACROSS THE UNITED STATES

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Carbon Solutions

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SECTION 1

Introduction

To meet current climate goals, the United States needs to pursue a variety of decarbonization strategies. In 2021, the three largest sources of CO_2 emissions were the transportation sector, the electric power sector, and the industrial sector, with 28%, 25%, and 23% of emissions, respectively.[1] While each sector faces unique challenges in meeting the nation's goal of 100% clean energy by 2035 and net-zero emissions by 2050,[2] the diversity in the emission sources and processes in the industrial sector requires a range of solutions, including electrification, changing fuel stocks, increasing energy efficiency, and carbon capture and storage (CCS). In the immediate term, CCS can provide a viable option to decarbonize while technical innovation proceeds to meet longer-term net-zero goals.

This project assessed different scenarios of CO_2 capture and storage (CCS) technology deployment on the US' existing CO_2 emissions sources for industry facilities. To understand the potential of carbon capture, we used the *SimCCS^{PRO}* toolset—integrated CCS network analysis (*SimCCS^{PRO}*), CO_2 capture (CO_2NCORD), CO_2 transport (*CostMAP^{PRO}*), and CO_2 storage (*SCO$_2$T^{PRO}*). The *SimCCS^{PRO}* optimization engine moves beyond "source-sink matching" by simultaneously assessing CO_2 capture, transport, and storage options; research has shown that you need to account for the feedback throughout the CCS value chain to find feasible, low-cost, and most likely CCS infrastructure configurations. *SimCCS^{PRO}* is also the only CCS planning tool that realistically routes CO_2 pipelines using a high-resolution "routing surface" and builds an integrated CO_2 pipeline network with CO_2 aggregated into low-cost, high-volume trunk lines.

Using the entire *SimCCS^{PRO}* toolset, this study explored several scenarios of industrial sector CCS. First, we ran models requiring certain capture targets to be met and then analyzed the costs, infrastructure, and industrial sectors that resulted from these capture targets. Second, we discounted storage costs for a range of potential tax credits to model how much CO_2 could be stored, and the costs and infrastructure build-out that would follow. Because of regional variations in both storage costs and industrial sector locations, we next considered how costs of capture and storage vary by region of the country. Next, we considered how trunklines in a few key regions of the country might impact the overall expansion of CCS nationwide. Finally, we examined how our results might impact disadvantaged communities, as defined by a selection of federal environmental justice metrics.

SECTION 2

Modeling CO_2 Capture, Transport, and Storage

2.1 Introduction

Determining the costs of carbon capture and geologic storage, along with the infrastructure costs and footprint that deployment will require, requires a variety of modeling approaches. While the model results are presented as a result of *SimCCS*^{PRO}, it is helpful to understand how the capture (*CO_2NCORD*), storage (*SCO_2T*^{PRO}), and pipeline network models (*CostMAP*^{PRO}) each provide input data to *SimCCS*^{PRO}, the source-sink optimization model. In each step of these separate models, there are different data required and model approaches employed, each of which will be discussed in detail below. A broad overview of how the tools interact with one another is in Figure 2-1 below.

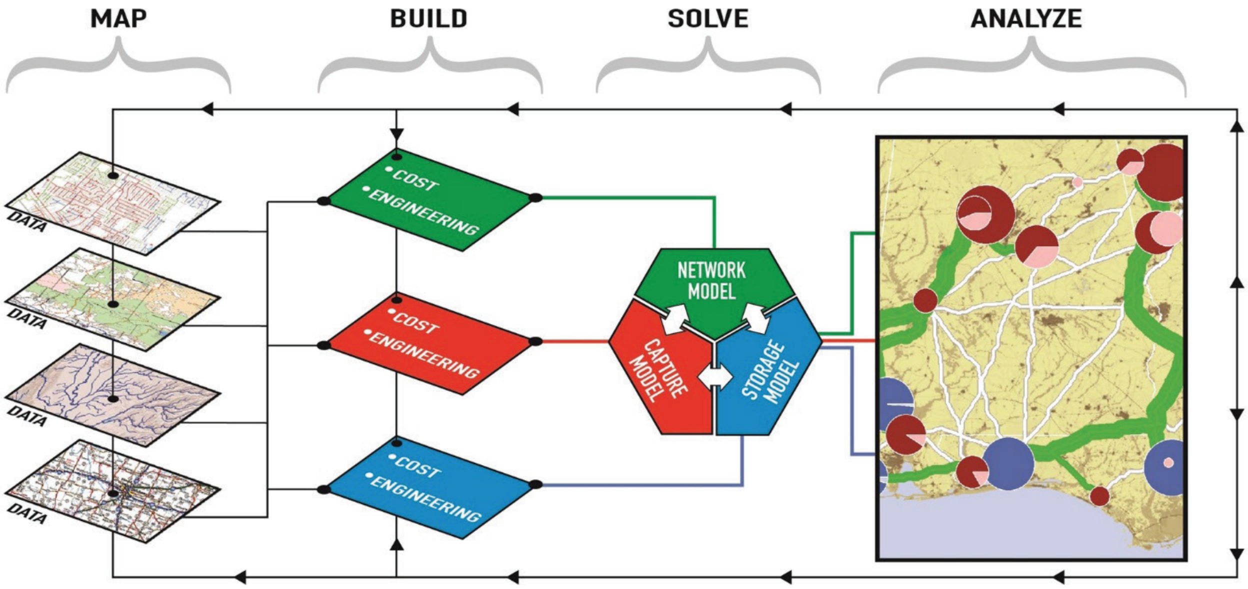

Figure 2-1. Relationships among capture, storage, and network modeling components.

2.2 Emissions costs and capturable CO_2: *CO_2NCORD*

2.2.1 Modeling Approach

The costs of capturing CO_2 for this study, including the estimated capture amounts and associated costs based on variable capture volumes, were calculated using Carbon Solutions' CO_2 National Capture Opportunities and Readiness Data (CO_2NCORD) software. CO_2NCORD is a novel software that utilizes the best available public data, including literature and expert input, to generate insights into point-source CO_2 emissions from US industrial facilities for capturable volumes, stream characterization, and associated capture costs (Figure 2-2). CO_2NCORD also reports CO_2 emissions data, along with capture rates and costs for capturing CO_2.

Emission data for this study was taken from the 2021 release of EPA's Greenhouse Gas Reporting Program (GHGRP).[3] Within this dataset, industrial facilities report data on multiple subparts, dependent on specific characteristics of the facility's industrial process components, unique to the facility type. For example, a refinery (Subpart Y) may also have hydrogen production (Subpart P). Therefore, *CO_2NCORD* capture rates and estimates are based on these Subparts reported at each facility. Capture rates and costs were taken from recent NETL reports when available, and then supplemented with literature as needed.

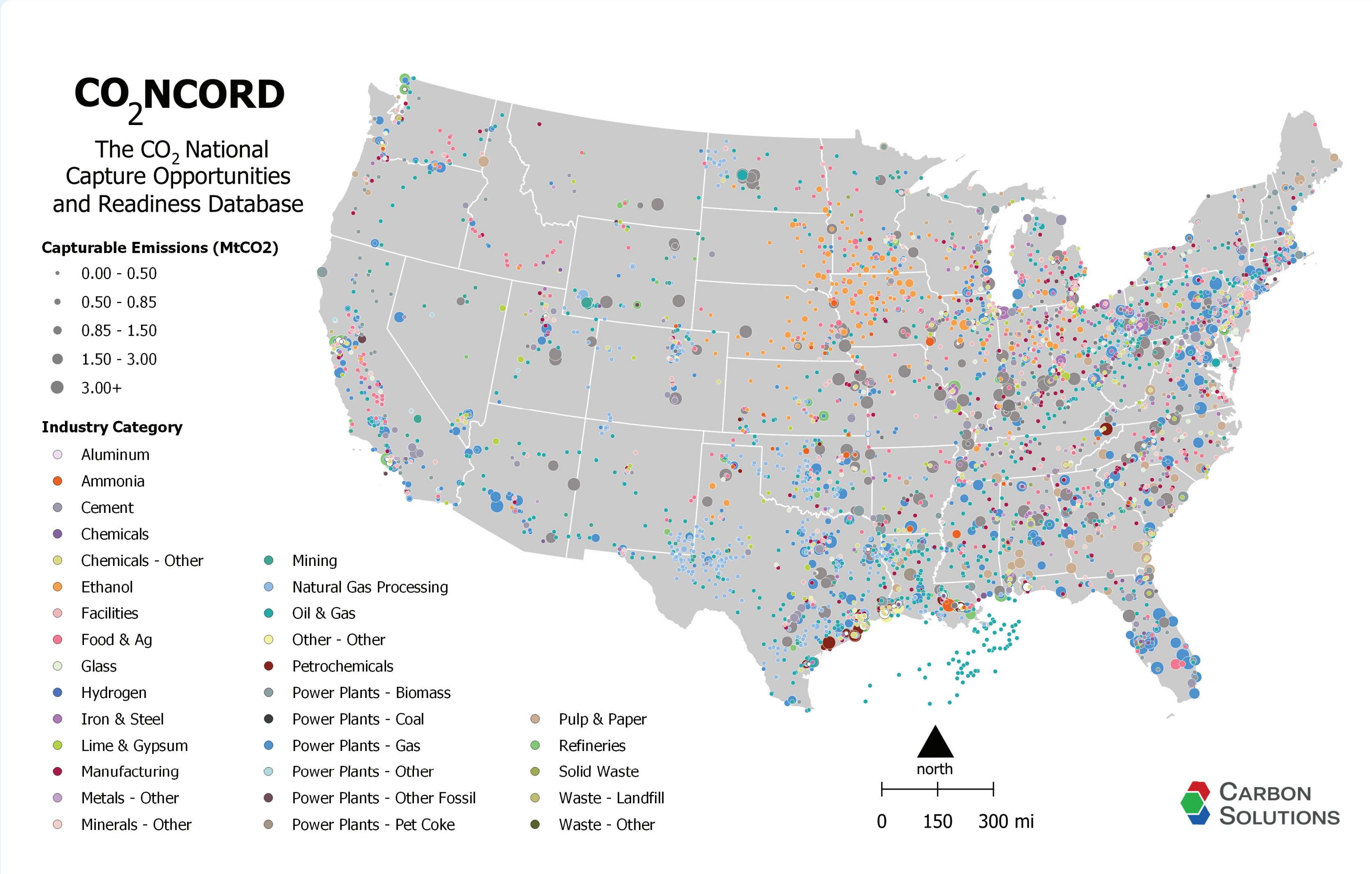

Figure 2-2. CO_2NCORD facilities with primary and secondary industrial categories and estimated emissions in $MtCO_2$ per year.

2.2.2 Data for current project

For this project, we were specifically interested in modeling those industrial sectors with the largest CO_2 emissions, while also considering sectors that had high emissions. An overview of the capture rates, cost, and corresponding literature source for sectors considered in this study is shown in Table 2-1. The table shows both the cost from the original study, as well as the cost adjusted to 2021 dollars.

Table 2-1. Costs of capturing CO_2 by sector, with EPA subpart.

EPA Subpart	Description	Capture Rate	Literature Cost and Dollar Year			Capture Cost [2021 USD/t]
			Cost [USD/t]	Dollar Year	Source	
AA	Pulp and Paper	90%	$48.00	2016	3	$54.00
F	Metals - Aluminum Production	90%	$55.70	2016	3	$62.66
G	Chemicals - Ammonia Manufacturing	100%	$19.00	2018	1	$20.48
H	Minerals - Cement Production	90%	$64.30	2018	1	$69.30
HH	Waste - Municipal Landfills	90%	$70.37	2017	4	$77.67
J	Other - Ethanol Production	100%	$32.00	2018	1	$34.49
K	Metals - Ferroalloy Production	90%	$48.45	2016	3	$54.51
b	Chemicals - Hydrogen Production	90%	$61.70	2018	1	$66.49
Q	Metals - Iron and Steel Production	90%	$65.90	2018	1	$71.02
S	Minerals - Lime Manufacturing	90%	$34.40	2016	3	$38.70
W	Petroleum and Natural Gas Systems	99%	$16.20	2018	1	$17.46
X	Chemicals - Petrochemical Production	100%	$26.20	2018	1	$28.24
Y	Refineries - Petroleum Refineries	90%	$51.95	2016	3	$58.44

Certain facilities are expected to combine emissions reported under two subparts. For example, cement and lime plants typically combine product (Subpart H or S) and combustion emissions (Subpart C). *CO_2NCORD* groups these emissions together into a single stream. Additionally, EPA reports both fossil and biogenic CO_2 emissions. Both are suitable for capture and included in capture estimates. However, emissions from some equipment are not expected to be suitable for capture. For example, although flares may have large CO_2 volumes, the high temperature of the exhaust does not make it a likely capture point. *CO_2NCORD* removes these emissions when possible. Finally, facilities that were determined to capture suitable emissions less than the 45Q limit were excluded from consideration. Cost ranges are illustrated in Figure 2-3.

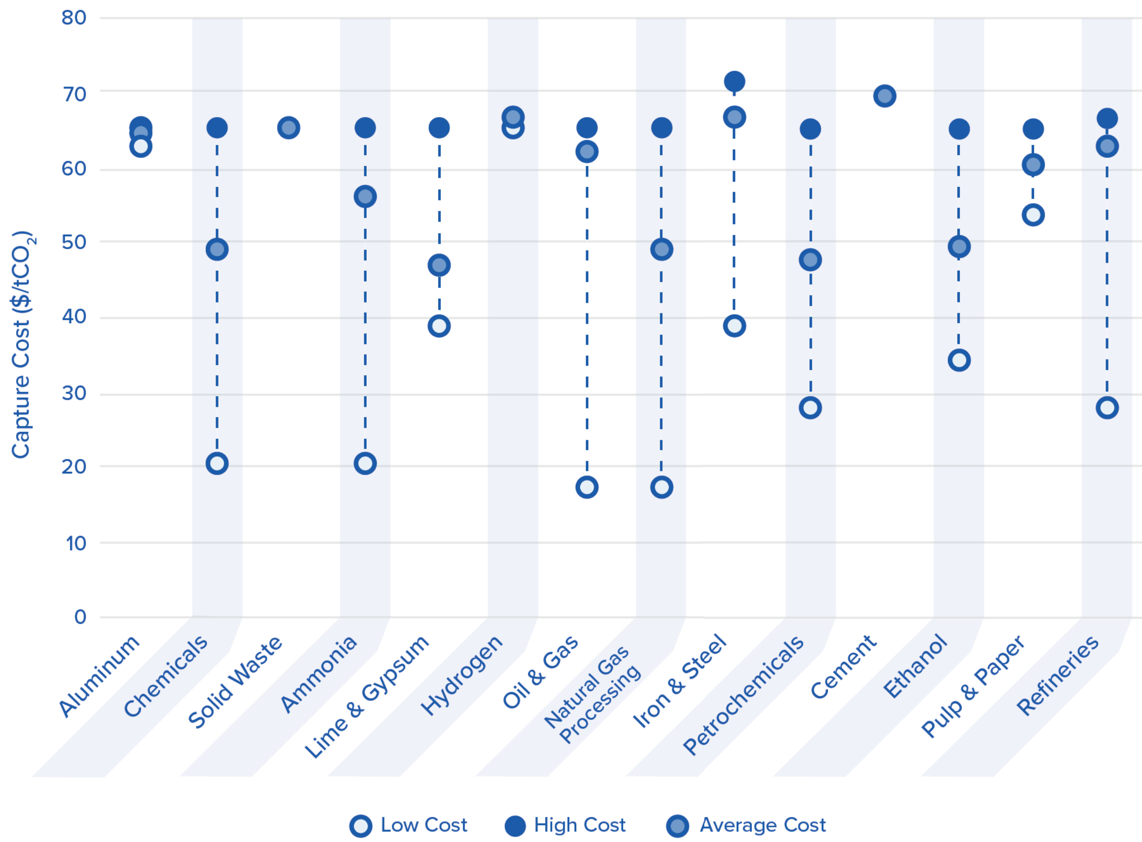

Figure 2-3. Range of capture costs by industrial sector from CO_2NCORD.

Capturable emissions by sector are in Figure 2-4. Approximately a third of the industries considered have total capturable CO_2 emissions of 60 $MtCO_2$/yr or more, with only the petroleum refineries industry reaching a total capacity of approximately 2.5 times that value. Pulp & paper processing has the next highest cumulative capturable CO_2 emissions with approximately 131.9 $MtCO_2$/yr. The industries with the next highest cumulative capturable CO_2 emissions are ethanol, cement, and petrochemical production with an average capturable CO_2 emissions of 61.3 $MtCO_2$/yr. The smallest three industries are aluminum production, chemicals manufacturing, and solid waste. These industries have cumulative capturable CO_2 emissions of 19.5 $MtCO_2$/yr.

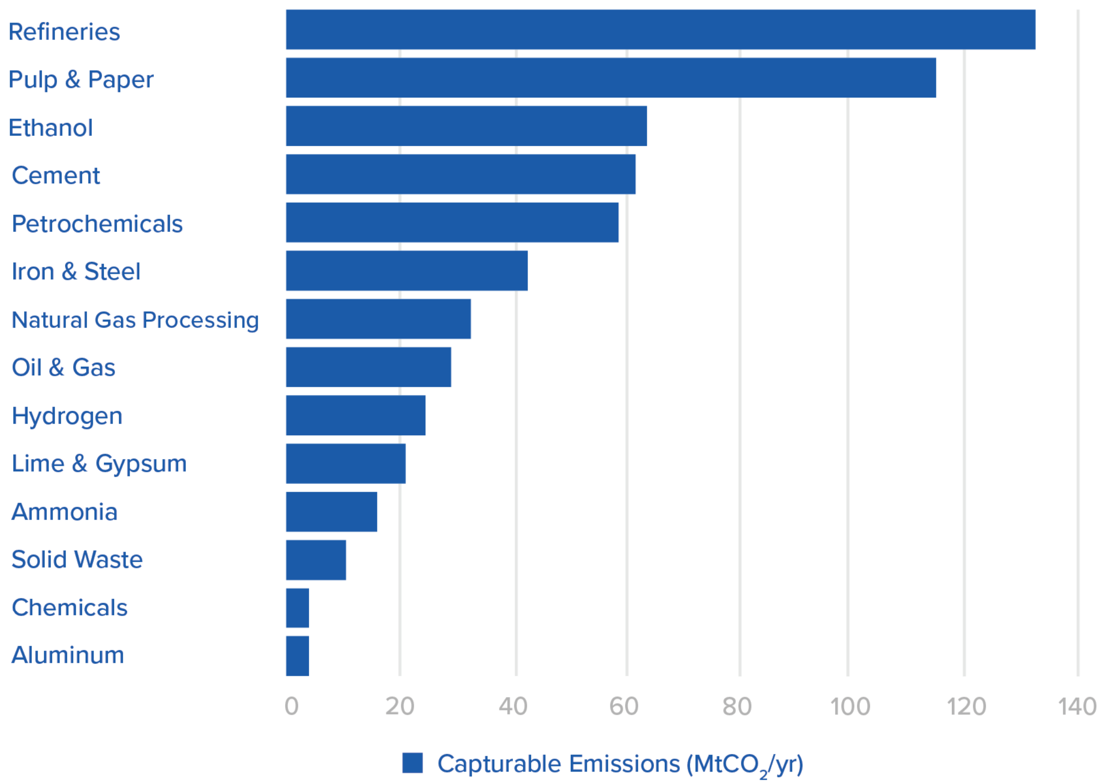

Figure 2-4. Total available capturable CO_2 by industrial sector.

2.3 Geologic costs and available storage: *SCO_2T^{PRO}*

2.3.1 Modeling Approach

The Carbon Solutions Sequestration of CO_2 Tool (*SCO_2T^{PRO}*) software allows users to estimate the cost and capacity of geologic CO_2 storage using the workflow summarized in Figure 2-5.

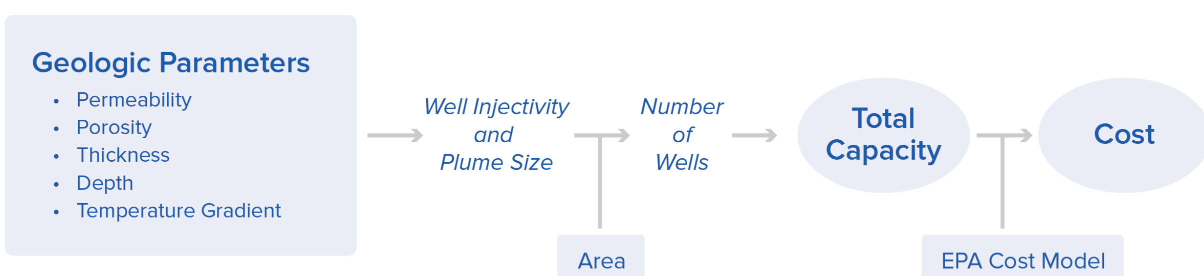

Figure 2-5. Workflow of the SCO_2T^{PRO}. [4]

SCO_2T^{PRO} first estimates well injectivity and the CO_2 footprint in the subsurface referred to as "plume size." This is done using reduced order models (ROMs) that were generated using machine learning and reservoir simulation data.[5] Each ROM requires five inputs: geologic formation depth (or pressure), thickness, permeability, porosity, and temperature (or geothermal gradient). The number of wells is then estimated using the plume size and the area available for CO_2 storage. Knowing the number of wells and well injectivity allows for the total capacity to be estimated. Lastly, the costs of geologic CO_2 storage are determined based on the most recent EPA cost model for CO_2 storage.[6]

In addition to the geologic inputs shown in Figure 2-5, there are additional user inputs that give flexibility to the engineering and/or site-level assumptions that impact cost (e.g., number of monitoring wells per injection well). Overall, this allows *SCO_2T^{PRO}* to provide highly disaggregated cost screening, including site characterization, post-injection site closure, and monitoring costs. For this reason, *SCO_2T^{PRO}* is a valuable tool for developing dynamic estimates of storage capacity and cost. In the subsections below the engineering and cost assumptions are discussed, as well as the geologic data that was used for this project.

2.3.2 Engineering and Cost Assumptions

For this study, the EPA cost model for geologic CO_2 storage was used, which was originally developed for the Geosequestration Cost Analysis Tool (GeoCAT).[7] Using this model, the cost of geologic CO_2 storage is a function of many site-level engineering and cost assumptions. For this study, we assumed the following: 9-inch diameter CO_2 injection wells; 10 old oil and gas wells needed to be plugged at each site prior to CO_2 injection; 1 backup CO_2 injection well was drilled per primary CO_2 injection to hedge against formation uncertainty; 2 above-zone and 2 in-zone monitoring wells were drilled per CO_2 injection well. These assumptions, such as the number of oil and gas wells that need to be plugged to mitigate the potential leakage of CO_2 into drinking water resources, were based on prior work[7] and internal analyses. Lastly, SCO_2T^{PRO} provides capital cost and operating cost estimates, and we assumed a 15% discount rate and a 30-year financing period when converting these to annualized costs.

2.3.3 Reduced Order Models (ROMs)

The Reduced Order Models (ROMs) used in this project were developed from FEHM reservoir simulation data.[5] The most recent version of the EPA cost model was used for *SCO_2T^{PRO}* cost estimates.[6]

2.3.4 Geologic Database

As described above and can be seen in Figure 2-5, *SCO_2T^{PRO}* requires a variety of geologic reservoir properties as inputs for estimating CO_2 storage costs and capacities for a potential storage site. No single publicly available dataset of saline storage formation reservoirs suitable for modeling CO_2 storage properties and sequestration costs via *SCO_2T^{PRO}* exists for the area of investigation, so a Geologic Reservoir Property Database was built by CARBON SOLUTIONS through identifying, interpreting, vetting, and incorporating suitable datasets from a wide variety of sources. These sources include but are not limited to: USGS National Geologic CO_2 Storage Assessment,[8] NATCARB CO_2 storage database,[9]use and storage (CCUS Regional Carbon Sequestration Partnership products,[10] State Geological Surveys,[11] reports and data from CCS demonstrations such as CarbonSAFE projects[12] and RCSP demonstrations,[13] various academic publications, and datasets generated by CARBON SOLUTIONS through interpretations of publicly available oil and gas well data available from state regulators/agencies. The resultant database includes location-specific geologic properties for more than 100 reservoirs from across the continental United States (Figure 2-6).

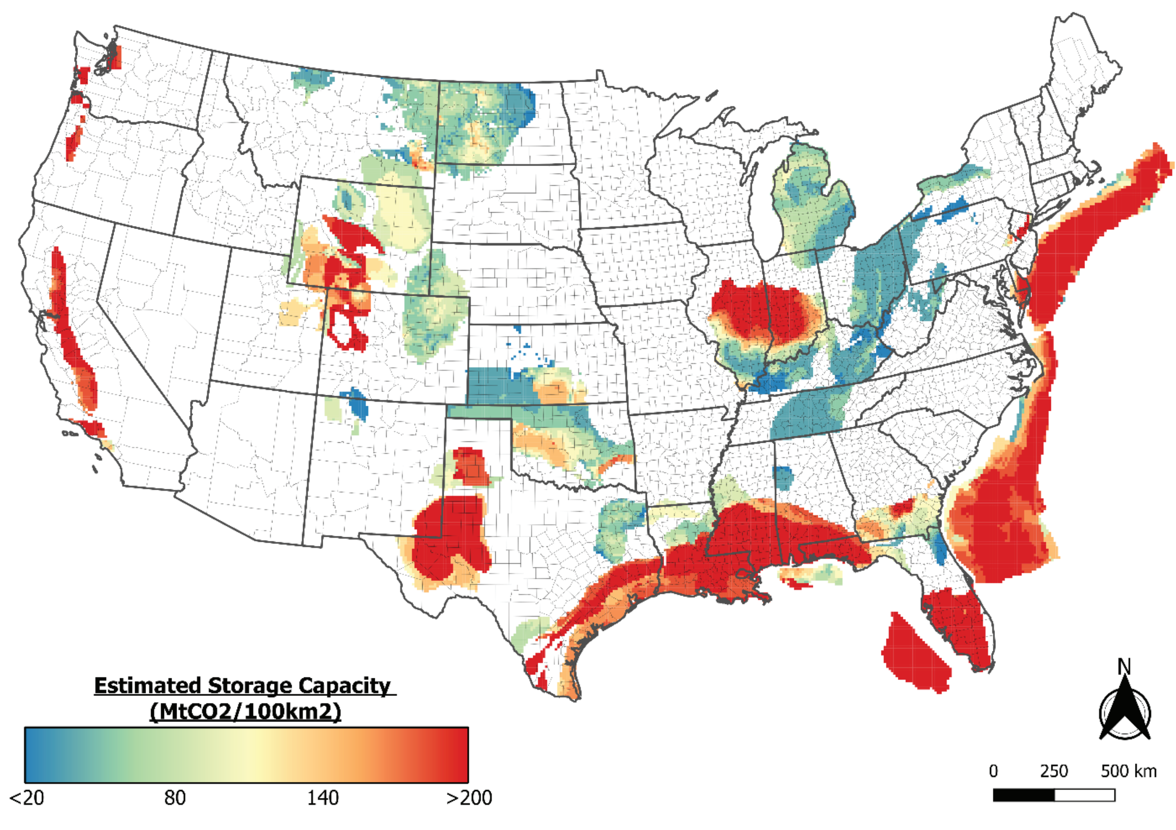

Figure 2-6. Estimated storage capacity of geological formations across the United States.[14]

Carbon Solutions' Geologic Reservoir Property Database and *SCO_2T^{PRO}* tool were used to model storage costs and capacities across the conterminous United States. Storage was only modeled for onshore, saline aquifer reservoirs. Depleted oil and gas fields, enhanced oil recovery, and offshore reservoirs were not considered. For this project, we modeled sinks as 10 x 10 km grid cells (x). Each cell has geologic input data specific to that location and thus location-specific modeled storage outputs. Note that the storage capacities estimated by *SCO_2T^{PRO}* represent the total capacity for the entire grid cell area. If multiple reservoirs with sufficient data for modeling were present within a 10 x 10 km cell, discrete results were generated for each.

The sink data used for the network optimization modeling via *$SimCCS^{PRO}$* was generated from the database described above. To provide a more regional view of storage due to the project's nationwide scale, the 10 x 10 km sinks were aggregated into 50 x 50 km grid cells. These coarser sinks were created from the weighted average of costs and the sum of storage capacity for the 10 x 10 km cells that fell within each 50 x 50 km cell. "Stacked storage" (i.e., storage via multiple reservoirs in the same location) was not considered. For 10 x 10 km cells where multiple reservoirs were present, only the lowest storage cost reservoir (based on *SCO_2T^{PRO}* estimates) was used to create the corresponding 50 x 50 km aggregate sink. We consider 1,864 distinct sink locations in each capacity scenario. Sink injection costs range from \$6.50/tCO_2 to \$604.25/tCO_2 with storage capacities of 1.31 $MtCO_2$ to 3775.13 $MtCO_2$.

2.4 Pipeline Routing and Costs: *$CostMAP^{PRO}$*

2.4.1 Modeling Approach

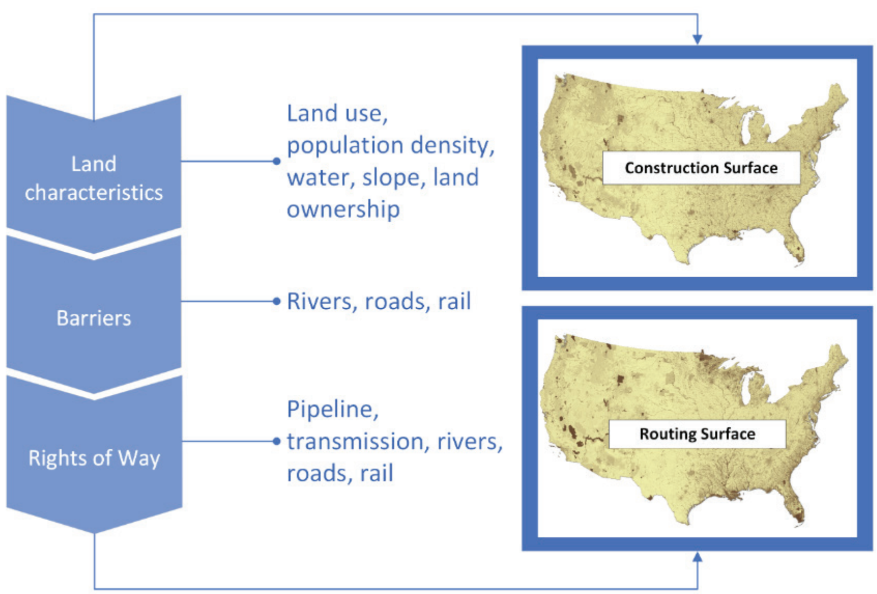

Figure 2-7. Example of data used to construct right of way and construction cost surface.

To calculate the cost of pipeline infrastructure and to route pipeline segments we use the *CostMAP^PRO^* software.[15–17] *CostMAP^PRO^* integrates various geospatial data layers to create both a routing network and a cost network which are integrated into *SimCCS^PRO^* to find both the most efficient path between nodes and to calculate the cost of pipeline infrastructure. *CostMAP^PRO^* is based on the Least Cost Path (LCP) analysis and provides the needed edge weights for LCP algorithms. Edge weights are first developed from accumulated data layers. These layers include fully distributed data such as land cover, federal lands, population density, slope, and environmentally protected areas. Additionally, *CostMAP^PRO^* also integrates linear features as both barriers (features incompatible with pipeline crossings) and corridors (features advantageous for pipeline routing). Barrier data layers include rivers, roads, and railways while corridor data layers include existing pipeline rights-of-way, transmission lines, and roads. For this project, we use default values from *CostMAP^PRO^* which assume a 720-meter resolution and routing and cost weights, all of which were determined through both literature and expert opinion from pipeline engineers and researchers. Barrier and corridor data is integrated at a resolution of 240 meters.

Every data layer is assigned both a cost and a routing weight. Cost weights are intended to represent the real cost incurred by building and operating a pipeline through an area. For example, routing a pipeline through a forested area would incur the additional cost of clearing the land for development. Routing weights are intended to include social and environmental concerns in addition to costs to create an overall affinity or aversion to pipeline routing for an area. The resulting output is both a routing network which is used to route the pipelines and a cost network which is used to calculate the cost of the routed pipelines. Disassociating the routing and cost networks from each other is important to ensure both realistic pipeline costs and routes. While cost is a major concern for pipeline developers, sensitive areas such as critical habitat require additional routing concerns that are divorced from the cost of pipeline development. However, by separating the cost and routing networks, we can create customized networks that weigh priorities according to the project's needs and concerns.

Once the cost and routing weights are chosen, a stepwise process computes the cost of moving from cell to cell, calculated as the average cost of the corresponding nodes normalized by the distance needed to travel between nodes (using a combination of rook and bishop movement). *CostMAP^PRO^* also utilizes a search kernel to determine the cost of encountering barriers and corridors. The search kernel is deployed at a spatial scale 1/3 that of the existing weighted surface allowing for a detailed analysis of the existence of corridors and barriers. This process is demonstrated in Figure 2-7, which shows an example of the existence of barriers(a) and corridors(b) between cells. A more detailed accounting of the function of *CostMAP^PRO^* can be found in Hoover et al. 2019.[15]

2.4.1 Data for current project

A variety of data and data sources are used as inputs in *CostMAP^PRO^*, as follows:

- The population distribution is taken from LandScan.[18]
- The land use characteristics are derived from the National Land Cover Database.[19]
- Federal land designations are derived from USGS.[20]
- Slope is calculated from the US Department of Agriculture's LANDFIRE dataset.[21]
- Railway data is from the US Department of Transportation Rail Network data.[22]
- River data is from the National Hydrography Dataset and the EPA.[40]
- Roads are from ESRI.[23]
- Pipeline and transmission line right-of-way data are from HIFLD.[24]

2.5 Network Optimization: *SimCCS^PRO^*

The cost and routing networks output from *CostMAP^PRO^* are closely integrated into the *SimCCS^PRO^* workflow. *SimCCS^PRO^* uses Delaunay triangulation with CO_2 source and sink information as end nodes to build a rudimentary pipeline network. Once the connections between end nodes have been determined, *SimCCS^PRO^* uses the routing network and Dijkstra's algorithm to determine the route between nodes that minimizes the total routing weight. Dijkstra's algorithm iterates through the possible paths of equal-weighted distance from the source node, incrementally expanding the total weighted distance until the destination node is found, thus resulting in the least cost path between the two nodes.[25]

For *SimCCS^PRO^*, the routing weights generated by *CostMAP^PRO^* are used to determine the cumulative weighted distance in Dijkstra's algorithm. The resulting network of routing weight-minimized pipeline paths is the Candidate Network. Each pipeline segment in the candidate network can then be assigned a cost using the cost network created by *CostMAP^PRO^* which can then be scaled depending on the volume of CO_2 required between nodes. The calculated pipeline costs are also used when *SimCCS^PRO^* performs the final global optimization to determine which pipeline paths are deployed.

SECTION 3

Results: Capacity Mode Scenarios

3.1 Introduction

The capacity mode ("cap mode") scenarios in *SimCCS^{PRO}* integrate CO_2 capture sources and storage sinks into a final CCS candidate network with the objective of sequestering a pre-determined volume of CO_2 at the lowest possible unit cost (in $/$tCO_2$). This final unit cost integrates expenditures across all three CCS phases – capture, transport, and storage. In cap mode, the *SimCCS^{PRO}* optimization engine minimizes these unit costs to reach a target volume.[17]

Carbon Solutions ran *SimCCS^{PRO}* in cap mode to optimize unit costs across seven scenarios, each with a different capture target (100 to 600 $MtCO_2$/yr at 100 $MtCO_2$/yr increments and 618.091 $MtCO_2$/yr, respectively). For each of these capacity scenarios, there were 1,874 capturable emission points at 1,302 facilities across 14 different industries available for selection. Each capturable emission point had its own capture cost assigned using *CO_2NCORD*. These sources were routed using *CostMAP^{PRO}* to storage reservoirs modeled using *SCO_2T^{PRO}*. Routes were chosen to achieve the lowest possible transportation and storage costs for each source. Sources were then selected for inclusion based on a final candidate network that achieved target volumes across the seven scenarios at the lowest possible unit cost.

3.2 *SimCCS^{PRO}* National Capacity Results

Table 3-1 summarizes the number of streams and sinks deployed in each of the seven cap mode scenarios, the total length of all pipelines deployed in kilometers, and the total costs and costs associated with point source capture, pipeline transport, and sink storage costs. Deployed pipeline length increases from 6,528.94 km at a capture target of 100 $MtCO_2$/yr to 54,684.29 km at a capture target of 618.091 $MtCO_2$/yr. Further, at the maximum capture target, 618.091 $MtCO_2$/yr, 298 sink locations and all 1,874 points of capturable CO_2 emissions are being utilized.

Table 3-1. Stream and sink counts, network length, and costs associated with Capture, Transport, and Storage for a range of CO_2 annual capture amounts.

Annual Capture Amount ($MtCO_2$/yr)	Streams (#)	Sinks (#)	Network Length (km)	Total Cost ($/t$CO_2$)	Source Cost ($/t$CO_2$)	Transport Cost ($/t$CO_2$)	Sink Cost ($/t$CO_2$)
100	300	116	6529	55.03	38.38	9.88	6.77
200	427	116	5005	65.53	53.77	5.23	6.53
300	670	136	9235	69.04	55.89	6.47	6.67
400	987	182	14681	69.41	56.77	5.84	6.80
500	1296	209	26846	76.19	58.06	11.40	6.74
600	1693	257	43060	78.88	58.85	13.30	6.73
618.091	1874	298	54684	81.46	58.98	15.63	6.84

The total costs for CCS infrastructure, including capture, transport, and storage, range from \$55.03/tCO_2 at the minimum 100 MtCO_2/yr capture target up to \$81.46/tCO_2 at the maximum 618.091 MtCO_2/yr capture target – an increase of \$26.42/tCO_2. Figure 3-1 breaks these costs into their three major components – capture (source), transport, and storage (sink). Capture (source) costs exhibit the largest difference across scenarios, rising by \$20.60/tCO_2 – from \$38.38/tCO_2 to \$58.98/tCO_2. This accounts for 78% of the total increase across scenarios. Transport costs rise by \$5.75/tCO_2, from \$9.88/tCO_2 to \$15.63/tCO_2. This accounts for almost all of the remaining 22% of the cost increase across the seven scenarios. There are minimal changes in storage (sink) costs across scenarios.

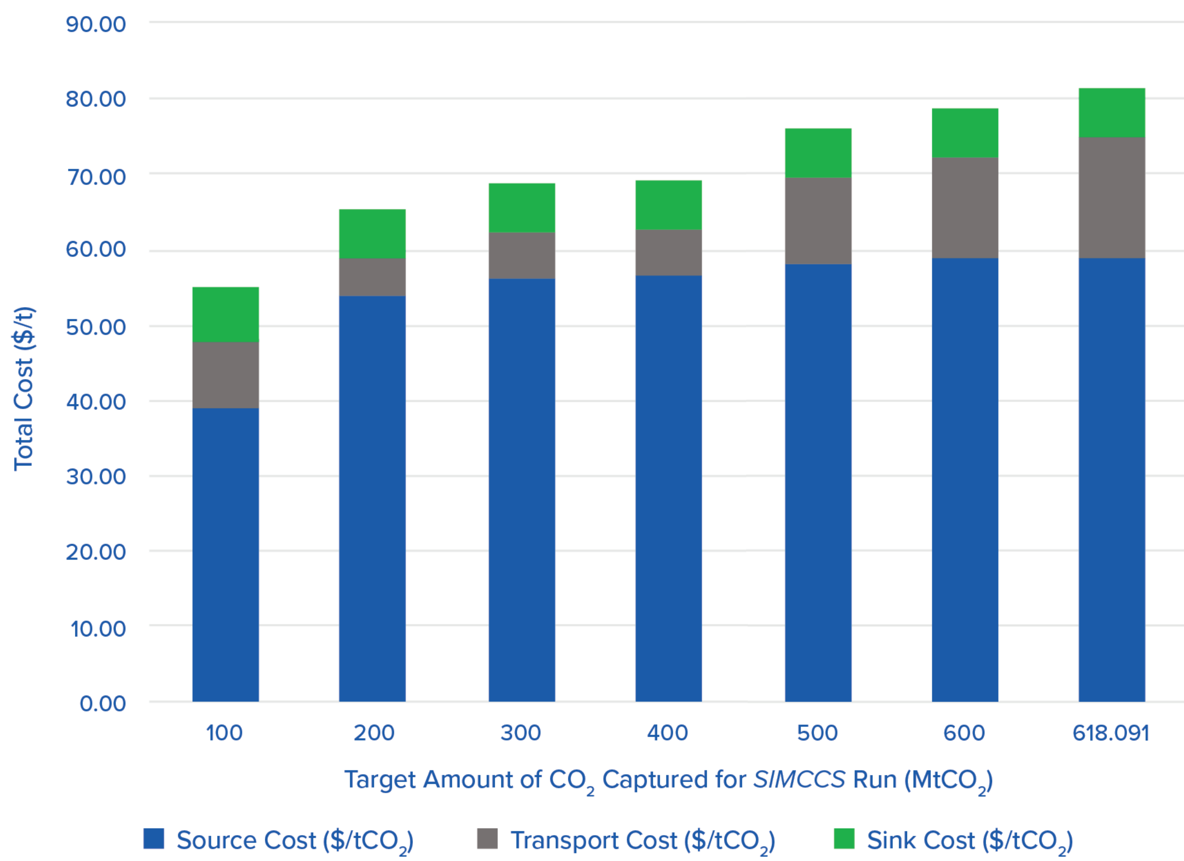

Figure 3-1. Total capture cost, by Source, Transport, and Sink costs.

As the capture target increases, capture (source) costs increase as more expensive capturable emissions points from corresponding facilities are deployed – driving over three-quarters of the overall cost increase. The transportation cost increases driving the remaining just under one-fourth of overall cost increases can be attributed to increases in the length of pipeline deployment needed to meet annual capture targets.

A geographic distribution of captured emissions from facilities, with increasing amounts of captured $CO_{2,}$ can be found in Figure 3-2 to Figure 3-5. At 100 $MtCO_2$/yr, facilities with CO_2 being captured are in California, the Rocky Mountains, the Midwest, and the Midcontinent regions. By 500 $MtCO_2$/yr, the geographic distribution of facilities capturing CO_2 is much more widespread.

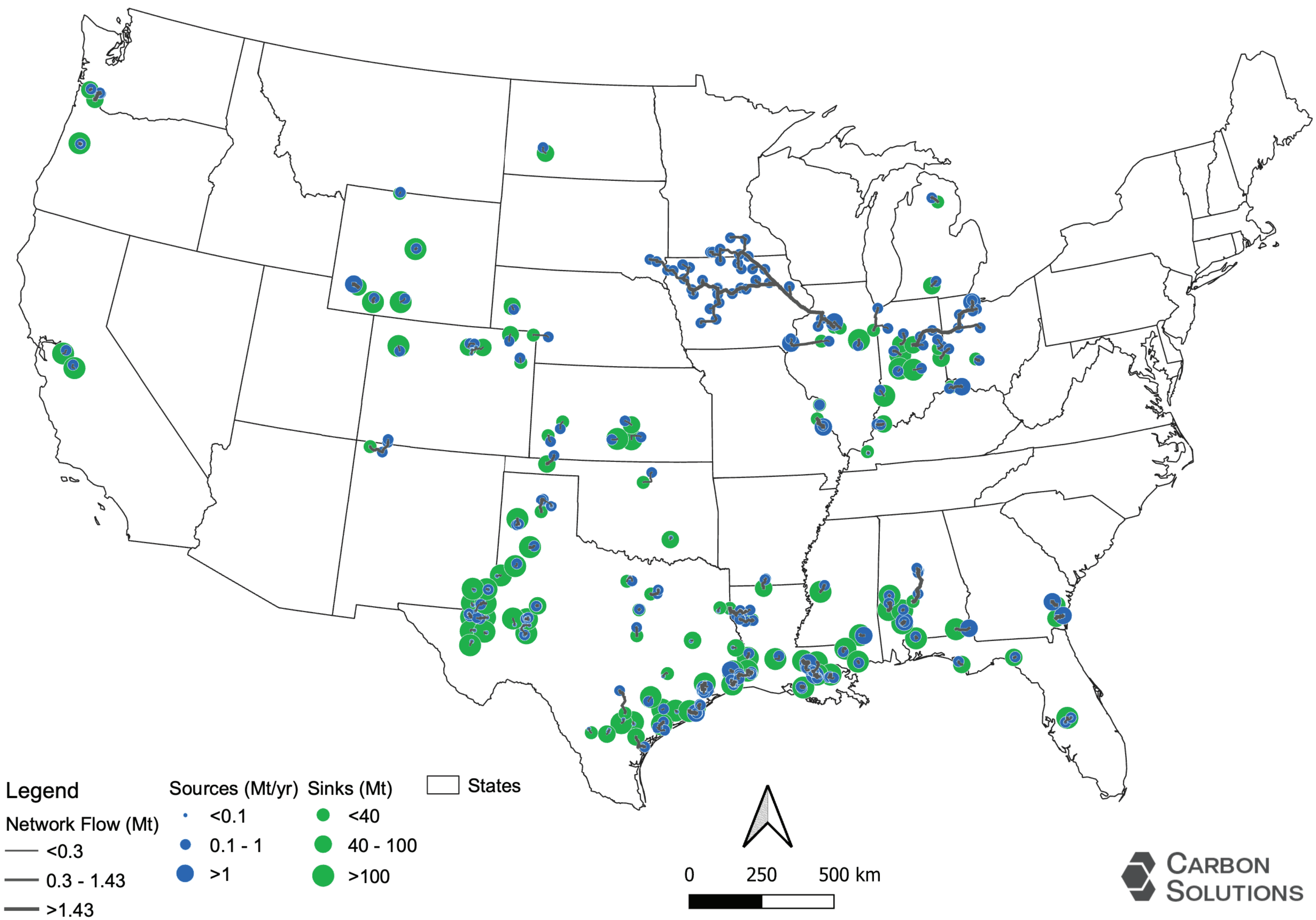

Figure 3-2. Location of sources captured, sinks deployed, and network required to capture 100MtCO_2/yr.

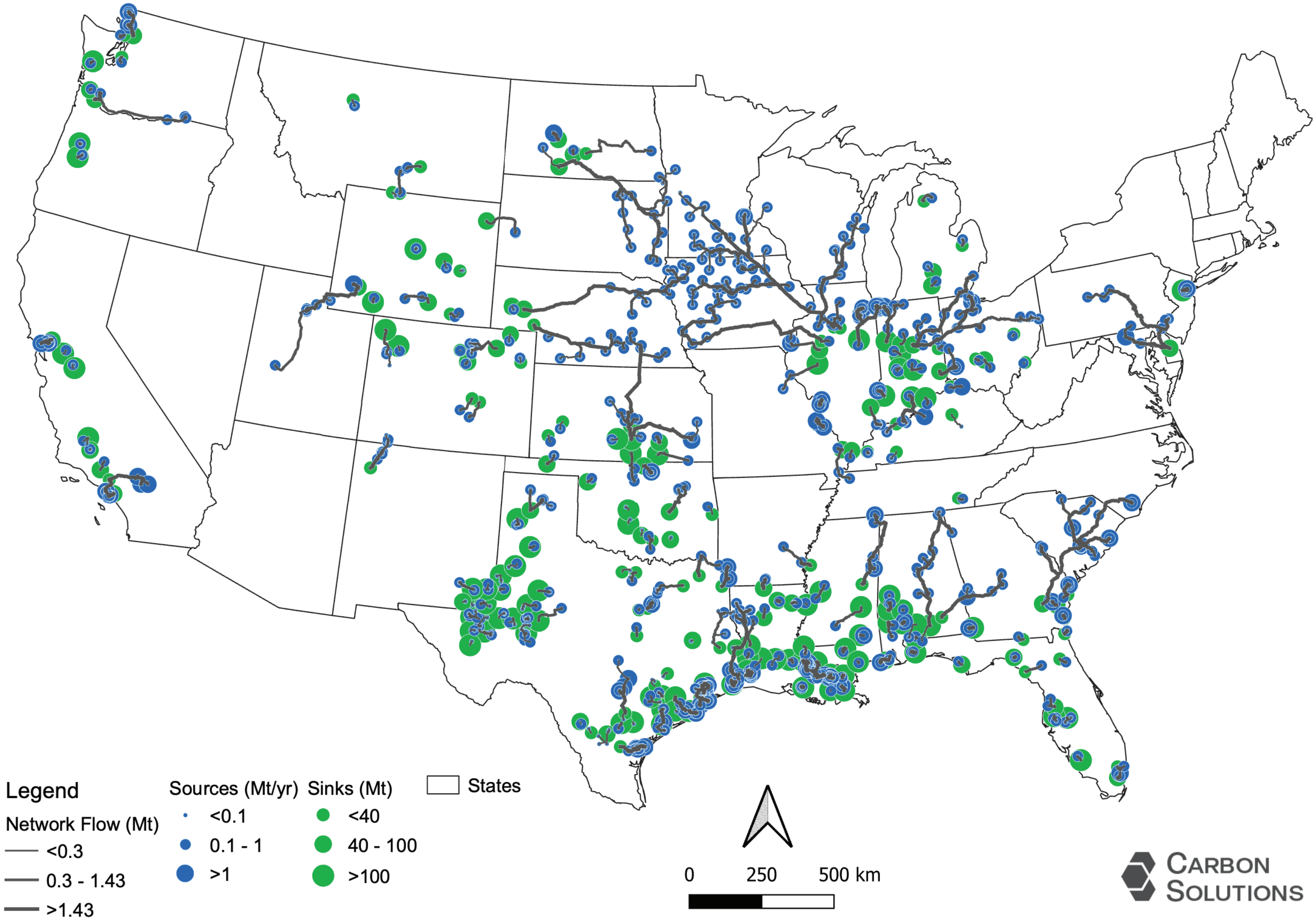

Figure 3-3. Location of sources captured, sinks deployed, and network required to capture 500MtCO_2/yr.

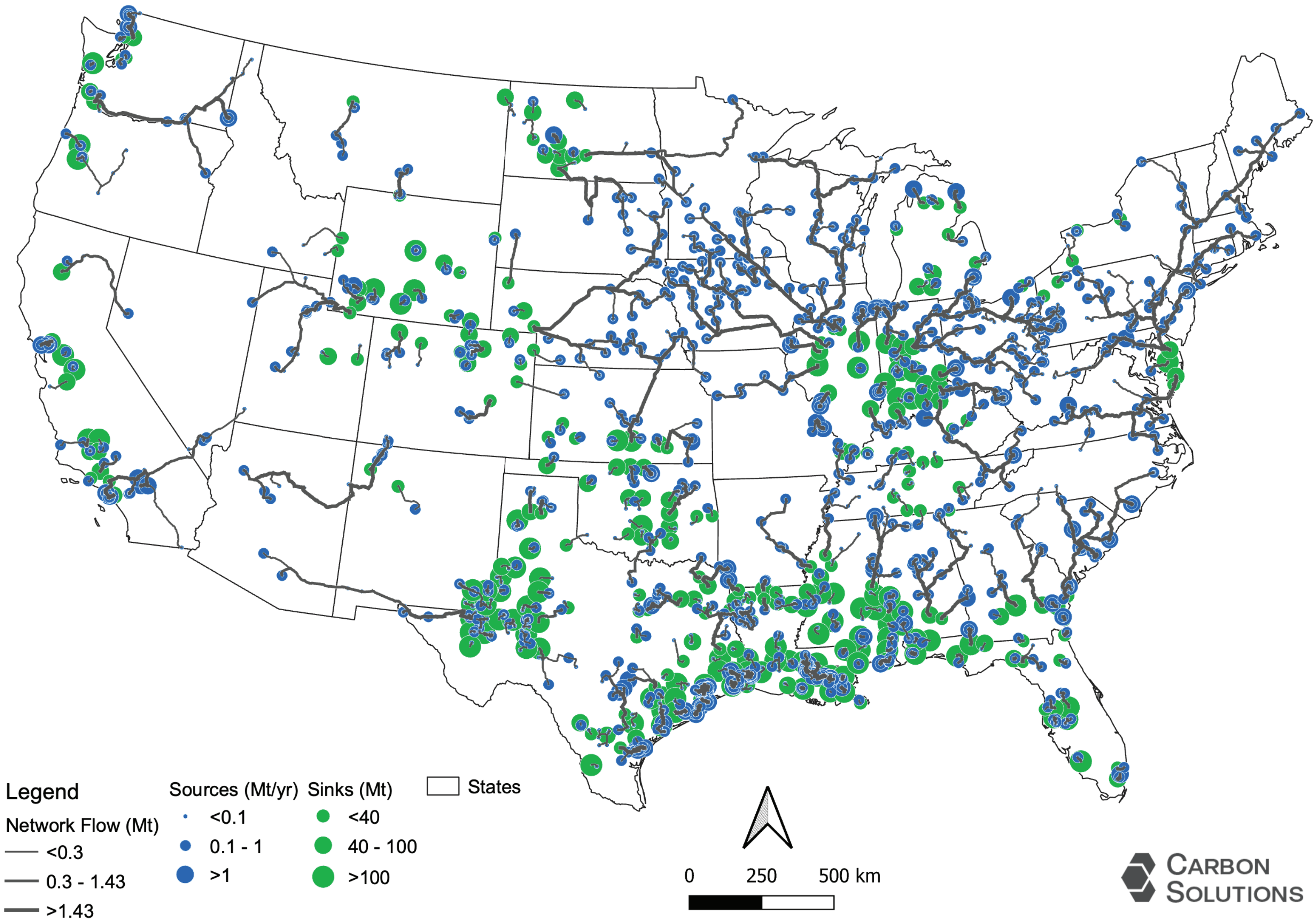

Figure 3-4. Location of sources captured, sinks deployed, and network required to capture 618.091 $MtCO_2$/yr.

3.3 *SimCCS^PRO* National Capacity Results by Industrial Sector

To capture CO_2 at greater targets, sources are included in optimized *SimCCS^PRO* networks that increase combined source (capture), transport, and sink (storage) costs. As stated in the previous section, over three-quarters of the change in total costs across the seven scenarios is driven by CO_2 capture cost increases. In cap mode, each capturable stream's capture cost, as well as transportation and storage costs, are all factors affecting how *SimCCS^PRO* prioritizes them in building an optimal CCS network at each targeted CCS volume. By and large, this means that CO_2 streams with lower capture costs will receive priority at lower targeted CCS volumes, with more expensive capture sources only included at higher targeted CCS volumes.

Table 3-2 and 3-3 show the inclusion of different industrial sectors in two ways. First, in Table 3-2, as a percentage of the capturable CO_2 emissions that are accounted for in each industrial sector across the seven cap mode scenarios run. As an example, in the 100MtCO_2/yr scenario, 5% of Refineries emissions are captured, and an additional 31% of its emissions are captured in the 200MtCO_2/yr scenario (or 36% of total emissions). In this table, each of the 14 industries will reach 100%.

Table 3-2. Percentage of emissions captured at each MtCO_2/yr capture target, across sectors.

Sectors	100 Mt	200 Mt	300 Mt	400 Mt	500 Mt	600 Mt	618 Mt
Refineries	5%	36%	66%	87%	95%	100%	100%
Pulp & Paper	20%	39%	52%	58%	75%	98%	100%
Ethanol	41%	23%	49%	79%	94%	99%	100%
Cement	0%	0%	7%	21%	66%	96%	100%
Petrochemicals	22%	78%	83%	93%	93%	100%	100%
Iron & Steel	0%	0%	0%	22%	62%	94%	100%
Natural Gas Processing	30%	38%	63%	79%	85%	97%	100%
Oil & Gas	7%	7%	22%	41%	53%	78%	100%
Hydrogen	0%	2%	47%	87%	95%	100%	100%
Lime & Gypsum	55%	52%	56%	57%	71%	96%	100%
Ammonia	41%	66%	70%	78%	92%	100%	100%
Solid Waste	0%	0%	0%	16%	33%	95%	100%
Chemicals	42%	61%	58%	64%	72%	94%	100%
Aluminum	0%	0%	18%	30%	53%	77%	100%
Total	**16%**	**31%**	**48%**	**64%**	**81%**	**97%**	**100%**

A second way of looking at this data is presented, in Table 3-3, where the percentage contribution that each industry's capturable streams make to achieving each cap mode scenario's pre-determined CCS volume target. In this table, each cap mode scenario will total 100%. For example, when 100 $MtCO_2$/yr of emissions are captured, the contributing sectors are Ethanol (26%) and Pulp & Paper (23%). When 618 $MtCO_2$/yr are captured, these sector's contributions fall to 10% and 19%, respectively, due to relatively greater contributions coming from other sectors at this volume.

Table 3-3. Percentage emissions captured across $MtCO_2$/yr of capture targets.

Sectors	100 Mt	200 Mt	300 Mt	400 Mt	500 Mt	600 Mt	618 Mt
Refineries	6%	25%	29%	29%	25%	22%	21%
Pulp & Paper	23%	23%	20%	17%	17%	19%	19%
Ethanol	26%	8%	10%	13%	12%	10%	10%
Cement	0%	0%	1%	3%	8%	10%	10%
Petrochemicals	13%	24%	16%	14%	11%	10%	9%
Iron & Steel	0%	0%	0%	2%	5%	7%	7%
Natural Gas Processing	10%	6%	7%	6%	6%	5%	5%
Oil & Gas	2%	1%	2%	3%	3%	4%	5%
Hydrogen	0%	0%	4%	5%	5%	4%	4%
Lime & Gypsum	12%	6%	4%	3%	3%	3%	3%
Ammonia	7%	6%	4%	3%	3%	3%	3%
Solid Waste	0%	0%	0%	0%	1%	2%	2%
Chemicals	2%	1%	1%	1%	1%	1%	1%
Aluminum	0%	0%	0%	0%	0%	1%	1%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Table 3-2 shows that the lime & gypsum, ammonia, ethanol, natural gas processing, petrochemicals, and pulp & paper industries all have at least one-fifth of their capturable CO_2 volumes included at the lowest pre-determined CCS volume target of 100 MtCO2/yr. As shown in Table 3-3, all of these industries except for ammonia contribute at least 10% (or 10 MtCO2/yr) to that scenario's pre-determined 100 $MtCO_2$/yr CCS volume target. By contrast, more "back-loaded" industries like petroleum refining, cement, and iron & steel see their contributions from relatively high-volume but also high-cost emissions streams scale their contribution up in scenarios with greater CCS volume targets.

Table 3-4 shows how many streams are in each of these 14 industries and provides information on their respective lowest-cost emission points emitting at least 0.5 $MtCO_2$/yr. It is apparent from this table that the lowest-cost streams from the more "front-loaded" industries are allowing for them to play a more influential role in the 100 $MtCO_2$/yr case, with the lowest-cost streams in back-loaded" industries like cement, iron & steel, and petroleum refining allow them to exert greater influence at greater cap mode volume targets.

Table 3-4. Capturable streams in each of the 14 industries and their respective lowest-cost streams emitting at least 0.5 $MtCO_2$/yr.

Industry	Unique capture stream	Least expensive capture stream	Cost ($/$tCO_2$)	Volume ($MtCO_2$/yr)	Facilities (#)	$MtCO_2$/yr/ facility
Refineries	4	Petroleum Refineries	$58.44	24.97	63	0.396
Ethanol	2	Ethanol Production	$34.49	46.42	168	0.276
Hydrogen	2	Stationary Combustion	$65.42	2.24	7	0.320
Lime & Gypsum	2	Lime Manufacturing	$38.70	19.58	44	0.445
Chemicals	6	Phosphoric Acid Production	$20.48	0.64	7	0.091
Iron & Steel	3	Stationary Combustion	$65.42	4.43	37	0.120
Pulp & Paper	2	Pulp and Paper	$54.00	71.40	99	0.721
Cement	1	Cement Production	$69.30	61.96	89	0.696
Petrochemicals	2	Petrochemical Production	$28.24	13.69	65	0.211
Natural Gas Processing	2	Petroleum and Natural Gas Systems	$17.46	9.70	97	0.100
Aluminum	2	Aluminum Production	$62.66	1.20	5	0.240
Ammonia	2	Ammonia Manufacturing	$20.48	6.60	6	1.100
Ferroalloy Production	2	Stationary Combustion	$54.51	1.35	6	0.225
Ethanol	2	Ethanol Production	$34.49	46.42	168	0.276

SECTION 4

Results: Price Mode Scenarios

4.1 Introduction

In addition to running in "cap mode," *SimCCS^PRO* can run in "price mode." In "price mode," *SimCCS^PRO* does not optimize CCS capture, transportation, and storage networks based on minimizing costs relative to a pre-determined CO_2 volume (in tCO_2/yr). Rather, it develops an optimal network to capture, transport, and store the greatest possible volume of CO_2 at a pre-determined maximum total CCS unit cost (in \$/tCO_2). This cost can be thought of as a tax credit for each tCO_2 captured, transported, and stored, providing a "breakeven cost" for each scenario.

To better understand how variations in tax credits could impact CCS project viability, *SimCCS^PRO* was run in price mode with "breakeven" cost ceilings ranging from \$65/tCO_2 to \$105/tCO_2 by increments of \$10/tCO_2 – providing five total scenarios to be examined. The results follow along largely similar lines to those examined in the previous section, but with somewhat greater priority given to very low-volume but also very low-cost sources. With no volume floor that projects needed to satisfy but rather a price ceiling, such sources made better candidates for incorporation into price mode scenario results.

4.2 *SimCCS^PRO* National Price Results

Table 4-1 and Table 4-2 summarize all *SimCCS^PRO* results across all five price mode scenarios. For scenarios with higher CO_2 tax credit / "breakeven cost" ceilings there was an increase in the amount of CO_2 being captured, beginning with 67.97 $MtCO_2$/yr at a tax credit of \$65/tCO_2 and increasing to 618.09 $MtCO_2$/yr at a tax credit of \$105/tCO_2, which is all of the capturable CO_2 from industrial sources. As CO_2 capture increased with higher CO_2 tax credit / "breakeven cost" ceilings, so did the pipeline network, which expanded from 3,884 km to 82,025 km across the same increase in tax credit. The number of source streams and sinks deployed also increases, from 213 capturable emission points and 106 sinks at the lowest ($65/t$CO_2$) tax credit to 1,874 capturable emission points and 164 sinks at the highest ($105/t$CO_2$) tax credit. The number of sink sites decreases at the highest capture target potentially due to economies of scale. In other words, it could be most optimal to combine multiple streams of CO_2 and inject them into one larger storage reservoir even if it is not the lowest cost storage option due to savings in transportation infrastructure.

Volumes captured, transported, and stored have been optimized in each of these scenarios, such that additional volumes could not be added without adversely affecting this outcome. Note that in the price mode cases, source (capture) costs again play the greatest role in determining project economics. Transport costs show minimal variation until the final $105/t$CO_2$ target is established, allowing for the inclusion of most available capturable CO_2 streams. Any variation in sink (storage) costs across scenarios is generally the result of the tax credit that is subtracted from each storage cost, rather than the storage costs themselves.

Table 4-1. Stream and sink counts, network length, and costs associated with Capture, Transport, and Storage for a CO_2 price ranging from $65/t$CO_2$ to $105/t$CO_2$ by increments of $10/t$CO_2$.

CO_2 Price ($/t$CO_2$)	# Streams	# Sinks	CO_2 Captured (MtCO_2/yr)
$65	213	106	67.97
$75	659	141	281.06
$85	1066	200	439.30
$95	1304	231	498.05
$105	1874	164	618.09

Table 4-2. Network length and costs associated with Capture, Transport, and Storage for CO_2 tax credits ranging from $65/t$CO_2$ to $105/t$CO_2$ by increments of $10/t$CO_2$.

CO_2 Price ($/t$CO_2$)	Network Length (km)	Source Cost ($/t$CO_2$)	Transport Cost ($/t$CO_2$)	Sink Cost ($/t$CO_2$)	Total Cost ($/t$CO_2$)
$65	3884	33.93	7.15	-57.78	-16.70
$75	9271	54.20	5.14	-68.27	-8.94
$85	15464	58.05	5.86	-78.09	-14.18
$95	23392	58.27	7.34	-88.15	-22.54
$105	82025	58.98	38.10	-99.13	-2.05

4.3 *SimCCS*[PRO] National Price Results by Industrial Sector

Table 4-3 and Table 4-4 summarize how different industry sources are included across price mode scenarios. Table 4-3 shows the inclusion of different industries as a percentage of the capturable CO_2 emissions that are accounted for in each industrial sector across the eight price scenarios (where each of the 14 industries will reach 100% in the final column). For example, in the $65/t$CO_2$ scenario, 20% of total Ethanol emissions are being captured, and 50% of total Lime & Gypsum emissions are captured, while in the $75/t$CO_2$ scenario, 56% of Ethanol emissions and 53% of Lime & Gypsum emissions are captured, respectively.

Table 4-4 shows the percentage contribution that each industry's capturable streams make to the CCS volumes for each price mode scenario (where each scenario will total 100% in the final row). For example, in the $65/t$CO_2$ price mode scenario, the largest contributing sectors are Pulp & Paper (20%), Ethanol (18%) and Petrochemicals (18%), while at $105/t$CO_2$, the largest contributors are Refineries (21%) and Pulp & Paper (19%).

Unsurprisingly, given the persistent importance of capture costs to modeling results under price mode, the "front-loaded" industries with cheaper capturable streams (lime & gypsum, ammonia, ethanol, natural gas processing, petrochemicals, and pulp & paper) when "cap mode" capacity was set at a 100 MtCO_2/yr could also be included for price mode scenarios with lower breakeven costs. Cement, iron & steel, and petroleum refineries remain relatively more "back-loaded," capturing greater emissions volumes at higher "breakeven cost" / tax credit amounts. Such industries may need more regulatory drivers for CCS at scale relative to others.

Table 4-3. Percentage of CO_2 emissions captured at each Price capture target, across sectors.

Sectors	$65	$75	$85	$95	$105
Refineries	0%	59%	91%	95%	100%
Pulp & Paper	12%	44%	61%	71%	100%
Ethanol	20%	56%	73%	92%	100%
Cement	0%	0%	46%	69%	100%
Petrochemicals	21%	90%	93%	93%	100%
Natural Gas Processing	26%	63%	80%	88%	100%
Iron & Steel	0%	0%	54%	63%	100%
Hydrogen	0%	45%	91%	93%	100%
Oil & Gas	7%	22%	48%	61%	100%
Lime & Gypsum	50%	53%	57%	64%	100%
Ammonia	39%	69%	83%	97%	100%
Solid Waste	0%	0%	28%	29%	100%
Chemicals	41%	61%	72%	81%	100%
Aluminum	0%	18%	41%	54%	100%

Table 4-4. Percentage of CO_2 emissions captured at each sector, across price mode scenarios.

Sectors	$65	$75	$85	$95	$105
Refineries	1%	28%	27%	25%	21%
Pulp & Paper	20%	18%	16%	17%	19%
Ethanol	18%	13%	11%	12%	10%
Cement	0%	0%	6%	9%	10%
Petrochemicals	18%	19%	12%	11%	9%
Natural Gas Processing	12%	7%	6%	6%	5%
Iron & Steel	0%	0%	5%	5%	7%
Hydrogen	0%	4%	5%	5%	4%
Oil & Gas	3%	2%	3%	4%	5%
Lime & Gypsum	16%	4%	3%	3%	3%
Ammonia	10%	4%	3%	3%	3%
Solid Waste	0%	0%	1%	1%	2%
Chemicals	2%	1%	1%	1%	1%
Aluminum	0%	0%	0%	0%	1%
Total	**100%**	**100%**	**100%**	**100%**	**100%**

The geographic distribution of streams, with increasing CCS volumes at higher breakeven costs, can be found in Figure 4-1, Figure 4-2, and Figure 4-3. At initially lower breakeven costs, the geographic distribution of facilities capturing CO_2 is initially concentrated in California, the Rocky Mountains, the Midwest, and Midcontinent regions, and is much more widespread at greater dollar amounts.

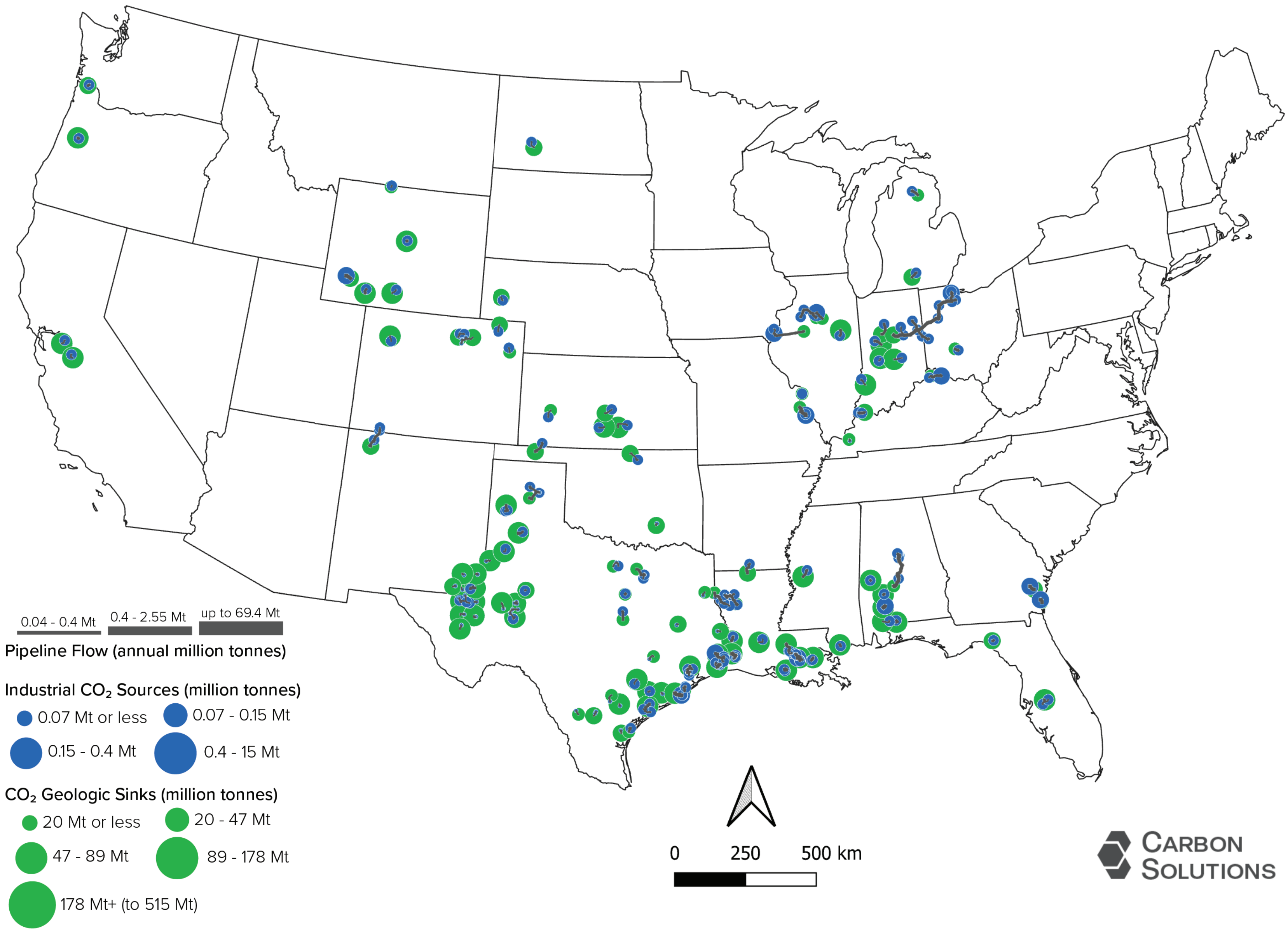

Figure 4-1. Geographic distribution of sources, sinks, and transportation network at $65/tCO_2$.

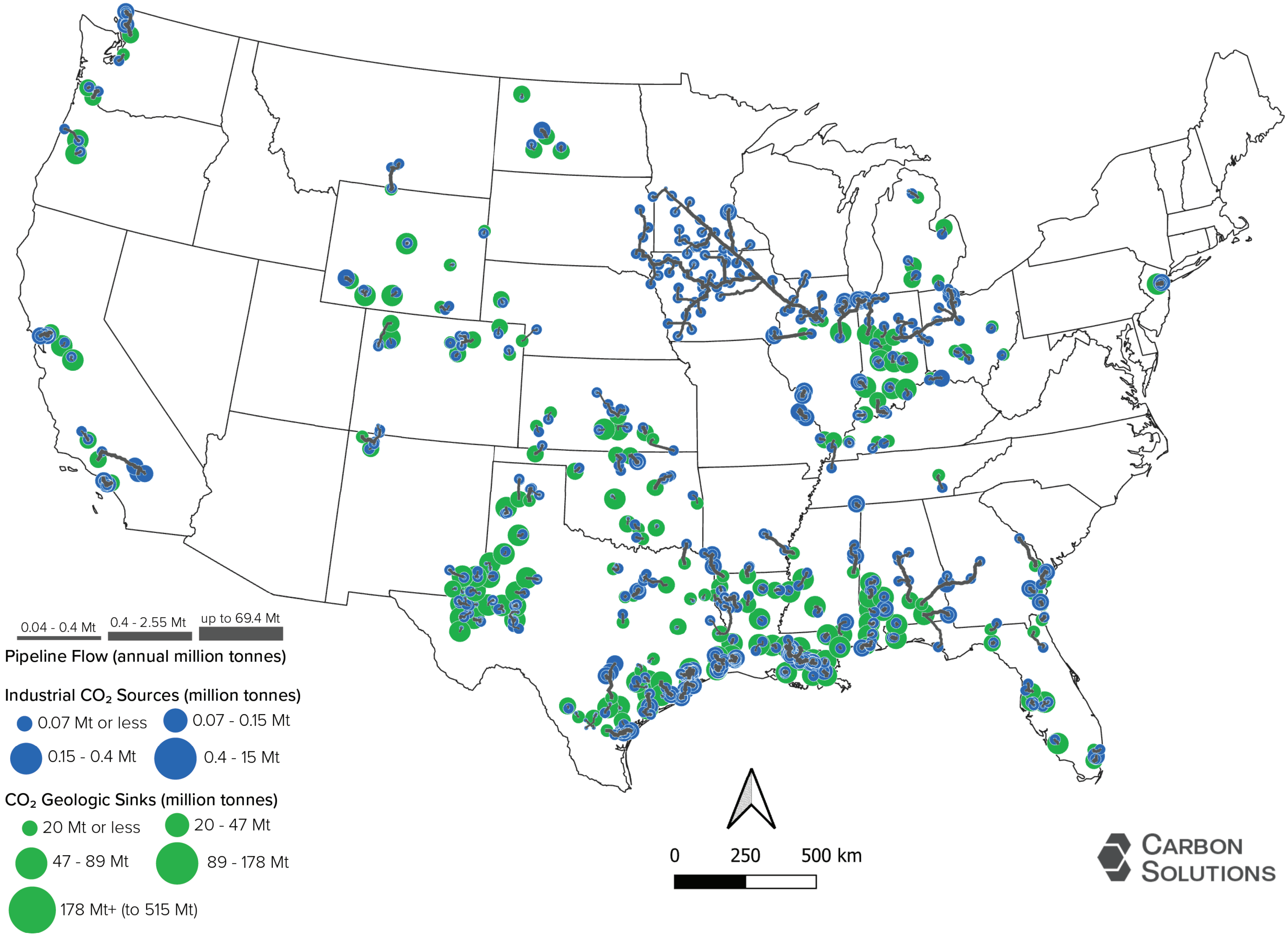

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Figure 4-2. Geographic distribution of sources, sinks, and transportation network at \$85/tCO_2.

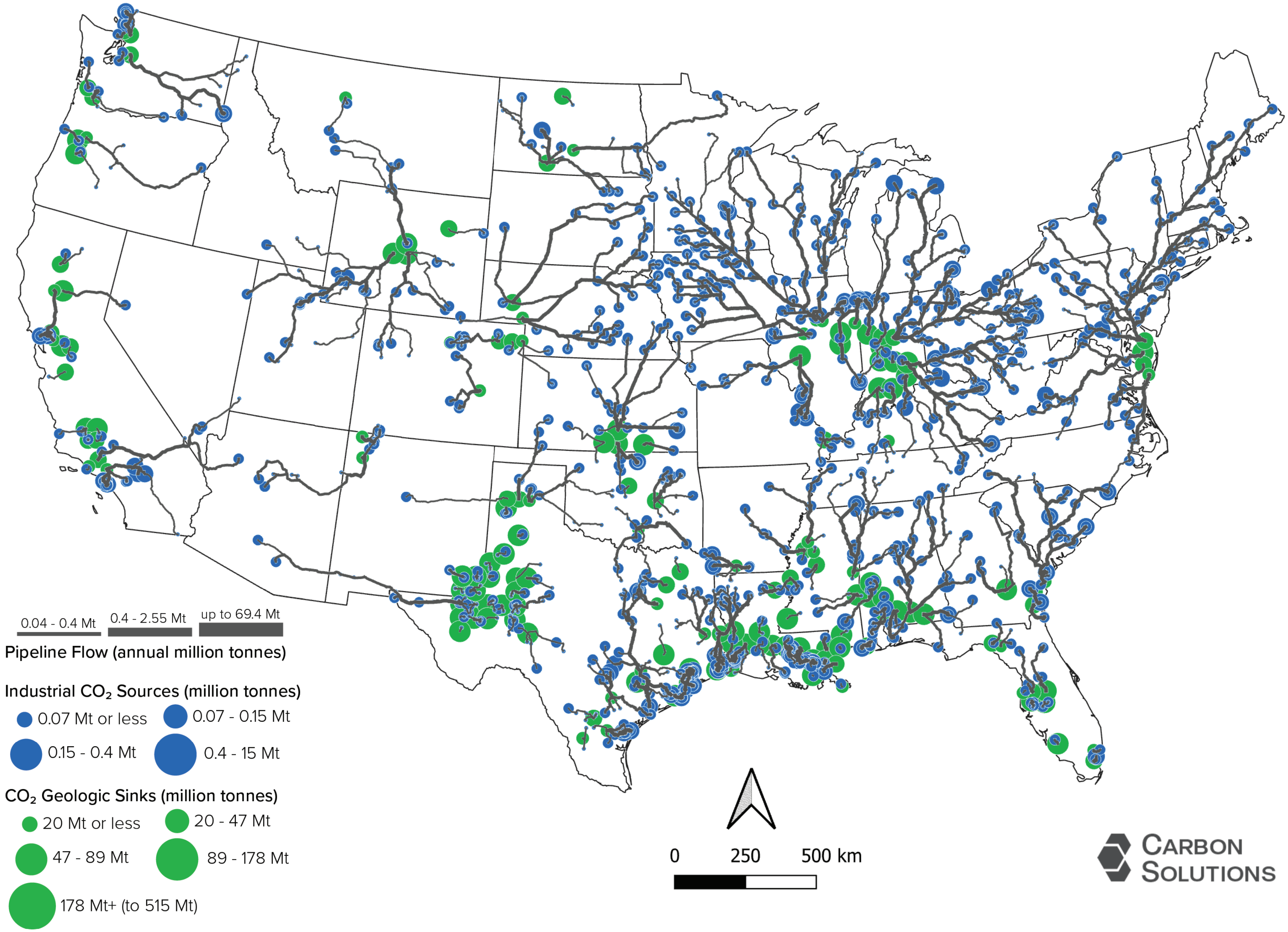

Figure 4-3. Geographic distribution of sources, sinks, and transportation network at $105/tCO$_2$.

SECTION 5

Results: Regional Capacity and Price Mode Scenarios

5.1 Introduction

Whereas Sections 3 and 4 examine national U.S.-wide CCS results across cap and price mode scenarios, respectively, this section aims to look at such results on a regional level. This is because region-specific capture and storage costs may make CCS more attractive to carry out in some U.S. regions compared to others. In addition, identifying U.S. regions where CCS is relatively more expensive allows us to consider areas where either policy incentives or infrastructure support might be needed for CCS deployment.

To explore these regional scenarios, we re-ran *SimCCS*^{PRO} in cap mode so that only the sources and sinks within a particular region were allowed to be deployed ("regional sink" scenarios), then reran these scenarios allowing any storage location in the nation to be selected ("all sink" scenarios). The location of the capturable emission sources, by region, is defined in Figure 5-1. Regions were identified based on a suite of local characteristics, including industry trends. Six regions were studied, noting that the aggregate six regions do not perfectly cover the conterminous U.S., specifically: 1) the Midwest, 2) Eastern Pennsylvania and New Jersey, 3) Western Texas, Oklahoma, and Kansas, 4) the Southern U.S., 5) the Mountain West, and 6) the West Coast.

Regional cap mode runs were only done for maximum capturable CO_2 emissions. The resultant transportation networks from these runs were used to define each U.S. region for further examination. We only assigned sources to a given U.S. region if its captured CO_2 was consistently routed to that given area of the country. As such, our defined regions did not follow perfectly with traditional definitions of U.S. regions like the Midwest from sources like U.S. Census Divisions or Regions.

One special consideration for these models is the degree to which industries providing capturable emissions varied by region. As seen in Table 5-1, the largest share of emissions in the Midwest comes from iron and steel, cement, and ethanol. While ethanol has a relatively low volume-weighted average cost of capture across all capturable streams ($32/t$CO_2$), iron and steel ($65.90/tCO_2) and cement ($64/t$CO_2$) do not. By contrast, the Southern US/Gulf Coast region's capturable emissions profile sees more prominent contributions from industries with lower volume-weight average capture costs across streams, such as from refineries ($51.95/t$CO_2$), petrochemical production ($26.20/t$CO_2$) and pulp & paper ($48.00 /tCO_2). As a result, we can assume there will be higher average capture costs for the Midwest than the Southern US/Gulf Coast, prior to considering the influence that transportation and storage will have on final project economics.

Table 5-1. Total CO_2 emitted, by sector, in each region. Darker colored areas indicate greater emissions.

Sectors	Midwest	E. PA/NJ	West TX, OK, KS	Southern US	Mountain West	West Coast
Refineries	9.94	2.21	6.28	63.59	2.80	17.16
Petrochemicals	4.02	0.00	1.31	51.91	0.00	0.00
Pulp & Paper	10.59	0.08	0.17	51.40	0.00	6.59
Hydrogen	0.59	0.00	0.00	16.40	0.00	3.82
Natural Gas Processing	1.50	0.00	8.63	10.88	9.05	0.00
Oil & Gas	5.36	0.06	1.10	10.78	3.88	0.53
Ammonia	0.09	0.00	1.71	8.58	0.15	0.07
Cement	14.43	0.49	0.51	7.09	1.98	1.14
Chemicals	0.79	0.00	0.00	2.77	0.40	0.00
Solid Waste	0.62	0.86	0.00	2.08	0.00	0.00
Iron & Steel	15.16	0.13	0.00	1.51	0.00	0.08
Aluminum	1.56	0.00	0.00	0.89	0.00	0.00
Lime & Gypsum	5.98	0.00	0.13	0.23	0.34	0.00
Ethanol	12.28	0.00	3.33	0.00	1.04	0.47
Total	**82.89**	**3.84**	**23.16**	**228.11**	**19.63**	**29.86**

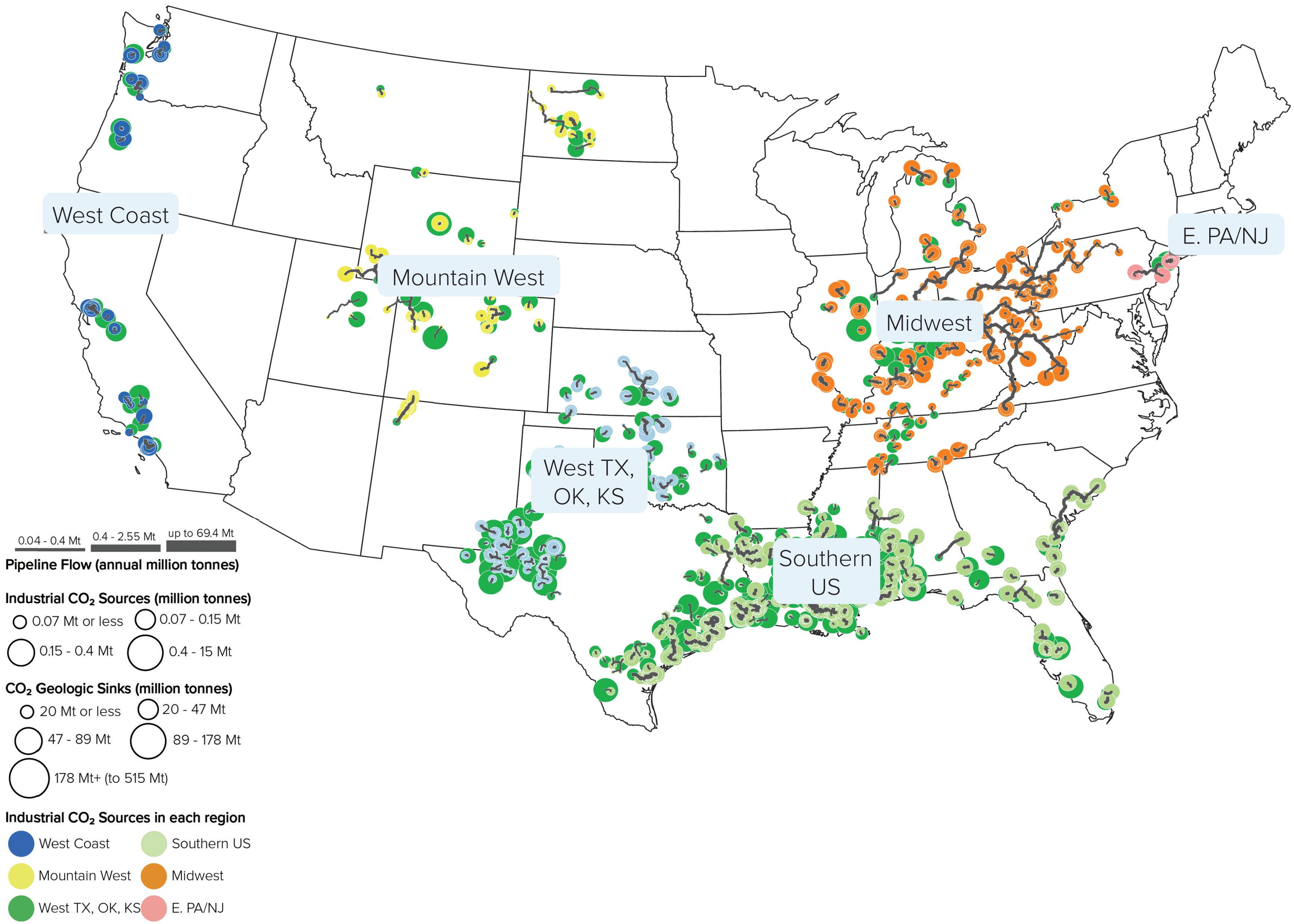

Figure 5-1. Geographic location of each respective region examined for regional capacity and price assessments.

5.2 *SimCCS*^PRO Regional Capacity Results: Regional & National Sinks

Results from regional *SimCCS*^PRO models can be found in Table 5-2 to Table 5-6. Regional cap mode results highlight CO_2 capture volumes for each region as well as the pipeline network lengths, in kilometers, and costs for each component of the regional CCS network.

Table 5-2 shows the wide variations in regional CO_2 emissions, with the Southern US, comprised of states from East Texas to Florida, emitting nearly 2.5 times as much CO_2 as the next largest region, the Midwest. The West Coast states and West Texas, Oklahoma and Kansas have similar emissions, of approximately 28 $MtCO_2$/yr, followed closely by the Mountain West states. The largest number of capturable streams is in the Southern US, at 524 unique capture locations, almost twice the count of emission sources as the Midwest. Although the emission amounts are similar in West TX, OK, KS, the Mountain West, and the West Coast, the number of sources in each region differs, with the West Coast having the highest average emissions per unit, followed by the Mountain West, and then West TX, OK, KS.

Table 5-2. Streams, Sinks, and CO_2 captured in regional capacity scenarios.

Region	Streams (#)	National Sinks (#)	Regional Sinks (#)	CO_2 Captured ($MtCO_2$/yr)
Midwest	267	54	55	82.89
E. PA/NJ	9	3	2	3.84
West TX, OK, KS	173	50	50	23.16
Southern US	524	110	108	228.11
Mountain West	95	36	33	19.63
West Coast	58	16	19	29.86

In addition to variations in the amount of CO_2 emitted in the regions defined here, there are differences in the number and industrial sectors present in each region, summarized in Table 5-3 and Table 5-4. For example, the West TX, OK, and KS region is notable for lower emissions, 23 $MtCO_2$/yr, relative to the number of sources, or 173 sources. The majority of these sources, 106, are Natural Gas Processing plants, emitting a total of 8.63 $MtCO_2$/yr. The only regions that have similar counts of Natural Gas Processing plants are the Southern US (92 sources, 10.88 $MtCO_2$/yr), and the Mountain West (50 sources, 9.05 $MtCO_2$/yr). The Southern US is notable for both the number of emissions and the variety of emissions sources; of the regions defined here, only the Midwest also has at least some emissions in each of the industrial sectors considered for this study.

Table 5-3. Annual emissions by industrial sector and region. Areas in darker blue have higher emissions.

Sectors	Midwest ($MtCO_2/yr$)	E. PA/NJ ($MtCO_2/yr$)	West TX, OK, KS ($MtCO_2/yr$)	Southern US ($MtCO_2/yr$)	Mountain West ($MtCO_2/yr$)	West coast ($MtCO_2/yr$)
Refineries	9.94	2.21	6.28	63.59	2.80	17.16
Petrochemicals	4.02		1.31	51.91		
Pulp & Paper	10.59	0.08	0.17	51.40		6.59
Hydrogen	0.59			16.40		3.82
Natural Gas Processing	1.50		8.63	10.88	9.05	
Oil & Gas	5.36	0.06	1.10	10.78	3.88	0.53
Ammonia	0.09		1.71	8.58	0.15	0.07
Cement	14.43	0.49	0.51	7.09	1.98	1.14
Chemicals	0.79			2.77	0.40	
Solid Waste	0.62	0.86		2.08		
Iron & Steel	15.16	0.13		1.51		0.08
Aluminum	1.56			0.89		
Lime & Gypsum	5.98		0.13	0.23	0.34	
Ethanol	12.28		3.33		1.04	0.47
Total ($MtCO_2/yr$)	**82.89**	**3.84**	**23.16**	**228.11**	**19.63**	**29.86**

Table 5-4. Count of facilities by industrial sector and region. Areas in darker blue indicate a higher facility count.

Sectors	Midwest (Count)	E. PA/NJ (Count)	West TX, OK, KS (Count)	Southern US (Count)	Mountain West (Count)	West coast (Count)
Refineries	20	3	18	76	14	22
Petrochemicals	5		12	109		
Pulp & Paper	27	1	2	78		17
Hydrogen	3			32		7
Natural Gas Processing	14		106	92	50	
Oil & Gas	56	1	9	80	12	5
Ammonia	1		4	6	1	1
Cement	16	1	2	10	4	2
Chemicals	7			20	1	
Solid Waste	1	2		5		
Iron & Steel	41	1		10		1
Aluminum	10			3		
Lime & Gypsum	15		1	3	3	
Ethanol	51		19		10	3
Total (Count)	**267**	**9**	**173**	**524**	**95**	**58**

Table 5-5. Network length and capture, transport, and storage costs in regional sources and regional sink scenarios.

Region	Network Length (km)	Source Cost ($/t$CO_2$)	Transport Cost ($/t$CO_2$)	Sink Cost ($/t$CO_2$)	Total Cost ($/t$CO_2$)
Midwest	7,706	60.16	18.89	9.06	88.11
E. PA/NJ	232	63.77	11.31	19.09	94.16
West TX, OK, KS	2,285	54.96	8.27	6.70	69.93
Southern US	5,746	59.68	4.37	6.56	70.61
Mountain West	2,275	52.23	12.43	9.57	74.23
West Coast	555	63.46	4.18	7.30	74.94

There are similar differences in the storage costs associated with each region when considering the regional source-regional sink scenarios in Table 5-5. Eastern PA/NJ has the highest total cost of capture at $94.40/t$CO_2$ with an annual capture target of only 2.73 MtCO_2/yr. This is primarily driven by relatively high sink injection costs

(\$29.78/tCO_2) and only a small number of capturable emission points. The regions of West TX, OK, and KS, the Southeastern US, and the Mountain West have the lowest total costs at \$69.93 /tCO_2 and \$70.51/tCO_2 and \$70.69, respectively.

The Southeast US/Gulf Coast region has the highest annual capture amount, capturing 228.11 MtCO_2/yr, followed by the Midwest, at almost 89 MtCO_2/yr. The costs of the Midwest are more expensive, driven largely by the facilities in Eastern Ohio, West Virginia, and Pennsylvania. Without good available storage opportunities nearby, these locations route their CO_2 to storage areas further west. The higher transportation costs and diverse mix of more expensive facilities that will be required to capture CO_2, such as iron and steel and aluminum, all contribute to the Midwest's higher regional costs.

The longest pipeline network in the regional source-regional sink scenario is deployed in the Midwest, with a total amount of 7,706 km, due largely to the size of this region and the need to route large CO_2 volumes from lower-cost capture sources in the eastern part of this region to better storage reservoirs to the west. Further, a large cluster of sources appears in the Western part of the region and thus will require longer pipelines to transport captured CO_2 to corresponding sink injection locations.

The southeast United States and Gulf Coast have the greatest number of capturable emission points and sink injection locations but deploy the second longest pipeline network with a total length of 5,746 km. The shortest network is deployed in Eastern PA/NJ, with a total length of 232 km, but is once again the most expensive network due to the high costs for sink injection in the region. Table 5-6 shows the total CCS network costs, including source capture cost, pipeline transport cost, and sink injection costs.

Table 5-6. Network length and capture, transport, and storage costs in regional sources and national sink scenarios.

Region	Network Length (km)	Source Cost (\$/tCO_2)	Transport Cost (\$/tCO_2)	Sink Cost (\$/tCO_2)	Total Cost (\$/tCO_2)
Midwest	8,893	60.16	20.51	8.81	89.48
E. PA/NJ	187	63.77	9.87	20.77	94.40
West TX, OK, KS	2,285	54.96	8.27	6.70	69.93
Southern US	5,666	59.68	4.26	6.57	70.51
Mountain West	1,726	52.23	8.84	9.62	70.69
West Coast	379	63.35	3.51	7.33	74.19

Figure 5-2 shows results when expanding *SimCCS^PRO^* runs to consider the same emissions sources but without the restriction of having to route capture emissions to intra-regional sink locations. The effect of removing the regional transport and storage restriction but keeping the same sources of capturable emissions means that the only change that occurs in this scenario is in terms of transportation and storage costs. However, the difference in these costs between the regional-sink and national-sink scenarios are minimal, and all within $1/t$CO_2$, apart from the Mountain West, which saw a decrease in costs from to $74.94 to $70.69/t$CO_2$, largely due to differences in transportation costs.

The most notable difference between the region-restricted and national scenarios is in terms of pipeline length. The E. PA/NJ, Mountain West, and West Coast regions all had decreases in the length of the pipeline network of 19%, 24%, and 31%, respectively in the national scenario compared to the region-restricted scenarios. The ability to route captured CO_2 from sources in these regions to sinks that are lower-cost for storage, transportation, or both that are closer by but on the other side of regional boundaries allows for reduced pipeline network length in the national scenarios.

In contrast, the West TX/OK/KS and the Southern US/Gulf Coast had very little change to their modeled network length in the national scenarios compared to the region-restricted scenarios, while the Midwest saw a 15% increase in the network needed for CO_2 storage. The increase in the network can be driven by the “regional” cutoff that would route sources within the region to sinks that might not be the closest available option, thereby increasing the size of the network. This becomes evident when comparing Figures 4-4 and 5-1, where sources in West Virginia that might be routed to the Eastern Seaboard instead move towards sinks in the Midwest region. This suggests many different source-sink matching scenarios can keep relatively stable prices depending on how sensitive communities may be to minimizing pipeline lengths.

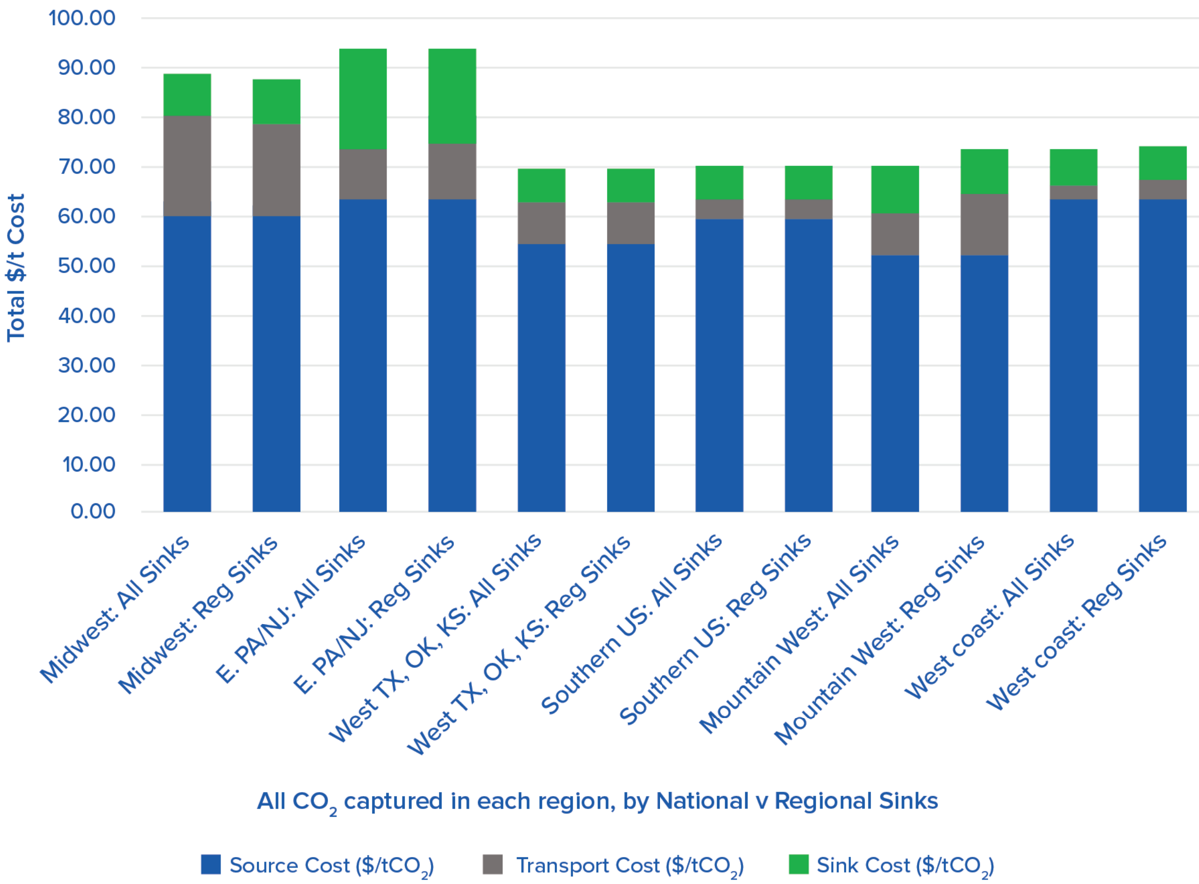

Figure 5-2. Regional source, capture, CO_2 pipeline transport, and sink injection costs for each region under a maximum capacity SimCCS^{PRO} scenarios capturing all CO_2 in each region.

SECTION 6

Results: Trunk Line

6.1 Introduction

In the previous sections, we ran a variety of *SimCCS*^{PRO} models to understand how the length of the pipeline changed as a result of considering a range of capacity and price scenarios. Each model resulted in a slightly different network configuration. In many areas, there were network segments that were repeatedly part of many solutions, regardless of whether we were considering relatively low tax incentives or relatively smaller amounts of CO_2 to be captured. One question this suggested: If the most frequently-selected pipeline segments could create a trunkline, how might the results change?

To explore the trunkline scenario, a network of the most frequently-selected network segments was created in three regions of the country; Nevada-California, Ohio-Indiana-Illinois, and Texas-Louisiana. Each price and capacity *SimCCS*^{PRO} scenario results in a network solution that links selected sources to sinks. To find the trunklines, we “stacked” all of the network solutions on top of one another, allowing us to create a count of the frequency with which every line segment appeared in each solution. These frequently-selected segments were then joined together using the original candidate network to create one uninterrupted trunkline. Next, *CostMAP*^{PRO} weights were adjusted to make the trunkline both more likely to be selected as a route, and a less expensive (25%) reduction in pipeline costs. The simulations from the previous capacity models were then re-run for the entire country for 100, 200, and 300 $MtCO_2$/yr. The model results from the trunkline and the non-trunkline scenarios were then compared to see how many more streams were captured as a result of both lowering the cost of the trunkline and making it more likely to be selected.

6.2 *SimCCS^PRO* Trunk Line Capacity Results

6.2.1 Texas – Louisiana Trunkline

Results from the 100, 200, and 300 $MtCO_2$/yr scenarios are summarized in Table 6-1. There is a large degree of overlap between the sources deployed in a trunkline scenario and that national capacity scenario for annual capture targets of 100 $MtCO_2$/yr and 200 $MtCO_2$/yr. This indicates that source deployment is largely independent of trunkline deployment. Connecting sources to cheaper storage locations does not greatly affect project economics. Yet at an annual capture target of 300 $MtCO_2$/yr, more sources are being deployed in just a trunkline scenario though there are still plenty of overlapping sources deployed. This could be explained by the fact that as there is an increase in the annual capture target, it is possible to begin capturing from more expensive streams that would typically be ignored but can now take advantage of the pre-existing infrastructure, reducing their barrier to entry. Further, under a capture target of 200 $MtCO_2$/yr, transportation costs are marginally higher in the trunkline scenario when compared to the national scenario. This can be explained by the fact that the trunkline, through routing weight reductions, is made more attractive than other potential pipelines in the region that would have lower costs but didn't benefit from the same routing weight reductions.

Table 6-1. Comparison of 100, 200, and 300 $MtCO_2$/yr with original capacity model and TX-LA trunkline scenarios.

	Annual Capture Amount ($MtCO_2$/yr)	Streams (#)	Sinks (#)	Network Length (km)	Total Cost ($/$tCO_2$)	Source Cost ($/$tCO_2$)	Transport Cost ($/$tCO_2$)	Sink Cost ($/$tCO_2$)
Original	100	300	116	6,529	55.03	38.38	9.88	6.77
	200	427	116	5,005	65.53	53.77	5.23	6.53
	300	670	136	9,235	69.04	55.89	6.47	6.67
TX-LA	100	270	130	5,285	54.06	40.15	6.89	7.02
	200	497	137	7,713	62.83	50.32	5.84	6.67
	300	683	147	9,729	67.59	55.28	5.51	6.80

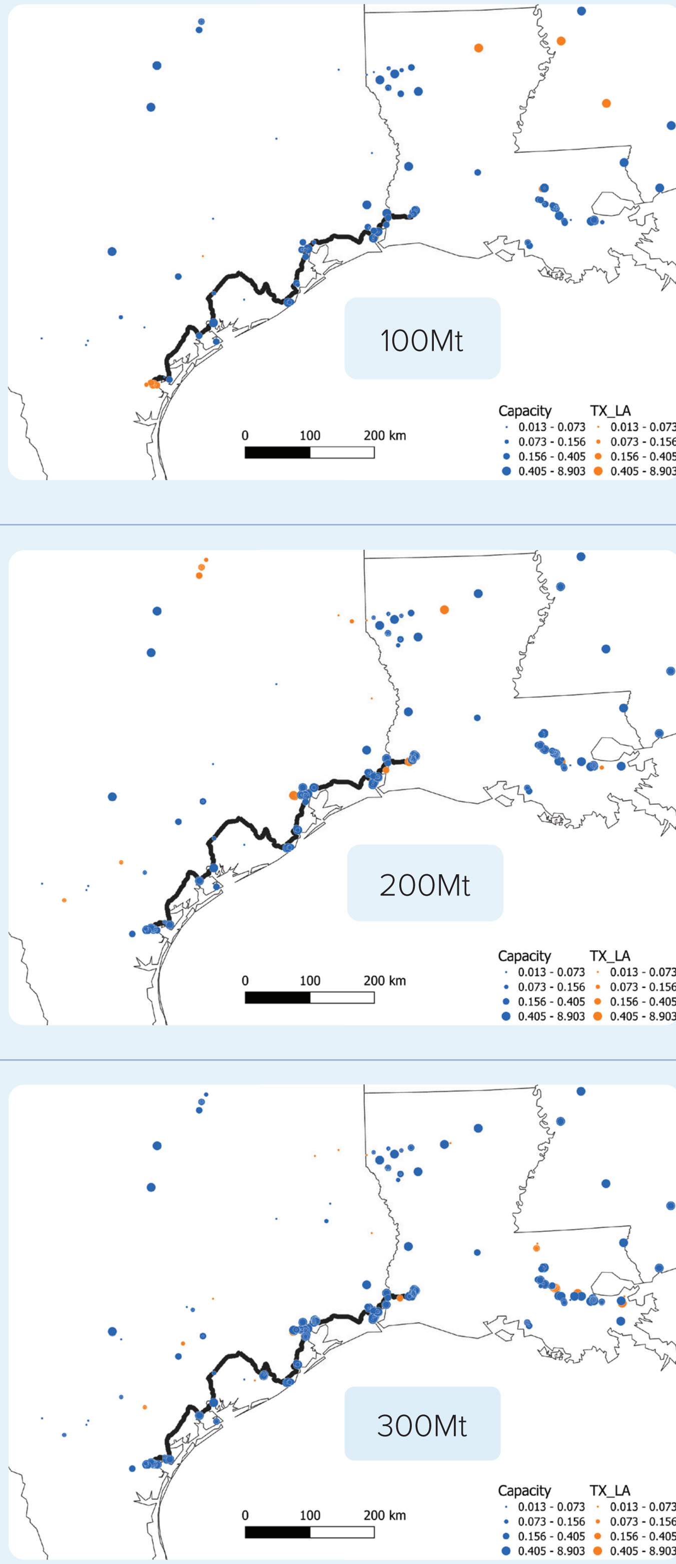

Figure 6-1. Differences between original (blue) and TX-LA (orange) sources selected for the 100, 200, and 300 $MtCO_2$/yr scenarios.

6.2.2 Midwest Trunkline

Source deployment under 100 $MtCO_2$/yr does not appear to be influenced by the addition of a trunkline. When the annual capture targets are increased to 200 $MtCO_2$/yr and 300 $MtCO_2$/yr, the addition of a trunkline in the Midwest appears to encourage sources in western Ohio and Northern Ohio/Southern Michigan. This indicates that there might be advantages to deploying a trunkline in the Midwest region under sufficiently high capture targets. Nevertheless, there remains a significant overlap between source deployment for a scenario where a trunkline is deployed versus not. Additionally, under a capture target of 200 $MtCO_2$/yr, we see the same pattern of higher transportation costs for the trunkline scenario that was observed for the Texas-Louisiana scenario. The same rational applies, where for this capture target there may be lower cost pipelines that are avoided due to the reduction in routing weights for the trunkline itself.

Table 6-2. Comparison of 100, 200, and 300 $MtCO_2$/yr with original capacity model and Midwest trunkline scenarios.

	Annual Capture Amount ($MtCO_2$/yr)	Streams (#)	Sinks (#)	Network Length (km)	Total Cost ($/$tCO_2$)	Source Cost ($/$tCO_2$)	Transport Cost ($/$tCO_2$)	Sink Cost ($/$tCO_2$)
Original	100	300	116	6,529	55.03	38.38	9.88	6.77
	200	427	116	5,005	65.53	53.77	5.23	6.53
	300	670	136	9,235	69.04	55.89	6.47	6.67
Midwest	100	282	118	6,684	54.00	37.99	9.21	6.80
	200	495	135	8,000	62.81	50.54	5.66	6.61
	300	703	157	10,045	66.49	54.62	5.12	6.75

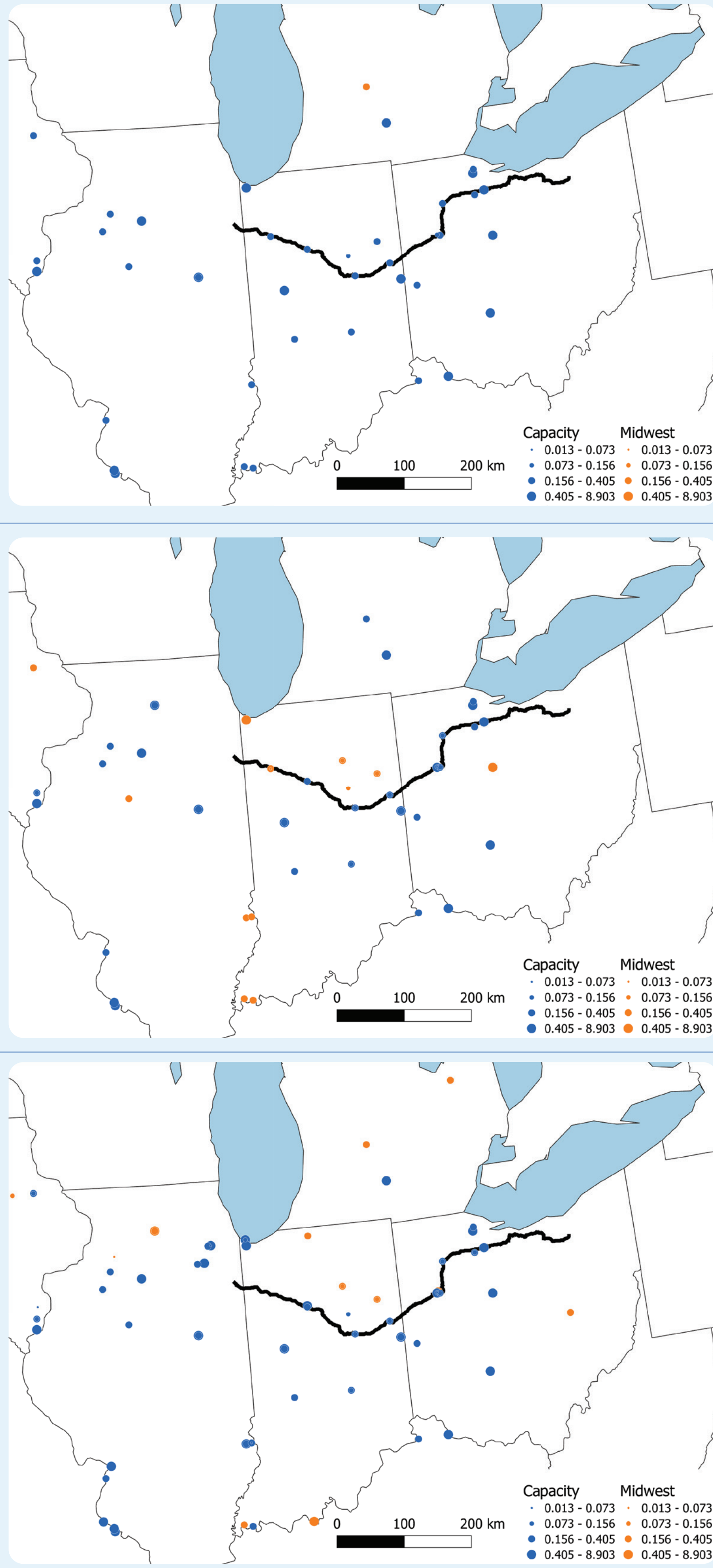

Figure 6-2. Differences between original (blue) and Midwest (orange) sources selected for the 100, 200, and 300 $MtCO_2$/yr scenarios.

6.2.3 California – Nevada Trunkline

As shown in Table 6-3, the trunkline between California and Nevada has no noticeable impact on source deployment across the three capture targets we analyzed, although it has slight differences in the amount of CO_2 pipeline required at the smallest capture target of 100MtCO$_2$/yr. Therefore, we can conclude that source deployment is largely independent of trunkline deployment in this region. For the 200 MtCO$_2$/yr capture target scenario, the same trend of marginally higher transportation costs that is observed in the previous two trunkline scenarios appears. These trunkline scenarios indicate that it might be advantageous to model trunkline deployment in regions where storage and capture costs are more expensive such as West Virginia. Further, more consideration can be given to pipeline cost reductions that would be provided under the Pipeline and Hazardous Material (PHMSA) department in the U.S. Department of Transportation, in the form of funding for maintenance and regulation, updating aging infrastructure, and monitoring of pipeline infrastructure to states.[26]

Table 6-3. Comparison of 100, 200, and 300 MtCO$_2$/yr with original capacity model and CA-NV trunkline scenarios.

	Annual Capture Amount (MtCO$_2$/yr)	Streams (#)	Sinks (#)	Network Length (km)	Total Cost ($/tCO$_2$)	Source Cost ($/tCO$_2$)	Transport Cost ($/tCO$_2$)	Sink Cost ($/tCO$_2$)
Original	100	300	116	6,529	55.03	38.38	9.88	6.77
	200	427	116	5,005	65.53	53.77	5.23	6.53
	300	670	136	9,235	69.04	55.89	6.47	6.67
CA-NV	100	277	122	6,198	53.74	38.45	8.43	6.86
	200	503	139	8,353	62.71	50.07	6.03	6.61
	300	697	150	10,383	66.38	54.40	5.26	6.71

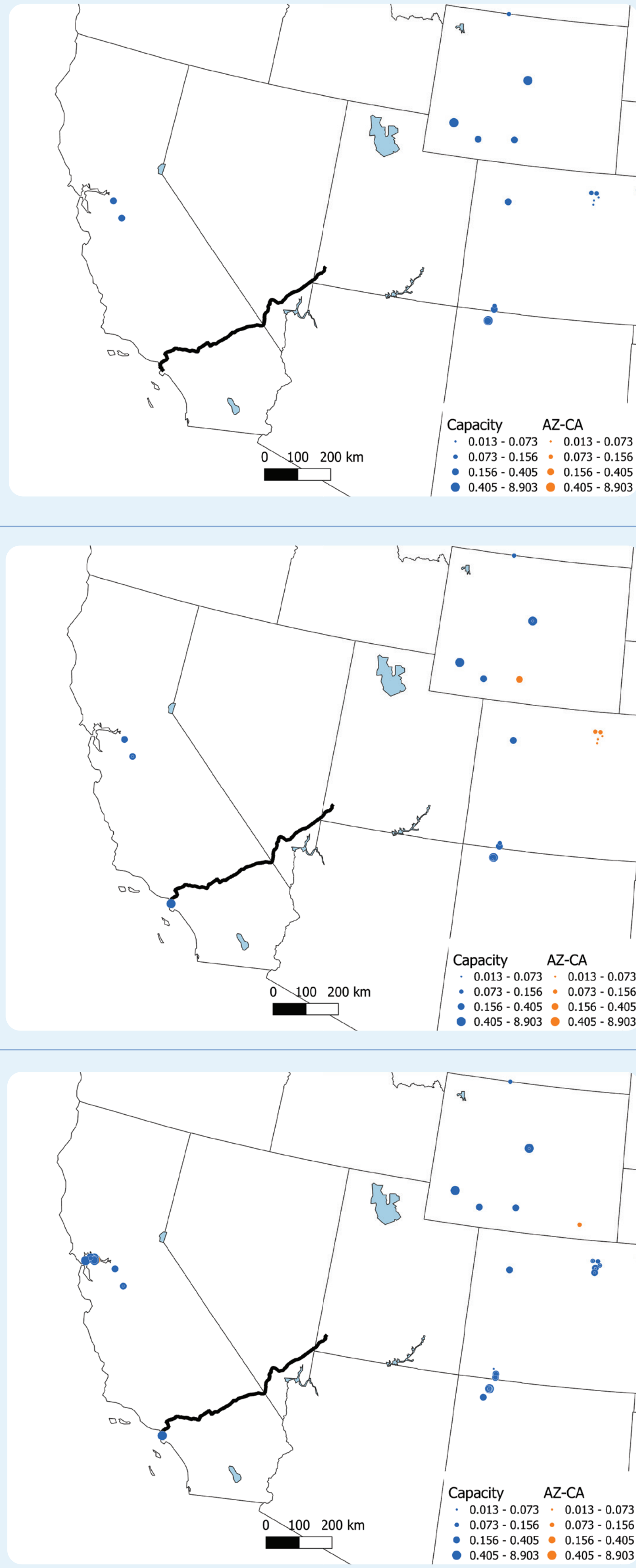

Figure 6-3. Differences between original (blue) and CA-NV (original) sources selected for the 100, 200, and 300 $MtCO_2$/yr scenarios.

SECTION 7

Environmental Justice Perspectives

7.1 Introduction

Over the last several years, there have been numerous approaches to defining disadvantaged communities, and increasingly, environmental justice communities (DAC-EJ). While disadvantaged communities have largely been defined by race, ethnicity, or income, environmental justice communities are most often identified as communities that have both legacy pollution concerns and are historically overburdened when considering the race, ethnicity, or income status of their residents. Federal goals related to Justice40, the idea that 40 percent of overall benefits of certain projects flow to disadvantaged communities, have required that environmental justice communities need to be easily identified so that project risks and benefits can be tracked relative to these communities.

To understand the potential DAC-EJ communities impacted by carbon capture, transport, and storage, we considered *SimCCS^{PRO}* capacity model results along with environmental justice definitions. Just as disadvantaged community definitions have evolved, so have the metrics used to define them. For this report, we considered DAC-EJ definitions using four separate tools: (1) the Department of Energy's Disadvantaged Communities Reporter (DOE-DCR), (2) the Council on Environmental Quality's Climate & Economic Justice Screening Tool (CEJST), (3) the Environmental Protection Agency's EJ Screening Tool (EJScreen), and (4) the Center for Disease Control and Prevention's Social Vulnerability Index (SVI).

While each tool uses different measures to define what a DAC-EJ community is, the approach of each tool is similar—each weights social, environmental, and economic data at Census tracts to determine whether a particular tract can be considered DAC-EJ. The definitions we used to define environmental justice in each of these tools are below, and the geographic footprint of these definitions is in Figure 7-1.

1. **DOE-DCR National**; A census tract is considered DAC-EJ if it ranks in the 80th national percentile of the cumulative sum of the 36 burden indicators and has at least 30% of households classified as low-income.[27]

2. **CEJST Pollution**; A census tract is considered DAC-EJ if it has at least one abandoned mine land OR Formerly Used Defense Sites OR is at or above the 90th percentile for proximity to hazardous waste facilities OR proximity to Superfund sites (National Priorities List (NPL)) OR proximity to Risk Management Plan (RMP) facilities AND are at or above the 65th percentile for low income.[28]

3. **EJScreen**; A census tract is considered DAC-EJ if it has more than five EJ Indexes exceeding the 80th percentile AND at least one Supplemental Index exceeding the 80th percentile.[29]

4. **SVI**; A census tract is considered DAC-EJ if it ranks in the 85th percentile of the overall cumulative sum of 16 variables across four themes: Socioeconomic Status, Household Characteristics, Racial & Ethnic Minority Status, Housing Type & Transportation.[30]

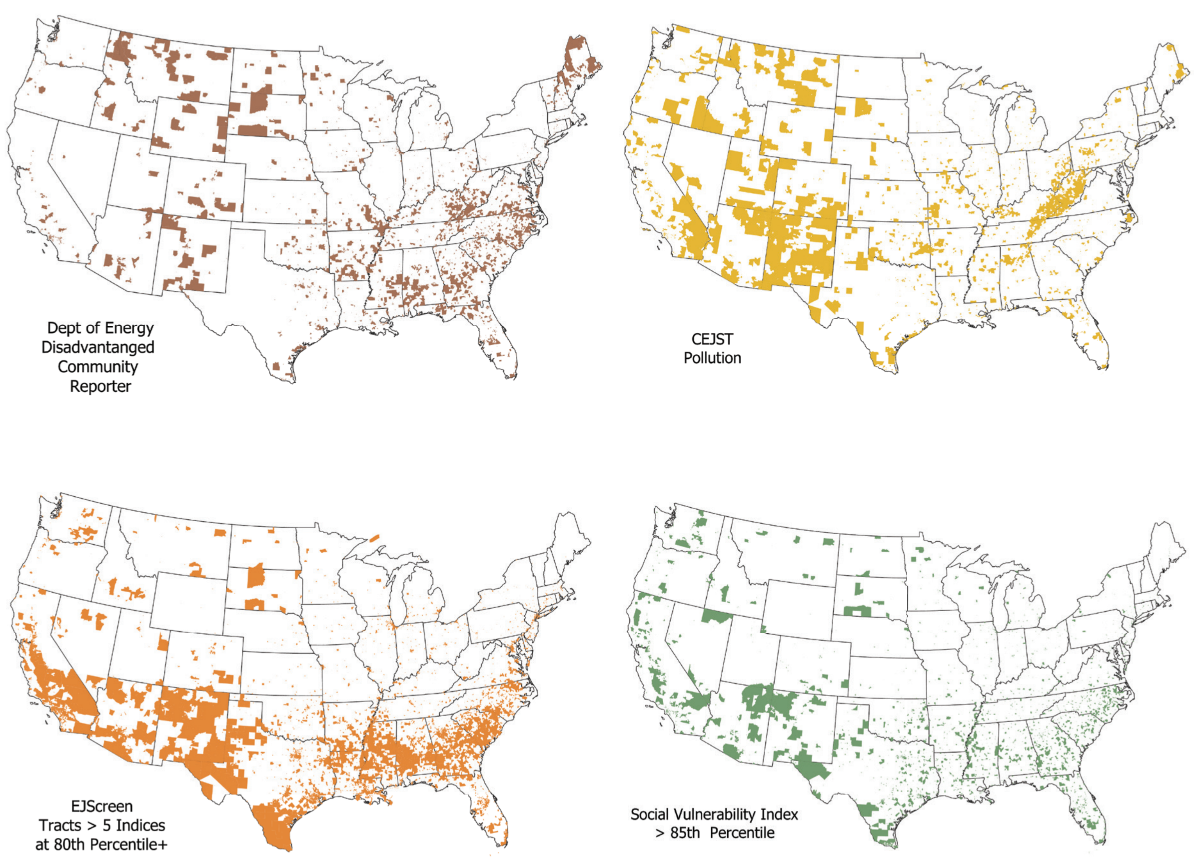

Figure 7-1. Geographic distribution of different DAC-EJ communities.

In Table 7-1 we show the percentage of communities classified as DAC-EJ communities throughout the US according to our four different metrics. We can see that both the geographic distribution of tracts and the counts of tracts that qualify as DAC-EJ communities are quite diverse. Part of this is due to the evolving landscape of definitions. However, these variations also reflect the difficulty of summarizing complex environmental, social, and demographic communities in any one tract-level value. Rather than conclude that the diversity of definitions undermines using DAC-EJ, we instead evaluate model results through the lens of multiple definitions, acknowledging that one metric, such as the CEJST Pollution variable, might be more important when considering the location of Class VI wells, while another, such as the SVI, may be more relevant in pipeline routing. Regardless, considering the proportion of DAC-EJ communities co-located where projected CCS activities may be located can help us understand the magnitude of the impact carbon capture deployment may have on environmental justice communities. Please note that differences in the count of census tracts can be due to many factors, such as the year of the census used, and whether island territories, such as Puerto Rico, are considered.

Table 7-1. Count of Census tracts and tracts qualifying as environmental justice tracts.

	DCR National	CEJST Pollution	EJ Screen	SVI
Count of Census tracts	74,170	74,134	86,081	84,122
% of DAC-EJ Census Tracts (count)	20.5% (15,172)	12.3% (9,135)	23.5% (20,211)	14.9% (12,504)

7.1.1 National Capacity Scenarios with Environmental Justice

Communities may be impacted by CCS activities based on whether capture, transport, or storage activities are occurring within a Census tract. We calculated the percentage of impacted EJ communities for each CCS activity by calculating the count of EJ tracts where an activity took place relative to all tracts (EJ + not EJ) where an activity took place, for each capacity model. These results are in Figure 7-2. In almost all cases but the 100 MtCO_2 scenario, the CCS activity that contains the largest percentage of DAC-EJ tracts relative to EJ and not EJ tracts is carbon capture at the source location. Considering all tracts where sources are most cost effective to capture CO_2 in the 100 Mt scenario, approximately 15%-20% are located in DAC-EJ tracts. For the CEJST-Pollution and DCR tracts, approximately 25% of tracts where sources are identified as having CO_2 being captured are also an EJ tract. When increasing the capture target from 100 and 200Mt of CO_2, there is a dramatic increase in the percentage of Census tracts that are identified as DAC-EJ as a share of total tracts where CO_2 is being captured, regardless of the definition used. In most cases, the percentage of tracts qualifying as a DAC-EJ community doubles. In the case of the CJEST and EJ Screen cases, this is partly due to the inclusion of air pollution as a way to define DAC-EJ communities; in many cases, industrial sources contribute to some amount of local air pollution, which in turn qualifies them as a DAC-EJ community. At 200-300 Mt of CO_2 captured, the sectors that are most economical for capture are also those that are located in communities identified as DAC-EJ communities. As capture targets continue to increase, so do the number of facilities where carbon capture will be deployed. The expansion of facilities where CO_2 is captured occurs in an expanding number of Census tracts, and as a consequence, the percentage of DAC-EJ communities as a share of all tracts where capture occurs decreases. The count of DAC-EJ tracts at different capture scenarios is in Table 7-2.

Table 7-2. Counts of DAC-EJ census tracts co-located with sources from capacity scenarios.

	100 $MtCO_2/yr$	200 $MtCO_2/yr$	300 $MtCO_2/yr$	400 $MtCO_2/yr$	500 $MtCO_2/yr$	600 $MtCO_2/yr$	618 $MtCO_2/yr$
CEJST -Pollution	54	91	137	182	228	301	322
DOE-DCR	54	87	137	199	255	320	343
EJ Screen	31	73	113	157	187	226	235
SVI	38	69	101	128	166	212	227

With the exception of the 100 Mt model scenario, in every capture target up to and including 618 Mt, the percent of tracts that have part of a pipeline network passing through them that also qualify as DAC-EJ is less than the percent of tracts that have sources of CO_2 that were deployed as part of the CCS infrastructure that also qualify as DAC-EJ. For the EJScreen and SVI measures, between 18 and 30% of capacity model results, whether it is a source, sink, or pipeline network, are co-located with DAC-EJ communities, although this increases to between 22% and 40% for CEJST and DCR definitions. The count of tracts designated as a DAC-EJ community that have some portion of a pipeline network passing through it is in Table 7-3. While there is a large count of tracts with DAC-EJ communities that may have a pipeline present, as a share of total tracts with pipelines, the percentage of DAC-EJ tracts with pipelines decreases as the geographic footprint of pipelines becomes more extensive. If sinks were more concentrated in DAC-EJ communities, this may not hold true – a larger network might impact more, rather than fewer, DAC-EJ communities as pipeline buildout occurs.

Table 7-3. Counts of DAC-EJ census tracts co-located with network locations.

	100 $MtCO_2$/yr	200 $MtCO_2$/yr	300 $MtCO_2$/yr	400 $MtCO_2$/yr	500 $MtCO_2$/yr	600 $MtCO_2$/yr	618 $MtCO_2$/yr
CEJST - Pollution	206	219	316	471	694	1097	1265
DOE-DCR	190	203	290	448	654	1008	1186
EJ Screen	134	150	231	385	510	746	851
SVI	134	181	254	362	538	759	900

The CCS component with the fewest impacted DAC-EJ communities is storage. The count of DAC-EJ tracts impacted by storage is in

Table 7-4. While fewer than 10% of storage locations are co-located with DAC-EJ locations with the EJScreen tool, for the CEJST, DCR, and SVI tracts, approximately 10-15% of storage locations are identified as DAC-EJ tracts.

Table 7-4. Counts of DAC-EJ census tracts co-located with geologic storage.

	100 $MtCO_2$/yr	200 $MtCO_2$/yr	300 $MtCO_2$/yr	400 $MtCO_2$/yr	500 $MtCO_2$/yr	600 $MtCO_2$/yr	618 $MtCO_2$/yr
CEJST - Pollution	10	13	15	21	22	29	34
DOE-DCR	15	14	18	23	29	30	36
EJ Screen	7	6	6	10	11	12	13
SVI	13	14	18	23	27	35	36

Carbon capture, transport, and storage will impact DAC-EJ communities differently. The transportation network required to transport CO_2 from where it is emitted to where it is stored is present in more Census tracts in every scenario than the number of tracts where capture or storage will occur. That is, if you consider only how many people are affected, more DAC-EJ communities will have a pipeline somewhere in the Census tract than they will have tracts with capture equipment or storage wells. However, if one considers the percent of tracts where CCS activities are modeled to occur that also qualify as DAC-EJ relative to all Census tracts where those CCS activities are modeled to occur, a higher percentage is found for capture compared to transportation or storage activities. If we consider that between 12-24% of the nation's Census tracts are considered a DAC-EJ tract, a lower percentage of tracts that have geologic storage also qualify as DAC-EJ (10%), a slightly higher percentage of tracts that have a pipeline present also qualify as DAC-EJ (18-40%, including the highest scenarios), and a higher percentage of tracts where CO_2 is captured from industrial sources also qualify as DAC-EJ (15-50%, including the scenarios). From a community impact and engagement perspective for DAC-EJ tracts, it will be important to understand how carbon capture at industrial facilities will impact local residents given that capture activities are in a larger percentage of DAC-EJ communities than transport or storage activities. As we increase our understanding of the community impacts of DAC-EJ, including health, job, and economic incentives at capture, transport, and storage sites can create a clearer picture of the potential impact of CCS on local communities.

Figure 7-2. Percent of Source, Sink, and Networks in EJ tracts, across different definitions and scenarios.

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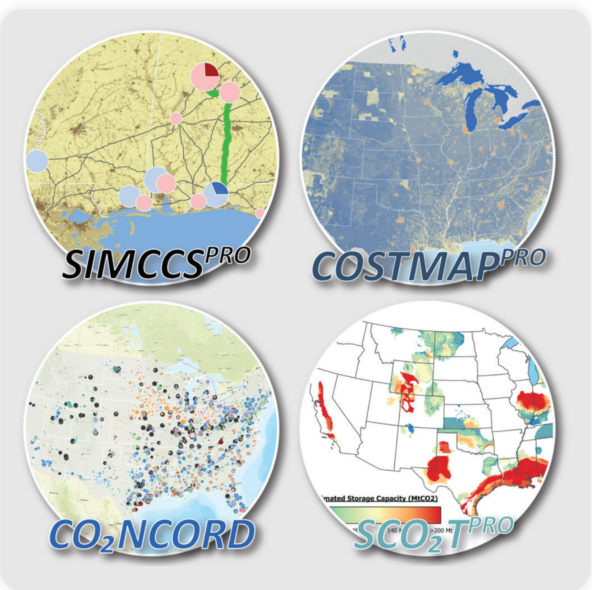
About Us

Carbon Solutions

Carbon Solutions is a mission-driven, fast-growing small business focused on low-carbon energy Research & Development and Software & Services.

Energy applications include CCS, direct air capture (DAC), energy storage, geothermal energy, wind energy, the hydrogen economy, and energy equity. Carbon Solutions was launched in 2021 and currently has around 30 employees with more than 50 projects to date. In addition, Carbon Solutions has around 25 expert energy consultants that cover the entire CCS value chain.

The company currently leads and participates in around a dozen DOE-funded R&D projects in a diverse range of areas, including CO_2 capture-transport-storage, energy storage, wind energy, geothermal energy, and next-generation carbon-negative power fueled by coal waste and biomass (carbonsolutionsllc.com/rd-projects). The company has developed unique award-winning, industry-leading SimCCS^{PRO} to understand, analyze, and support decisions for CO_2 capture, transport, and storage, including when, where, and how much CO_2 to capture and store, when and how to route CO_2 pipelines, and to assess economics across the entire CCS value chain.



SimCCS^{PRO} is the world's leading software to optimally understand how and when to optimize CO_2 capture, transport, and storage investments. SimCCS has won two prestigious R&D 100 Awards and is the most-used and most-cited CCS infrastructure software.

CO_2NCORD is a dynamic software and database that characterizes thousands of CO_2 capture opportunities across the United States. The software uniquely fuses and analyzes CO_2 emissions data from multiple data sources and develops unique approaches to calculate capturable CO_2 and advanced capture economics.

CostMAP^{PRO} is the most advanced CO_2 pipeline routing and cost tool, combining multiple geographies—such as population, land cover, lane ownership environmental challenges, social impacts, topography, existing rights of way, etc.—to produce custom-weighted pipeline routes and potential networks.

SCO_2T^{PRO} is a dynamic CO_2 sequestration screening tool for identifying potential CO_2 storage sites based on dynamic CO_2 injection and dynamic plume evolution coupled with advanced economics.

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