How can the cement industry enable widespread industrial CCUS adoption?

MIT CSHub Research Brief

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MIT CONCRETE SUSTAINABILITY HUB

CCUS Opportunities in the Cement Industry

Carbon capture, utilization and storage (CCUS) will play a key role in the decarbonization of the cement industry. Eventually, some of this captured carbon will be converted into valuable products that can be shipped like any other good. Today, subsurface mineralization (e.g., CO_2 injection through wells or under water) is gaining traction because of efficiency and technological flexibility. However, most cement facilities in the U.S. are not co-located with suitably deep geologic CO_2 storage. As a result, to support CCUS at scale, a CO_2 transportation system will be needed. To be cost effective, this will require the buildout of an extensive carbon pipeline system.

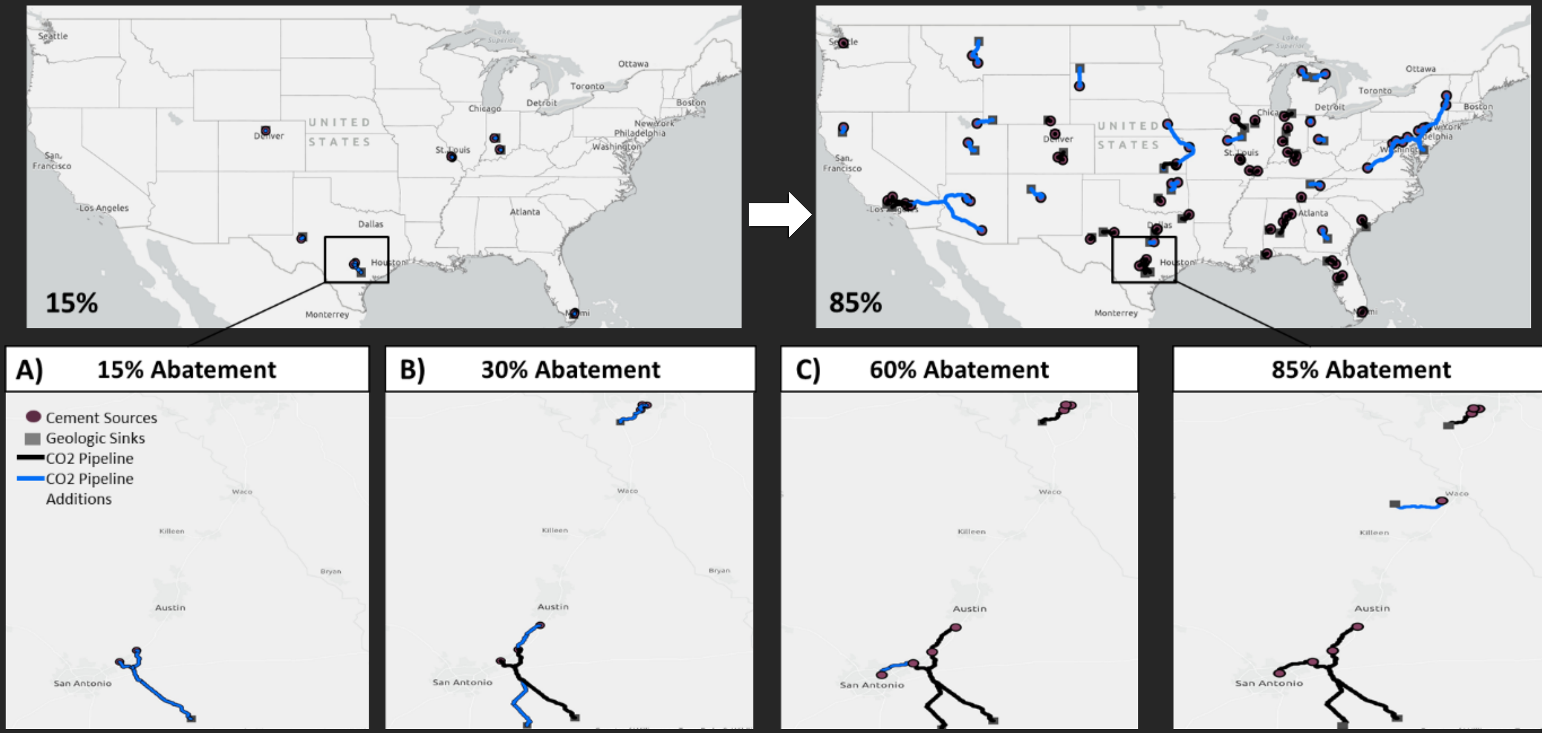
While pipeline transportation is the most efficient transport option,[i] there are challenges in designing the system. To inform the diameter and length of the pipeline system, sufficient information about the location of CO_2 sources and sinks and estimates of maximum annual flow is needed. An economical pipeline design must also consider environmental and regulatory factors such as rights-of-way regulations as well as avoidance of mountains, tribal and federal lands, and highly populated areas.

Various studies have provided estimates for the magnitude of pipeline scale and investment required for U.S. decarbonization. The results are sensitive to assumptions of pipeline diameter, calculations for CO_2 mass flow rate, and assumptions of suitable storage locations. The reported pipeline distances range from 70,000 km[ii] to 200,000 km[iii]. These studies assume that all types of carbon-emitting facilities are equally motivated to invest in and implement carbon capture. Clearly, carbon transport costs would be minimized if every emitting firm shared in that cost. However, real-world market pressures and constraints do not align with the assumption that all firms will participate. Different industries have different timelines for achieving carbon neutrality at regional and national levels. As shown in the Portland Cement Association's *Roadmap to Carbon Neutrality*,[iv] the cement industry will not wait for all stakeholders to be motivated to decarbonize.

This study explores the design of a transport network to serve the cement industry and how that network would enable carbon capture across a much larger swath of the economy. Specifically, geospatial optimization is used to design

Key Takeaways

- Carbon capture, utilization and storage (CCUS) will play a key role in the decarbonization of the cement industry. Spatial economic models can help inform cost-effective deployment strategies for carbon capture at cement facilities.
- Carbon capture equipment installed at the plant represents on average 80% of the total CCUS system cost for cement facilities. (The balance being for carbon transport and storage facilities.)
- At plant capture costs can vary by about 50% for cement facilities depending on the presence of pre-treatment facilities, air-in leakage, fuel types, and kiln type.
- There is a need to identify gaps between current cost model estimates and real-world demonstration costs.
- Spatial-economic analysis identifies optimal cement source, pipeline routing, and sink locations with total pipeline length ranging from 247-6,864 km to abate 15% - 85% of the cement industry's emissions.
- If the cement industry leads industrial CCUS deployment, spatial analysis can identify carbon-hubs made of the nearest industrial neighbors to the pipeline to significantly reduce systems costs.
- In the 85% abatement scenario, carbon hubs could enable capture from ~100 additional industrial sources capturing 5X the emissions for 2X the infrastructure investment.
- This information can be used to help policymakers understand what incentives are needed to enable widespread industrial CCUS adoption.



Cement Abatement (%)	15%	30%	60%	85%
Transport Cost ($/tCO₂)	3.32	4.71	7.58	14.86
Sink Cost ($/tCO₂)	6.48	7.2	7.69	8.63
Pipe length (km)	247	584	2220	6864

Figure 1 (Above). The pipeline network for abating different fractions of the cement industry from 15% to 85% abatement across the U.S. The pipeline additions for each subsequent fraction are shown in blue with the area of Austin, TX as an example of how the pipeline evolves as the amount of CO_2 abated increases.

pipelines and CCUS deployment scenarios to abate various fractions of cement industry emissions. These pipeline designs were then used to identify potential carbon hubs – collections of nearby industrial facilities which could attach to and make use of this pipeline at little cost.

Key Results

The research team analyzed systems designed to abate four different fractions of the US cement industry emissions – 15%, 30%, 60%, and 85% based on the defined CO_2 capture target and the lowest total system cost (capture + transport + storage) to achieve that target. The level of abatement strongly affects the length of the pipeline network which varies from 247 km (to abate 15%; see Figure 1a.) to 6,864 km (85%; Figure 1b). As higher fractions of the cement industry CO_2 are captured, costs also rise due to higher transport costs and the use of more expensive storage formations. However, pipeline transport is much more cost effective compared with trucking transport. For the 85% captured scenario, the trucking distance required to transport carbon from the cement sources to the sinks for a single trip would be 12,260 km, 56% more than the pipeline distance required. Assuming a truck cost of $0.11/tonne-km[i] the cost to transport carbon via truck is significantly higher (about 3X higher).

Each segment of the cement-centric pipeline network creates an opportunity for many other nearby facilities to tap into the carbon transport and storage infrastructure. For example, the network associated with the 85% abatement scenario is within 50 km of 531 candidate industrial facilities. Figure 2 shows both the 50 km enabled region and for a network in Texas and the 16 nearby facilities who would be candidates to form a carbon hub.

To capture 5x the CO_2 emissions from 100 additional facilities, the total carbon transport infrastructure cost would only increase by ~2x.

It is important to note that connecting into a carbon hub may not be economical for all the facilities within 50-km. If a facility is small and at the edge of the region, the cost to build out a pipeline may not be justifiable. Figure 3 plots each of the 531 candidate facilities for the 85% abatement scenario (inset of first 30 facilities) in terms of their annual capturable emissions (Mt/yr) on the x-axis (each bar width represent the capturable emissions from a facility) ranked by each industrial facility's estimated carbon pipeline cost ($/t, plotted on the y-axis)) to connect to the carbon hub. The pipeline cost estimate includes construction, right-of-way costs, and annual

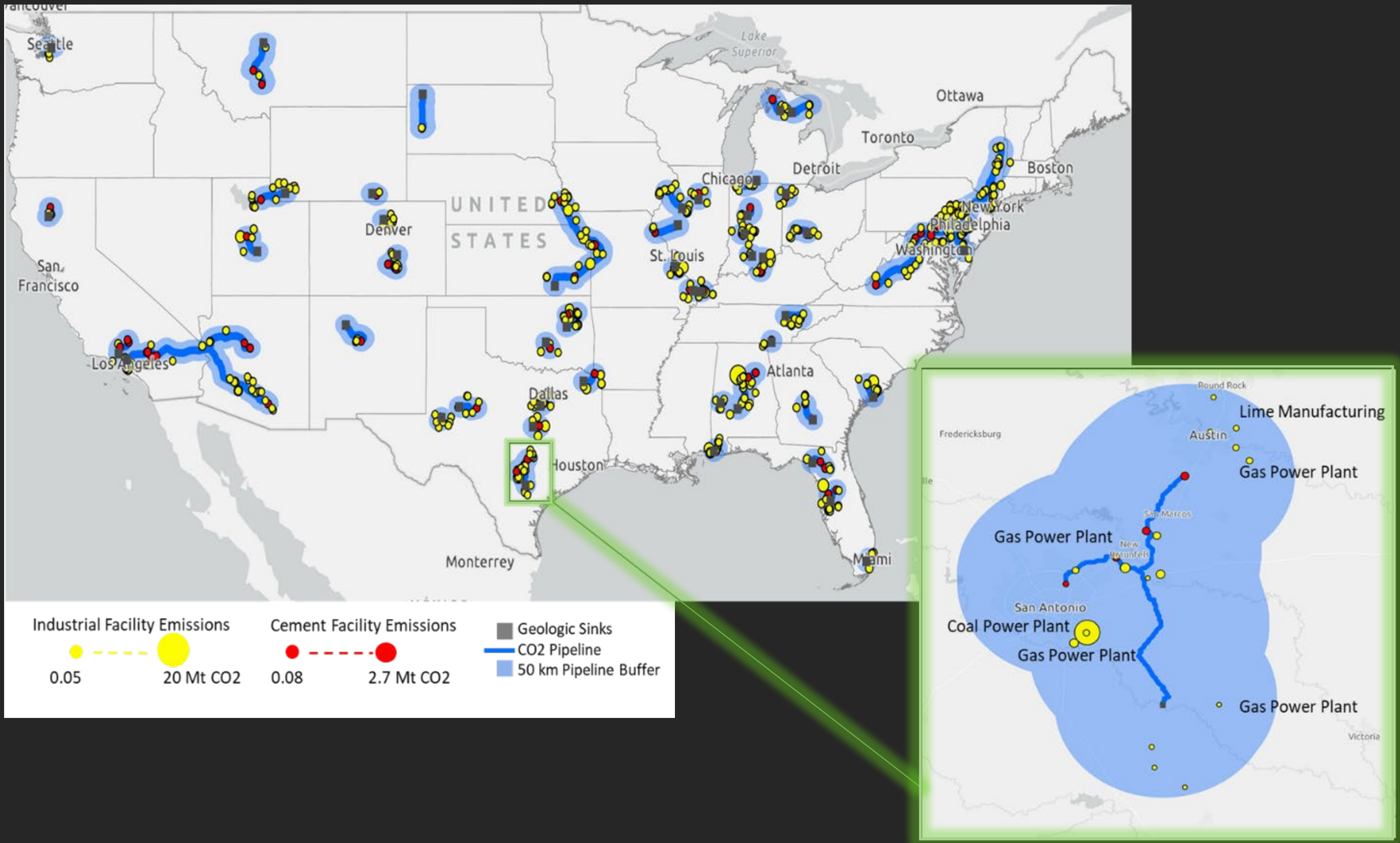


Figure 2 (Above). The closest industrial neighbors (within 50-km) of the carbon transport pipeline for the 85% cement industry abatement scenario. The red circles represent cement sources (emissions ranging from 0.08 to 2.7 Mt CO_2), the grey squares are geologic sinks, and the blue line is the CO_2 pipeline needed. The 50-km buffer is shown as the light blue area outside of the pipeline. The nearest industrial neighbors are represented by the increasing yellow circles with facility emissions ranging from 0.05 to 20 Mt CO_2.

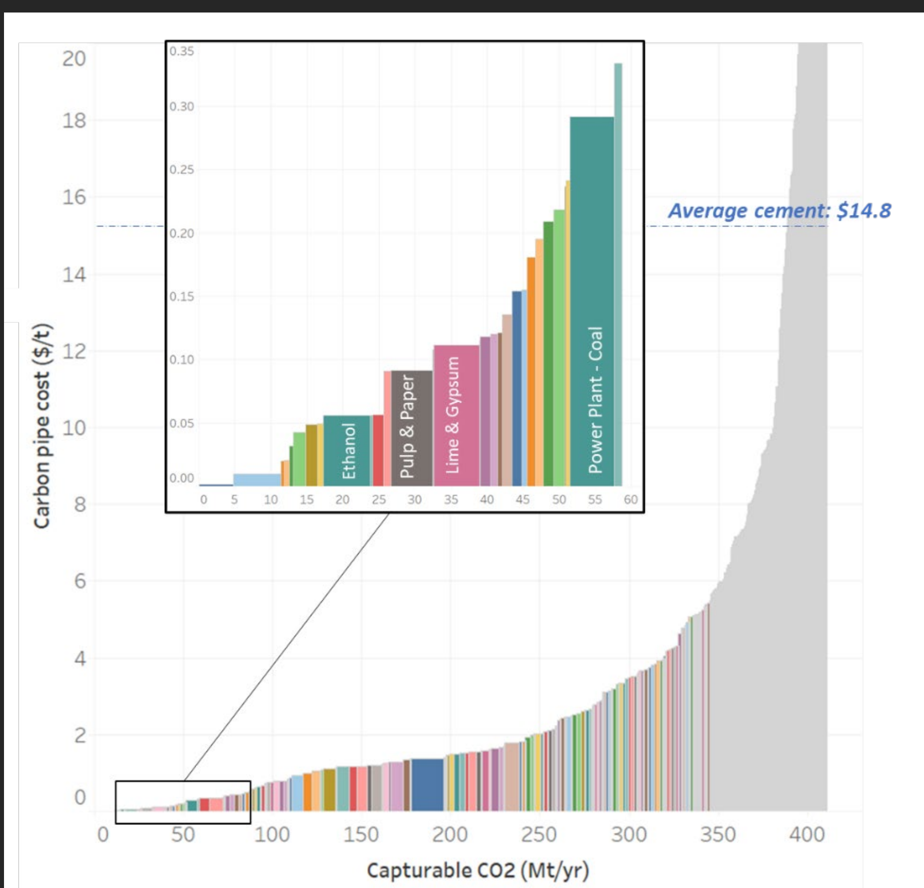


Figure 3 (Left). The nearest industrial neighbors within 50-km of the pipeline represents ~410 Mt of capturable emissions for the 85% abatement scenario. When combined with all potential neighbors, 470 Mt of emissions (an ~8X increase) could be captured with an increase in pipeline and storage infrastructure of ~4X. At 7X of emissions, the cost is still below the average cement pipeline cost of $14.8/t. The pipeline cost estimate includes construction, right-of-way, and annual operating and maintenance costs.

facilities on the left of this plot are highly economical, while connections to facilities on the right-hand side are costly. To capture an additional 60 Mt (2X the cement emissions) only 30 facilities need to add to the 85% network. The average transport cost for the 30 facilities is only $0.12/t CO_2. This analysis shows that, if facilities are selected wisely, the carbon hub network could capture seven times (7X) the emissions captured from cement facilities alone while keeping the additional transport cost ($7.16/t) well under the average cement-only pipeline cost of $13.5/t. Beyond 7X, the cost required rises significantly to capture the "last emissions."

It is important to note that in order to capture emissions beyond the cement industry, pipe capacity for the cement-centric network would need to be increased. On average, we estimate that the cost of the cement-centric network would increase by 75%. Nevertheless, this additional investment rapidly pays off as additional emitters join the network. In Table 1, the additional emissions captured vs. investment required is shown for capturing 2-8X the amount of cement emissions for the 85% abatement case if carbon hub facilities are chosen rationally.

Total Carbon Hub Emissions Captured (Mt)	*Add'l Facilities*	*Add'l Investment*	*Add'l Emissions*
120 (2X)	30	175%	198%
177	62	179%	295%
237 (4X)	80	188%	396%
300	102	200%	500%
361 (6X)	151	220%	601%
421	231	255%	701%
470 (8X)	531	385%	784%

Table 1 (Above). The additional investment required for capturing 2-8X the emissions of the 85% cement industry abatement scenario. There is an opportunity to identify the most economical carbon hubs to maximize the emissions captured while minimizing the overall system cost.

Collaboration with the Cement Industry is Critical to Understanding Realistic CCUS Costs

The next phase of this work is to provide a total infrastructure cost estimate for the cement industry and potential carbon hubs, based on plant specific data. The MIT CSHub is working to collect facility-level data to improve current cost estimates. Subsequently, the analysis will include two other hard-to-abate industries, the chemical and steel industry. Pipeline scenario analysis of industrial leaders will provide updated cost estimates that reflect real-world conditions. The CSHub will also explore other capture technologies and their costs (e.g., oxycombustion) as well as the potential for carbon capture and utilization opportunities. The goal of this effort is to develop cost-effective CCUS deployment plans for industrial carbon hubs and identify policies that can incentivize and support the strategic design of these carbon hub partnerships.

Modeling Methodology

The MIT CSHub and Carbon Solutions[a] have performed integrated cost and spatial modeling to simultaneously design cost-effective transport networks and estimate the capture, transport, and storage costs to abate various fractions of the cement industry.

The Carbon Solutions *SimCCS*[*PRO*] tool, originally developed out of Los Alamos National Laboratory, is an optimization model for integrated CCUS system design[v vi] used widely by government, academia, and industry. The model performs cost-based optimization of geologic storage site selection and pipeline routing considering existing rights-of-way (ROW), topography, land ownership, land use, crossings, geographic obstacles, tribal and federal lands, and highly populated, dense areas[vi]. Separate weighted-cost surfaces are generated for construction and ROW costs (e.g., slope will impact construction costs but not ROW costs). Prior to selecting the optimal pipeline network, several candidate pipeline routes are developed using the *SimCCS*[*PRO*] tool. The network selected is the least cost path between the source and storage locations based on Delaunay triangulation and Steiner tree methods. Specifically, systems were designed to achieve the lowest total cost (capture + transport + storage) for various levels of abatement. The analysis presented here excludes cement facilities that emit less than 50,000 t CO_2/year (n=5) and assumes a capture rate of 90%.

The pipeline cost estimate includes the construction, ROW (e.g., permitting, inspections, etc.), operating and maintenance, and financing costs. While additional legal costs (e.g., future lawsuits) could increase pipeline network costs, the optimal network solution is unlikely to change. To compare the pipeline cost to another transport mode, trucking, the ArcGIS Network Analyst Closest Facility tool with the OpenStreetMap dataset was used to compute the total road distance between sources and sinks for a single trip.

To understand which industries are closest to the cement facilities and pipeline for different abatement fractions, spatial modeling in ArcGIS Pro was used to identify facilities located within a defined distance buffer using the ArcGIS Pro Buffer tool. Using the Near tool, the distance for each facility within the buffer distance to connect to the pipeline is calculated. To improve the calculated straight-line distance, a detour index was applied[vii] to estimate the actual network distance. The total additional investment required for the industries to connect is estimated as well as the increase in capturable emissions.

Current cement carbon capture cost results have significant uncertainty due to a lack of key plant data. Capture costs can vary significantly across cement facilities (up to 50%)

depending on facility scale, the presence of pre-treatment technologies, air-in leakage, fuel types, and kiln types[viii]. Primary data from cement plants can help reduce the uncertainty in capture cost estimates to inform a cement industry cost estimate for capture, transport, and storage infrastructure.

Endnotes

[a] Carbon Solutions works with industry, government, non-profits, researchers, and other stakeholders to identify and implement real-world solutions for low-carbon energy challenges.

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