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Carbon capture, utilization and storage hubs: A necessity to achieve emissions goals in hard-to-abate sectors

Introduction

Carbon capture, utilization, and storage (CCUS) is a process aimed at reducing greenhouse gas (GHG) emissions to curb global warming. It involves capturing carbon dioxide (CO_2) emissions from sources such as the atmosphere, power plants, and industrial processes—utilizing the captured CO_2 for beneficial purposes and/or storing the remainder underground in geological formations.

Most carbon capture today is deployed against so-called point sources of CO_2*, such as power plants and industrial facilities. Another form of carbon capture, known as direct air capture, aims to remove CO_2 directly from the atmosphere. Point capture is a relatively mature technology. Though not yet very widely deployed—around 40 commercial facilities are operating—hundreds of CCUS projects are in various stages of development.[1] Direct air capture is a newer technology and currently much more costly per ton of CO_2 captured. It has recently received increased investment from private and public sectors.[2]

CCUS is gaining attention because it is considered one of the key strategies to achieve global climate goals by reducing atmospheric CO_2 levels. The Intergovernmental Panel on Climate Change (IPCC) foresees a critical role for carbon capture in getting to net-zero emissions and for carbon utilization in the production of critical materials.[3] The International Energy Association (IEA) projects that around 1.2 Gt CO_2 of CCUS per year will be required to reach net-zero emissions by 2050, up from less than 45 Mt CO_2 per year today.[4] Like many topics related to climate change, CCUS is not without controversy. One critique is that implementation of CCUS will prolong the use of fossil fuels and that - to date - most captured CO_2 is used in enhanced oil recovery (EOR). Putting aside any potential future use of CO_2 for EOR, the fact remains that economically essential activities, including the production of hydrogen, chemicals building blocks and intermediates, concrete, and steel, are expected to continue to generate CO_2 emissions for the foreseeable future—necessitating carbon capture in some form.

The chemical sector is highly illustrative of this point as its products are crucial for building a sustainable global economy. The chemical and materials industry currently accounts for about 5% of global gross domestic product (GDP), and over 96% of all manufactured goods are directly touched by the chemistry business.[5] The industry provides critical materials to other major industries, such as health care, transportation, communications, and retail. Even as the world faces the challenge of reducing GHG emissions to "decarbonize," it is not desirable to "dematerialize" but rather to use materials most efficiently to sustain and advance the human condition.[6] This is why the IPCC states: "It is important to close the use loops for carbon and carbon dioxide through increased circularity."[7]

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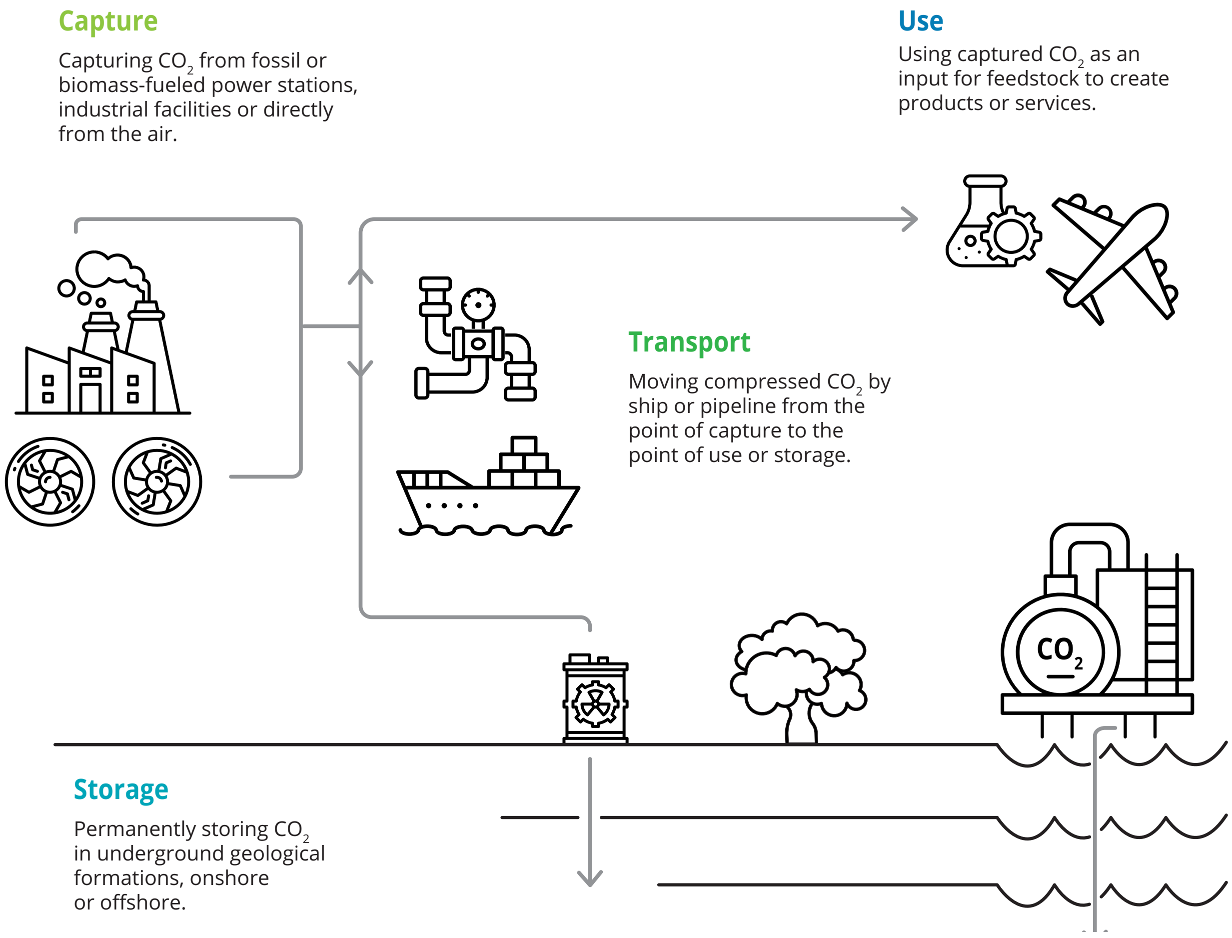
* Industrial CO_2 sources, in reality, constitute multiple individual sources in a facility, but are treated as point sources for this discussion because they are fairly concentrated in comparison to direct air capture where the CO_2 will be captured from the vast atmosphere

Overview of CCUS technology and types of CO_2 sources

The technology and use cases for gaseous CCUS fall broadly into two categories: point source carbon capture and direct air capture. These differ significantly in cost, technology, and application space (figure 1).

Figure 1. Carbon capture, utilization, and storage (CCUS) falls into two categories - point source carbon capture and direct air capture



Capture

Capturing CO_2 from fossil or biomass-fueled power stations, industrial facilities or directly from the air.

Use

Using captured CO_2 as an input for feedstock to create products or services.

Transport

Moving compressed CO_2 by ship or pipeline from the point of capture to the point of use or storage.

Storage

Permanently storing CO_2 in underground geological formations, onshore or offshore.

Source: IEA

While this paper focuses on point source CCUS of industrial emissions, some comments on direct air capture (DAC) are relevant. DAC is a path to scrub the atmosphere of CO_2 that has already been emitted. It is one of the promising technologies needed to cover emissions that are impossible to abate with other technologies—essentially one of the key approaches behind the word "net" in most net-zero emissions.[8] The IPCC Sixth Assessment (AR6) Working Group III report explicitly states that CCUS, in its various forms, "will be required to mitigate remaining CO_2 emissions." Estimates of "remaining hard-to-abate" emissions vary based on assumptions and targets; however, all land in the gigaton range underlines the essential need for direct carbon removal.[9] But because of the low concentration of CO_2 in the atmosphere (as of 2020, 424 parts per million; 0.0424%) it is very expensive and energy-intensive. Therefore, it is best deployed in locations with very low-cost renewable energy and favorable geology for carbon storage. DAC costs are also expected to come down as experience curves are traveled.

Carbon capture on industrial point sources is currently the focus of most announced CCUS investments and planning studies. It is an approach seen as essential for hard-to-abate sectors to make progress against sector, or country-specific, GHG reduction goals. The IPCC and widely respected climate modeling groups consider industrial CCUS to be essential for staying on a realistic path to achieve Paris Accord levels of emission reductions.[10]

And while there is consensus among climate modelers on the general need for point source CC, the agreement breaks down when it comes to specific use cases. Industrial processes where there is no alternative technology—a classic example is cement manufacturing—are widely accepted, even by opponents of CCUS. More debated are use cases where, in principle, there would be alternatives to CCUS. An example would be blue hydrogen. Opponents argue there is an alternative green hydrogen and that all investments should flow to electrolysis routes to hydrogen rather than steam methane reforming (SMR)—the most common production route to hydrogen in the United States and globally—plus CCUS. Another example would be the production of key chemical building blocks, such as ethylene, which require temperatures above 800°C that are only achieved in combustion furnaces. In principle, there are alternatives such as bio-based ethanol dehydration and early-stage efforts in cracker electrification.[11]

And while these arguments are in principle true, they neglect the low-technology readiness (cracker electrification), current costs (electrolysis hydrogen) of alternatives, long capital planning cycle of industrial investments and, particularly, the urgency to bend down the emissions curve of heavy industry sooner rather than later. One does not have the luxury of time to wait for perfect solutions when the world has not even achieved peak GHG emissions. Indeed, according to the IEA, global CO_2 emissions from the energy sector are now 1% above pre-COVID-19 pandemic levels.[12] With the points above as overall context, this paper focuses on the quantitative results and insights from modeling a complex combination of factors to implement CCUS in a real-world industrial cluster of industrial point sources. This is the kind of implementation that will be required over upcoming decades (figure 2).

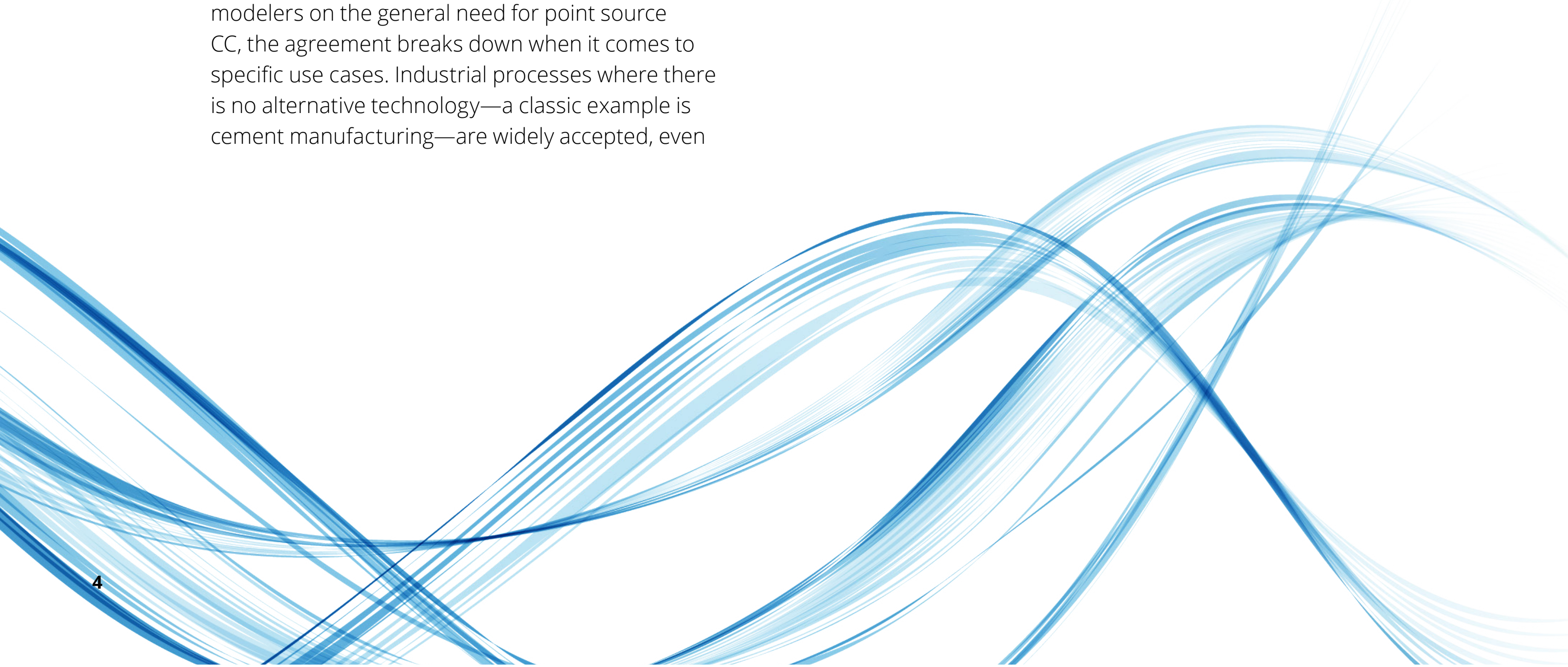
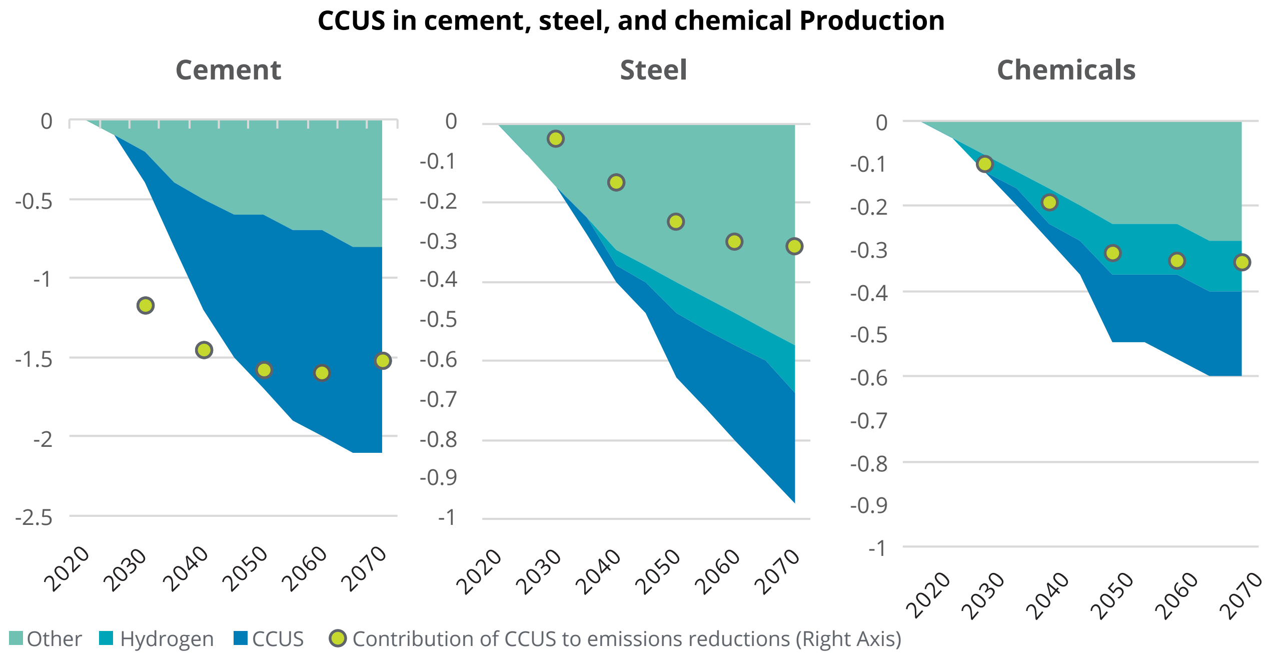


Figure 2. Over the next five decades, CCUS will be integral to achieving net-zero in industrial processes with CO_2 as an inherent byproduct



CCUS will be integral to achieving net-zero in **industrial processes with CO_2** as an **inherent byproduct**.

CCUS will be required within these industries as **it is difficult to reduce industrial process emissions without CO_2 capture**.

CCUS will account for a **proportion of heavy industry emissions reduction**, even after alternative energy sources have been developed.

Source: IEA

The Andlinger Center modeling study

Recently the Andlinger Center for Energy and the Environment at Princeton University completed a detailed analysis and modeling of CCUS opportunities in a dense cluster of industrial facilities along the US Gulf Coast (specifically Southeast Louisiana). The study addressed a gap in the CCUS literature, namely detailed modeling of mostly industrial point sources that require a retrofit of existing facilities with carbon capture and transport technology.[13]

Retrofitting the established fleet of industrial facilities represents both an opportunity and a challenge. The opportunity is tied to the life cycle of a typical industrial facility. The capital planning of many industrial investments envisions a useful asset life measured in decades rather than years. Furthermore, the so-called shale revolution triggered significant investments into petrochemical assets over the past decade. The American Chemical Council tracks such investments and has reported that $200 billion has been invested in that sector in the United States since 2010.[14] Thus, retrofitting established facilities with carbon abatement technologies offers a pathway to manufacture chemicals and material products with lower emissions without abandoning a valuable asset that still has years of productive value. The challenge is that individual retrofits of isolated facilities with complete carbon capture, transport, and eventual utilization or storage burden all the investment cost on the products of that unit's operations. The most likely path forward is the clustering of point emissions, capture, transport, and storage facilities. Sharing infrastructure in such a cluster can create economies of scale that can lower the cost per ton of CO_2. This concept is often referred to as a CCUS hub.

The Andlinger Center study considered the state of Louisiana. This was a deliberate choice and one that allows for first insights into what would be a prototypical CCUS hub. One can view this as the GHG abatement version of "supply and demand" dynamics. The supply side is anthropogenic CO_2 emissions. This may seem counterintuitive: Are there not an overabundance of CO_2 emissions globally? That is the very source of climate change. While true, the point sources of industrial GHG emissions are not evenly distributed. They tend to be tightly clustered in subregions in Europe, North America, and Asia. In the case of CCUS, this is fortunate because, as we will see, CC costs are strongly tied to location and concentration of CO_2 in industrial emissions.

The demand side of CCUS is twofold. For utilization of CO_2, the demand is linearly tied to the business economics of CO_2 as a feedstock (for example, with clean hydrogen a route to decarbonized methanol). However, economywide modeling of GHG abatement pathways inevitably concludes that most captured CO_2 will be stored or sequestered.[15] Using CO_2 at scale as a feedstock—at least for next five to 10 years—will be the exception. The bulk of captured CO_2 will be stored. Here the "demand" side is tied to available, reliable, low-cost options—nearly always geological in nature. Geologies with favorable structures such as depleted oil and gas reservoirs, saline formations, and mineralization formations are also unevenly distributed. While North America has widespread favorable geology, Europe has less so, and Japan has almost none.

Both "supply" and "demand" considerations make Louisiana in the United States an ideal case study. Louisiana is considered to have excellent prospects for underground geological storage of CO_2. It is also one of the most industry-dense states in the country, with 190 industrial facilities that emitted 130 metric tons of carbon dioxide ($MtCO_2$) per annum (p.a.) in 2019, or nearly three-quarters of the state's total emissions.[16]

A closer look: The Andlinger Center modeling study on CCS hubs

Analysis and key numerical findings

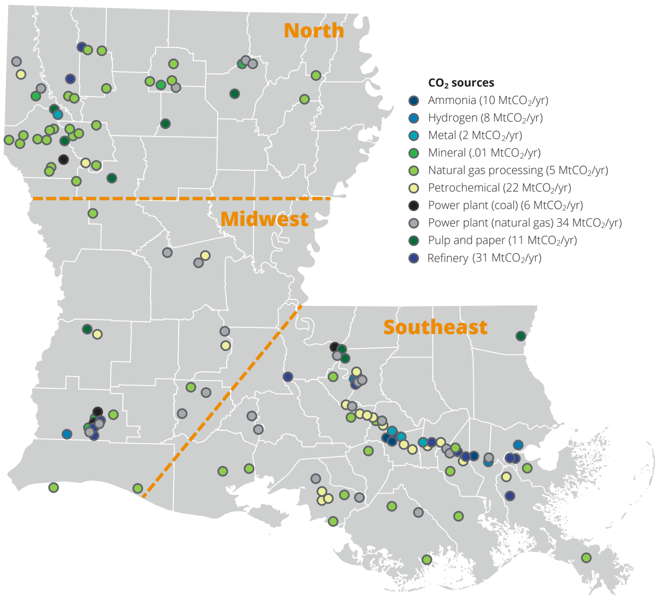
The Andlinger Center study considers the potential to reduce industrial GHG emissions using CCUS in Louisiana from three vantage points: 1) the costs of capturing CO_2 emissions, 2) the location of industrial point source emissions for capture, and 3) the optimum location of a network of CO_2 pipelines both from costs and community support perspectives. Optimization and consideration (in the case of stakeholder support) of all three will be essential for any implementation of CCUS at a scale that can meaningfully reduce industrial CO_2 emissions. [17]Let's consider each in turn.

Capture cost modeling

Modern amine solvent-based carbon capture units can capture 95% of CO_2 emissions and are thus a viable approach to decarbonizing industrial point sources. The specific steps of the process include capture, compression, and dehydration—the last step being critical for transport in pipelines (CO_2 and water form carbonic acid, which can damage pipes and equipment, already a source of damage in oil and gas equipment and infrastructure). Key variables in an industrial stream are concentration of CO_2 in the stream and the total volume flow of the stream. CO_2 concentration varies significantly based on the actual chemical stoichiometry of the process. Typical fossil fuel combustion processes (in industrial settings often a boiler or furnace) are between 4% and 14% (volume percentage) whereas the direct CO_2 process emissions from chemical conversions can be much higher and are also often less contaminated, making these processes especially good candidates for CO_2 abatement via CCUS.

Detailed chemical engineering modeling of a typical point source carbon capture unit showed that the levelized cost per ton of CO_2 captured varied significantly from below \$25 to just under \$200. The biggest driver is CO_2 concentration in the capture stream with an additional impact from annual capture rate (measured in Mt CO_2 captured per year). These two cost drivers offer hints at what would be an ideal location for establishing a network of CC units—namely an area with a number of large volumes and relatively concentrated emissions.

Figure 3. The state of Louisiana, with high density of industrial facilities and point sources of CO_2, was chosen as the case study for prototyping a CCS hub



Industrial facilities in Louisiana reporting emissions of 25,000 t/y or more of CO_2 in 2019 Aggregated total emissions by type of facility are shown in the legend. The Southeast region accounts for 64% of total industrial emissions and the largest number of individual emitting facilities.

CO_2 emissions ($MtCO_2$/yr)

Region	Number of facilities	Per facility		
		Total	Average	Median
Midwest	34	31	0.92	0.07
North	49	15	0.31	0.37
Southeast	107	83	0.75	0.31
Louisiana	190	130	0.67	0.19

Source: Gunawan, T.A., Luo, H., Greig, C., and Larson, E., Shared CO_2 capture, transport, and storage for decarbonizing industrial clusters, Applied Energy, vol. 359, p. 122775, 2024.

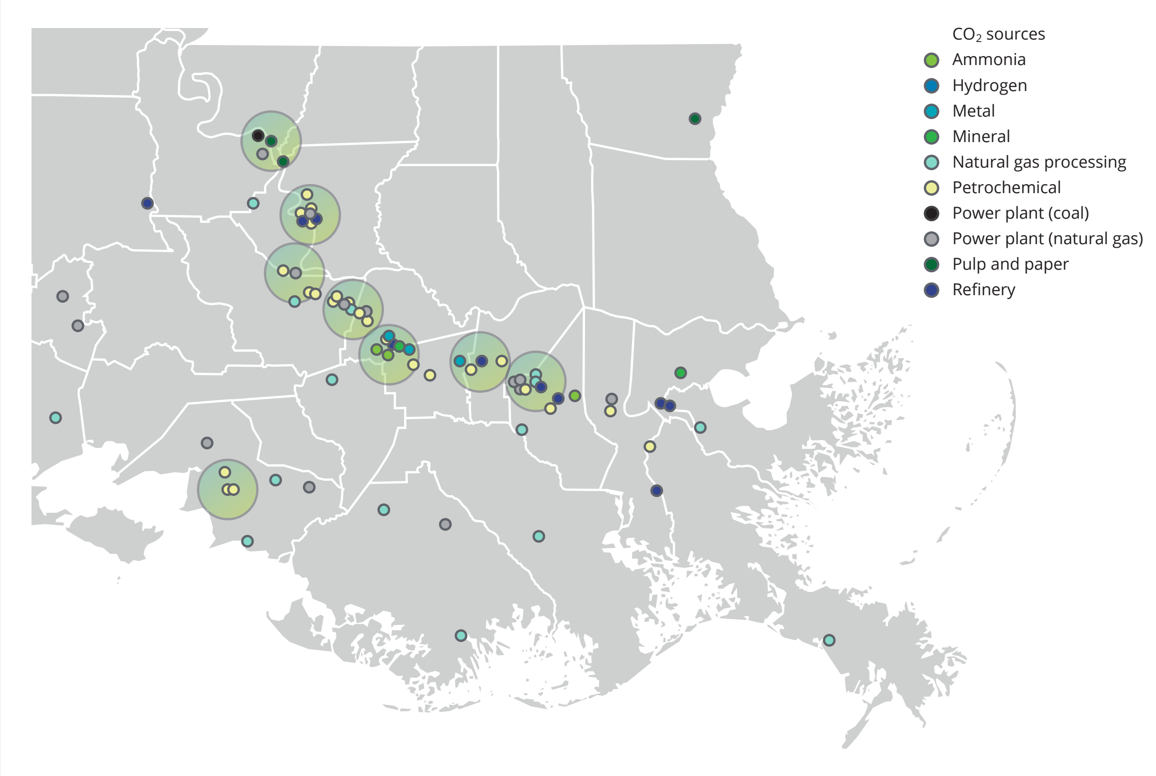
Clusters of industrial emissions

With carbon capture costs and drivers in hand, the study chose Louisiana as a test bed to consider an optimized CCUS network. As mentioned above, Louisiana has excellent underground CO_2 storage resources[18] —and a high number of industrial point source emissions.

For a sense of the scale of these emissions, only Texas has higher total industrial GHG emissions—Texas and Louisiana combined are larger than the next eight states in the top 10 industrial emitters combined.[19] Nearly two-thirds of Louisiana's industrial emissions are from facilities in the Southeast part of the state. And while there are single facilities with emissions greater than 5 Mt p.a., 25% of emissions are from smaller sites (less than 1 Mt p.a.), which accounts for 78% of Louisiana's industrial facilities. One could expect that such smaller facilities have higher CO_2 capture costs than larger facilities.

Using a geoprocessing algorithm,[20] eight clusters in Southeast Louisiana were identified by the Andlinger Center study that encompassed 77 individual emissions sources. The kinds of facilities in these clusters capture well the diversity of emissions sources, ranging from natural gas processing to production facilities for hydrogen, ammonia, methanol, ethylene, and various types of power plants. The CO_2 concentration varied from 4% in natural gas power plants to 99% in natural gas processing. Annual capture rates also varied over two orders of magnitude, highlighting the additional complexity of CCUS implementation.

Figure 4. With two-thirds of Louisiana's industrial emissions coming from Southeast region, 8 clusters in the region were identified for further analysis



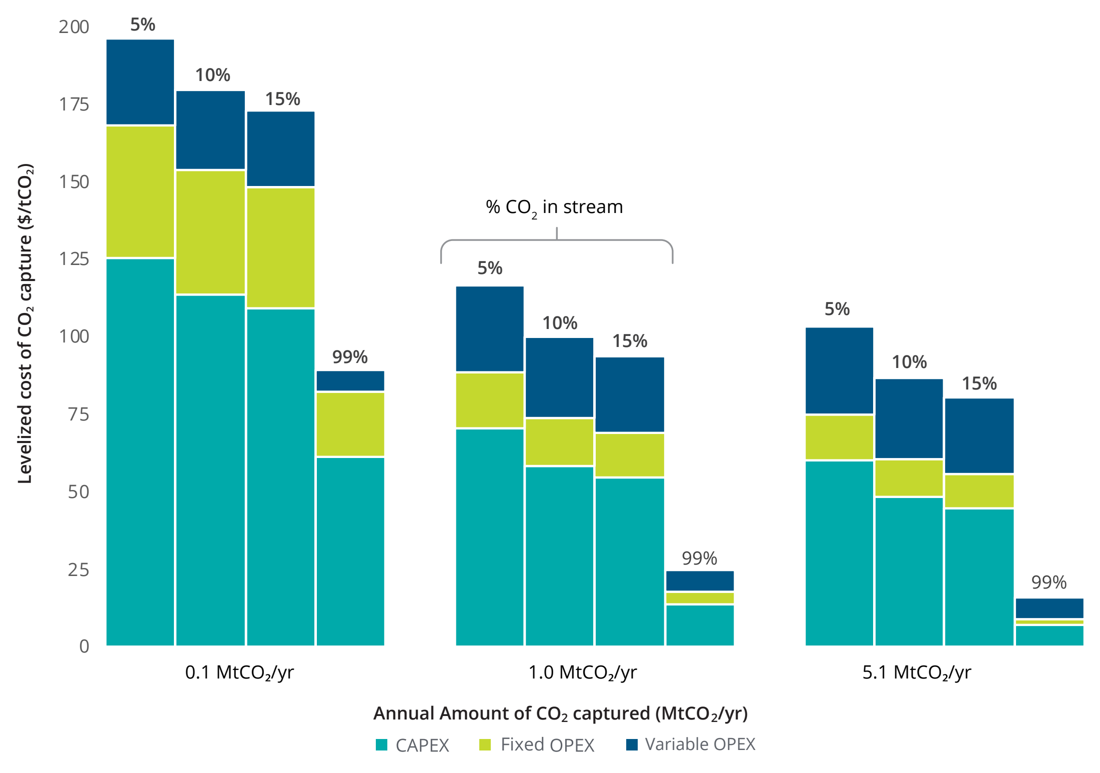
Source: Gunawan, T.A., Luo, H., Greig, C., and Larson, E., "Shared CO_2 capture, transport, and storage for decarbonizing industrial clusters,"Applied Energy, vol. 359, p. 122775, 2024.

Transport costs and options

CO_2 pipeline costs typically depend on pipe diameters and lengths as well as routing topography.[21] The study[22] employed an open-source model, SimCCUSPRO, that includes various categories of costs: 1) land or right-of-way acquisition costs; 2) materials and construction costs; 3) operating costs; and 4) the ability to adjust the pipeline costs to topographic features of various routes.

Not surprisingly, shorter lengths and increased sharing of CO_2 pipeline infrastructure lowers transport costs. The study evaluated a scenario with a two-thirds reduction in transport costs from $12 per ton of carbon dioxide (tCO_2) to $4 per tCO_2 by reducing aggregate CO_2 pipeline kilometers (km) from more than 700 km to a bout 200 km.[23]

Figure 5. Levelized cost of CO_2 capture varies significantly with concentration of CO_2 in the steam, amount of CO2 produced and position along experience curve

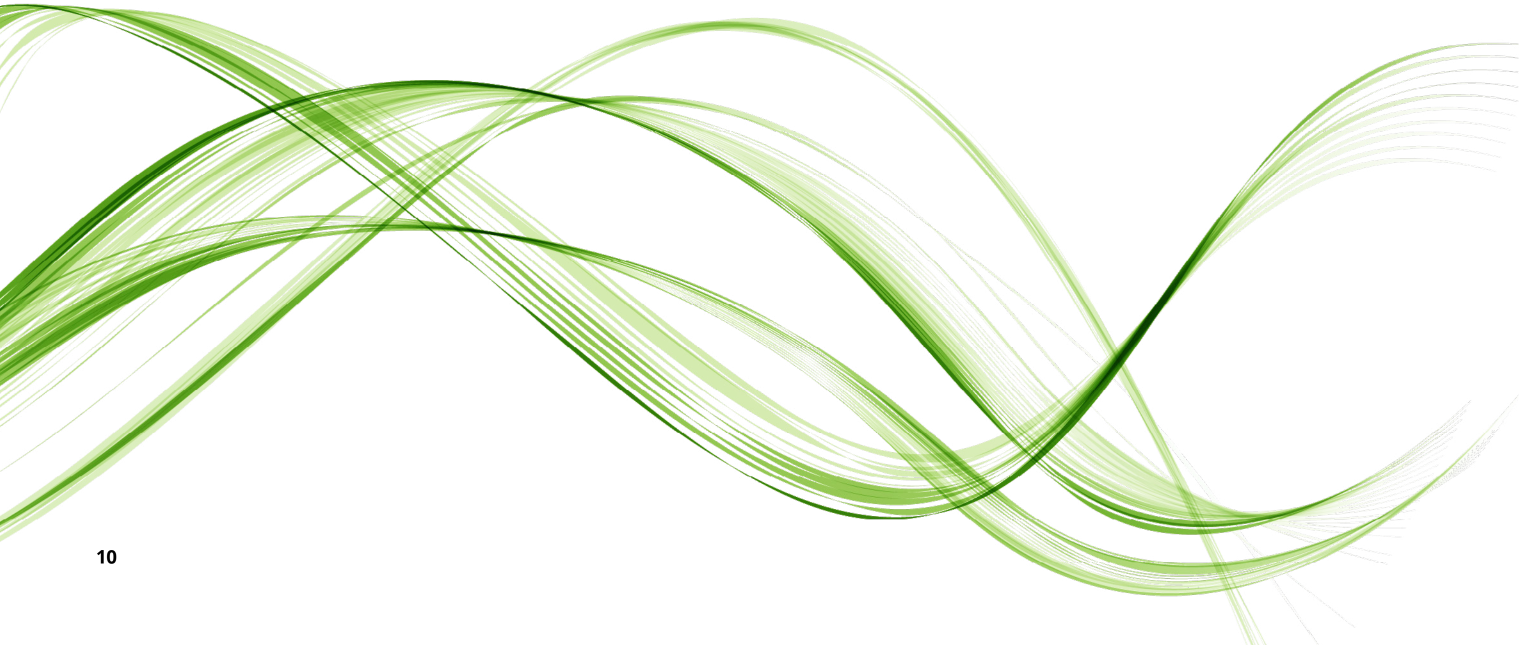


Levelized CO_2 capture cost estimates for 28 simulated capture plants, assuming Nth-of-a-kind plants. Target- stream CO_2 concentration (mol%) is shown above each bar. The annual capture rate (x-axis) is for capture of 95% of the target-stream CO_2 and 90% annual plant capacity factor.

Gunawan, T.A., Luo, Greig, C., and Larson, E., Shared CO_2 capture, transport, and storage for decarbonizing industrial clusters, Applied Energy, vol. 359, p. 122775, 2024.

Summary of the Andlinger Center modeling study

- Industrial sources of GHG are quite varied and differ significantly in the unit operations generating the emissions (power plant, chemical product, gas processing, refinery, etc.)
- Despite the complexity of the process, actual capture costs are most strongly dependent on concentration of CO_2 in the stream and the total amount of CO_2 produced per year.
- There are significant differences between first-of-a-kind and Nth-of-a-kind units, with as much as a 43% decrease in levelized costs. This effect is often seen in the implementation of new technologies as one moves through an experience curve—such as described by "S" curves and Wright's Law.
- Even in areas of dense industrial facilities, there are a significant number of smaller facilities. These especially benefit from being part of, and sharing, infrastructure within a cluster.
- Optimization of the CO_2 transport network (fewer miles of larger pipelines are best) reduces costs by as much as two-thirds.
- Of all the steps in the complete CCUS process, storage is the most binary. An area must have favorable geology. If present, injection, storage, and monitoring contribute \$10/tCO_2 to overall CCUS cost.
- In all scenarios, the carbon capture step is by far the largest contributor to overall costs, suggesting that sharing CC units (for example, through common flue ducts) is a path to further reduce levelized costs.
- Optimizing all variables for a specific cluster of GHG point emissions yielded costs of capture, transport, and storage of \$132/tCO_2 for point capture with shared transport and storage (using the average of the levelized capture cost for all plants in that cluster).
- Average costs lowered further to \$116/tCO_2 when capture units can be shared via flue ducts from ombustion sources.



Implications for businesses

The data and insights from this study can be valuable inputs for business and public policy decisions around the decarbonization of heavy industry. The study demonstrates an analytical method for assessing the economics of CCUS hubs in a given region. It makes it clear that CCUS hubs may be an attractive emissions abatement strategy only in areas with favorable geology and a high concentration of emissions sources.

In the right regions and under the right conditions, the study found that the hub model of CCUS deployment can help achieve significant cost savings. Industrywide collaboration for shared infrastructure can help cut the cost in half compared with point-to-point projects for the same CO_2 capture per storage. With capture as the biggest cost component of CCUS, a shared flue gas capture facility can help bring down capture cost. And shared transport and storage across large and small sources can significantly improve the economics for small sources.

For the region studied, the analysis calculates the cost of CO_2 capture, transport, and storage to be as low as around $115/t$CO_2$, not far from the benchmark of $100/t$CO_2$ often cited as the cost required for capture to be economically viable at scale.[24] This suggests that the region of Southeast Louisiana and others with similar characteristics may merit consideration for CCUS absent the availability of decarbonization options with superior economics.

The study calculated the total capital cost required for capturing 100% industrial CO_2 emissions in Southeast Louisiana (that is, 73MtCO_2 per year) to be approximately $45 billion spread over two decades, or $2.25 billion per year. That is equivalent to an average annual capital expense for each of the 77 emitters of around $30 million. These economies of scale could only be achieved by industrywide collaboration to allocate costs in a way that is acceptable to all participants. Given the number of facilities and organizations involved, this presents a coordination challenge, but one that appears worth exploring.

Multiple factors will influence the shape that industrywide collaboration can take, some of them purely economic in nature. For example, first movers are likely to face a cost disadvantage in building CCUS units, as the cost of the equipment reduces with adoption and scale. This puts the onus on bigger companies to drive initial adoption.

Another challenge, and one that government and commercial participants should consider from the outset, is social acceptance of such infrastructure projects. There has already been some backlash against proposed CCUS projects in several areas.[25] It is crucial to account for the views of stakeholders such as nearby populations, environmental groups, and regulators in the development of large-scale projects such as a CCUS hub.

Conclusion

Summary of key points discussed in multiple, authoritative analyses have concluded that there is no path to net-zero emissions by 2050 that doesn't make use of CCUS. Compared to the dozens of industrial emissions mitigations technologies under development, CCUS is relatively mature—meaning it can be deployed effectively in the short term and, as this study shows, can have favorable economics under the right circumstances. The task that industrial emitters and policymakers face is understanding how and where to deploy it to maximize cost-adjusted benefits and minimize risks compared in a socially acceptable manner to other alternatives.

The study finds that implementing CCUS hubs in industrial clusters located in areas with favorable geology can lead to economies of scale that provide relatively attractive economics. Achieving this would require collaboration among industry participants, regulators, and government, and consultation with stakeholders including citizen and environmental groups.

It's worth noting that the US Inflation Reduction Act of 2022 extends and increases the economic incentive for constructing industrial CCUS facilities. Given the urgency of the climate change challenge, this study provides timely insight to industrial emitters and policymakers.

Contact us

Robert J. Kumpf, PhD
Managing Director
Deloitte Consulting LLP
+1 412 338 7406
rkumpf@deloitte.com

David Yankovitz
Principal
Deloitte Consulting LLP
+1 216 589 1305
dyankovitz@deloitte.com

Scott Corwin
Managing Director
Deloitte Consulting LLP
+1 212 653 4075
scottcorwin@deloitte.com

David Schatsky
Managing Director
Deloitte LLP
+1 646 582 5209
dschatsky@deloitte.com

Authors

Robert J. Kumpf, PhD
Managing Director
Deloitte Consulting LLP
+1 412 338 7406
rkumpf@deloitte.com

David Schatsky
Managing Director
Deloitte LLP
+1 646 582 5209
dschatsky@deloitte.com

Isha Gupta
Manager
Deloitte Consulting LLP
+1 347 237 1359
ishagupta2@deloitte.com

Deloitte would like to thank the following authors of *Shared CO_2 capture, transport, and storage for decarbonizing industrial clusters* at the Andlinger Center for Energy and the Environment, Princeton University, for their contributions to this content:

Eric Larson
Tubagus Aryandi Gunawan
Chris Greig
Hongxi Luo

The authors would like to acknowledge the contributions of:

Prachet Prakash | Consultant | Deloitte Consulting LLP
Tushar Pareek | Consultant | Deloitte Consulting LLP

Endnotes

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