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Net Zero in Texas: The Role of Carbon Capture, Utilization, and Sequestration

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Executive Summary

Reaching net-zero in Texas by 2050 will require intense and collaborative efforts across all sectors of the economy. The continued use of hydrocarbons across the economy, and especially in hard-to-decarbonize sectors, will require the broad commercial deployment of carbon capture, utilization, and storage (CCUS) in ways that will result in affordable, reliable, and sustainable energy. Moreover, reversing some of the accumulation of greenhouse gases in the environment will require technologies and solutions that address carbon dioxide (CO_2) removal (CDR).

Texas is uniquely situated – by its emissions profile, existing industries and infrastructure, geology, and its available current and future workforce – to lead this effort. The scale and impact of Texas on the overall US profile of carbon emissions reduction are unmatched. CCUS in Texas is central to meeting the challenge of the energy transition: reducing carbon emissions while supplying energy to satisfy increasing global demand.

The energy transition is driven by the scientifically grounded, international recognition that emissions of CO_2 and other gases must be reduced to slow global warming. That reality has prompted growing scientific consensus that various forms of carbon removal, both nature- and technology-based, will be required, backed by the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC), and the U.S. Energy Information Administration (EIA), among other authorities.

CCUS will be a key enabler of the energy transition. However, carbon capture cannot succeed without the adoption of technologies and policies that will make it cost-effective and thus broadly deployable within the construct of a market-based commercial framework. More investment will be required, both in the short term to ensure new projects are launched and infrastructure is developed, and in the long term to ensure the continued deployment of at-scale emissions reductions and the success of the resulting new markets for low-carbon products. Lastly, investment will also be required to meet the increased energy demands associated with carbon removal technologies.

Despite the challenges, Texas is uniquely prepared to demonstrate the economic and climate benefits that accompany decarbonization. Even under current capital costs, input costs, and tax incentives, more than 250 million tons of CO_2 could be captured in the state annually, and Texas could serve as an opportunity zone for the growing carbon removal industry while advancing the sustainable use of hydrocarbons. This early-mover commitment by the industry has been recognized, and initial projects are in development. But we must also plan for future challenges and recognize that existing advantages cannot be sustained without the growth of infrastructure and further project investments.

Commercialization will also need to be addressed and is still in the preliminary stages globally, although CCUS has been successfully demonstrated at scale, including the first commercial-scale demonstration, the Petra Nova plant built by NRG Energy Inc. (NRG), and JX Nippon Oil Exploration Limited just outside Houston. Here and in other parts of the world, there are growing signs that the right political, economic, and regulatory ecosystem can attract substantial amounts of investment in CCUS. As that happens, regions, where the work is already underway, will have a comparative advantage in the global economy as the race to provide decarbonized products picks up speed.

The state of Texas cannot reach net-zero and maintain life as we know it without carbon capture. The research described in this white paper reviews existing CCUS and carbon removal projects, regulations, and incentives for carbon removal in Texas. Using Energy Information Agency (EIA) predictions and current national energy policy, we built an economic model to identify potential candidates for CCUS projects and evaluate the economics of such projects. Additionally, we evaluated approaches that can further incentivize the growth of the carbon removal industry in Texas.

Our key findings include:

• Texas is essential to advancing carbon capture technologies. It is the nation's top emitter of carbon, at almost 14% of total U.S. carbon emissions, and many of those emissions are clustered along the Gulf Coast and in the Permian Basin, providing efficiencies of scale for capture-related technology and infrastructure. Moreover, some of the needed infrastructure is already in place, reducing up-front costs, and the state's geology is unmatched globally for carbon storage.

• Both onshore and offshore geological targets have been identified as suitable for long-term carbon storage in terms of porosity and permeability. Challenges remain, however, in terms of the legal and regulatory framework required to build the geologic business case. That includes the lack of clear guidance on ownership rights to subsurface pore space in which CO_2 is injected and stored and regulations allowing the state to take primacy over Class VI injection wells, potentially speeding the current laborious permitting process.

• Existing CO_2 pipelines in Southeast Texas and the Permian provide some infrastructure available to meet the demand for some of the increased transport and storage, but they cannot provide sufficient capacity to meet the full expected demand. More pipelines and capacity must be built to connect those point sources to other enhanced oil recovery or storage opportunities.

• Twenty-five new CCUS and direct air capture (DAC) projects have been announced in the state, with an announced capacity to capture 38.3 MMt CO_2 annually, and storage projects with a capacity of 325 MMt, as corporations look to take advantage of tax credits recently increased in the Inflation Reduction Act and meet net-zero corporate or local goals. The state also has 127 million acres of land used for farming and ranching, which can serve as potential sites for nature-based solutions.

• With the use of CCUS, DAC, and changes to agriculture processes, an estimated 212 million to 362 million tons of CO_2 can be sequestered annually in Texas. Supportive policies and regulations could increase that.

• Approximately 255 million tons of CO_2 can be captured without costs to the emitter given current capital costs, input costs, and tax incentives. This represents ~63% of emissions analyzed in the state. While these projects are economically feasible now, obstacles such as access to larger transport pipelines, storage fields, storage permitting, labor, and capital all could contribute to a delay of a decade or more.

• Increasing the tax credits under 45Q, reducing transportation and storage costs, and charging a premium for low-carbon products would increase the amount of carbon that could be captured at no cost to the emitter. Meaningfully reducing transportation and storage costs by 80% could result in an additional 14 million tons of carbon being captured annually.

• Changing agricultural and ranching practices could have a significant impact. If at least half of the 88 million acres of land used for grazing and pasture could be transitioned to multi-paddock grazing, an estimated 58 million additional tons of CO_2 could be stored annually. Switching to no-till farming practices on acres currently being heavily tilled could store an additional 1.4 million tons of CO_2 annually in the state.

• Additional meaningful state policy changes could include state-funded transportation and planning, much like the buildout of transmission from Competitive Renewable Energy Zones (CREZs) in the Panhandle and West Texas to population centers in East Texas, mandated by 2005 legislation, which encouraged the growth of wind energy in the state. State-owned storage sites could reduce storage costs and reduce public concerns over long-term liability. Alternatively, tax breaks in the form of credits specifically for transporters and storage operators might offset the costs enough to have a similar effect as state-owned infrastructure.

• Expanding CCUS, including DAC, will require careful planning to account for the additional electricity required. Estimates for CCUS on coal and natural gas-fired plants suggest the CCUS plant may consume as much as one-third of the power produced at the plant. Our models also suggest that by 2050, DAC may consume 6.5 GW of energy – or over 8% of the peak demand on the ERCOT grid historically. To meet this demand through solar, for instance, would take an estimated 65,000 acres of new solar panels – and even then, additional build-out of storage, wind, or other low-carbon resources would be needed for when solar is not available.

• The lack of an identified price on carbon emissions presents another challenge to the business marketplace. This creates a business model that is challenged to meet a demand for low carbon but not supported by a carbon price.

• Other energy technologies are supported by not only tax credits for investment but also in electricity markets where the electricity produced is required to be consumed while fossil-fueled plants are then relegated to the second tier of suppliers and are often unable to compete.

Chapter 1: Texas and Carbon Removal

There are ~ 172 million acres of land in Texas making it the second-largest state in the nation and the largest in the lower 48 states of the United States. Approximately 127 million acres – or nearly 74% - is used for farming and ranching according to the Texas Department of Agriculture.[1] Texas also emits more CO_2 than any other state, due in large part to the state's robust industrial economy and because the state produces more electricity than any other state – approximately 11% of the total electricity produced in the entire country. Together, the industrial and electric generation industries enable the state to produce 9% of the gross domestic product of the United States. Texas is also home to innovation and has a history of advancing carbon reduction technologies. As the United States and nations across the globe race to decarbonize, Texas' history of innovation in carbon reduction will be critical to reaching decarbonization targets.

The state was one of the first to enact renewable portfolio standards and invested heavily in the infrastructure to support the wind industry in the late 1990s and early 2000s. The effort was so successful that the state exceeded the legislative goals for wind production fifteen years ahead of schedule. Today, Texas produces more electricity from renewables than any other state, with over 37,000 MW of installed wind capacity with another 2,000 MW of planned additions by mid-2024. The state also has close to 15,000 MW of installed solar capacity and 3,000 MW of installed battery storage with another 20,000 MW and 8,000 MW of planned capacity additions for each respective technology by mid-2024.[2]

While advances in the production and storage of renewable energy sources (*i.e.*, wind and solar power) have been observed in recent years, other strategies to reach net-zero by 2050 are still needed. For instance, despite efforts to incorporate more wind and solar power into the electricity grid, especially in the United States and elsewhere in the developed world, the continued use of fossil fuels will be required to provide electric power globally, including to developing nations. Furthermore, less than 40% of global energy is in the form of electricity, with the remaining 60% in the form of fossil feedstocks such as oil, gas, and coal which are used to meet the global appetite for transportation fuels, chemicals, and other manufactured goods, many of which are produced along the Gulf Coast. With the broad deployment of CCUS, those products will not only continue to be available in a carbon-constrained world, but they will also launch a new generation of low-carbon fuels, chemicals, and other products, meeting what is expected to be strong demand for more sustainable products in the global marketplace.

To meet this need for low-carbon fuels, carbon removal will need to be utilized. Carbon removal typically suggests technology-based CCUS, either capturing carbon at the source, such as a power plant, or through ambient air capture systems known as direct air capture, or DAC. In both cases, the carbon is captured and then either used for enhanced oil recovery (EOR) or as a component in another product, such as fuel or concrete, or permanently stored. CO_2 that is used or "utilized" is removed from the emissions profile. Texas offers natural advantages, including geology that is well-suited to carbon storage and substantial concentrations of emissions clustered along the Gulf Coast and in the Permian Basin, providing efficiencies of scale for capture-related technology and infrastructure.

Outside of CCUS, nature-based solutions will also play a critical role in carbon removal. These solutions typically involve landowners acting to preserve and enhance the ability of natural systems to sequester carbon via forests, grasslands, farmlands, and urban areas. Companies, governments, and researchers are also exploring nature-based solutions relying on public lands such as wetlands, coasts, and oceans. A third party will then estimate the additional CO_2 stored on an annual basis because of those actions, allowing landowners to be compensated by companies, governments, and individuals seeking to offset their emissions. Nature-based solutions often are less expensive than technological methods, but they aren't a permanent solution, because much of the sequestered CO_2 will be released when plant life dies and decays. They also can't reduce CO_2 concentrations enough on their own to replace technology-based CCUS. An honest approach to real life-cycle analysis demands that the CO_2 must be permanently removed; the ability of CCUS to measure, monitor, and verify stored CO_2 makes the value proposition irrefutable.

Beyond being home to an immense amount of renewable energy, Texas is also the home of the first commercial-scale demonstration of post-combustion capture. The Petra Nova plant was built by NRG Energy, Inc. (NRG) and JX Nippon Oil Exploration Limited (JX) and was partially funded by the U.S. Department of Energy (DOE). The Petra Nova plant included capital costs of $635 million and operated for three years before temporarily shutting down in 2020. During its operation, Petra Nova captured 3.9 million short tons of CO_2 from a coal-fired power facility. While some have criticized the project due to the need for a cogeneration unit built to power the carbon capture process, outages during the three years, or because the project ceased operations in 2020, the project met or partially met every goal set for it by the U.S. Department of Energy (DOE).

Over the three years Petra Nova operated, the project demonstrated that carbon capture can be successful at a commercial scale. Recently, it was announced that the project will be restarted and begin capturing CO_2 in the second half of 2023.[3] The success of Petra Nova and the lessons learned, along with the recent increase to tax credits for CCUS in the Inflation Reduction Act has resulted in several new projects being announced and companies investing in CCUS throughout the country including additional projects by Net Power, OnePointFive, and Carbon Engineering. The latter companies have partnered to initiate DAC operations, capturing 400,000 – 500,000 tons of CO_2 annually in 2025, with additional project sites being assessed.

Recently, organizations across the globe, from governments, corporations, and scientific communities have recognized that while massive amounts of renewable energy are needed, renewables alone will not get us collectively to decarbonize in time to prevent the most serious impacts of global warming by 2050. Accordingly, recent investment, research, and attention have been drawn toward CO_2 removal technologies and techniques. In Texas alone, 25 new CCUS and DAC projects have been announced and are being developed as corporations look to take advantage of tax credits that were recently increased in the Inflation Reduction Act and to meet net-zero corporate or local goals. Of those projects, at least two are DAC projects, four are storage-only projects, six are post-combustion projects at power plants, and thirteen are post-combustion projects at industrial facilities.[4] Despite this innovation in carbon removal and the past success of renewables, the state and the businesses operating within the state, still have significant hurdles to overcome to address CO_2 emissions. This paper explores the potential role that CCUS and CDR might play in addressing those emissions and explains why Texas has a competitive advantage over other states.

1.1 Current State of Emissions

In 2021, the United States emitted approximately 4.9 billion metric tons of CO_2 of the 36.3 billion metric tons produced worldwide.[5] Within the United States, Texas emits about 680 million metric tons or 13.9% of the nation's annual CO_2 emissions.[6] Point source emissions from facilities reporting to the Environmental Protection Agency (EPA) accounted for 384 million metric tons of CO_2 equivalent emissions.[7] While Texas emits more CO_2 than any other state, Texas also has the second largest economy in the United States, is home to 30% of national refining capacity, produces 75% of the nation's petrochemicals, produces 9% of the nation's manufactured goods, and is the nation's top exporter. Figure 1 shows the emissions in the state by sector through 2019. Nearly two-thirds of all emissions in the state come from the industrial and electric power sectors.

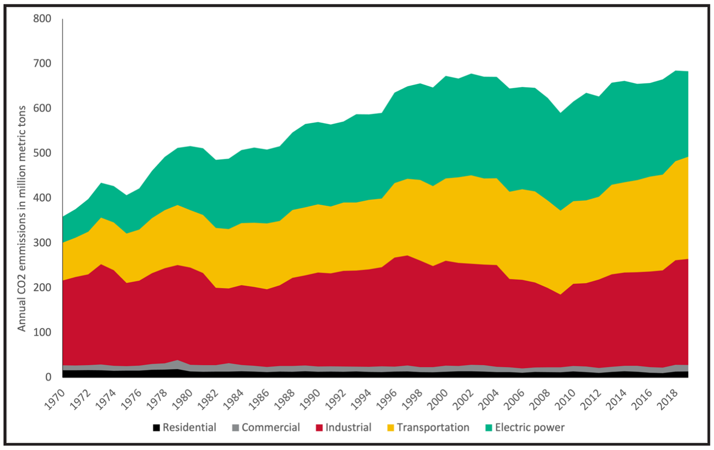


Figure 1: Annual sectoral carbon dioxide (CO_2) emissions in Texas from 1970 to 2019 (in million metric tons). Data source: EIA.

Since plans to decarbonize the transportation and residential sectors are dependent on the broad adoption of electric vehicles or hydrogen-fueled vehicles, installation of electric appliances, and electrifying goods production and transport, decarbonizing the electric and industrial sectors are required to in turn successfully decarbonize the transportation and residential sectors. Further, a better understanding of the sources of emissions in the industrial and power sectors helps to inform why Texas has an inherent competitive advantage for large-scale deployment of CCUS, DAC, and emissions reductions through adopting nature-based solutions and making those credits available to emitters economy-wide.

1.2 Emissions Hubs

The deployment of DAC is limited by available storage and the availability of inexpensive renewable energy to power DAC operations. Nature-based solutions are limited by the availability of land and verification. However, deployment of CCUS is dependent on having a point source - or stream of gas from the combustion of fossil fuels – from which to capture CO_2. Additionally, CCUS and DAC are almost always considered to be a cost, rather than a stream of revenue, to any business seeking to capture their CO_2 emissions. This is in large part because CO_2 utilization currently is a small industry in comparison to the scale of CO_2 emissions globally. Today, about 230 MMt CO_2 is utilized annually, with 130 MMt going to manufacturing urea and 80 MMt used for EOR. This is 0.6% of global emissions and 5% of U.S. emissions.

Currently, costs for CCUS and DAC in the U.S. are typically offset by tax credits made available at the federal level and voluntary carbon markets where credits for stored CO_2 can be sold to businesses seeking to offset their emissions. Because of this, the broad-scale adoption of CCUS is aided by reducing costs as much as possible. One way that this can be achieved is through having multiple capturers of CO_2 utilize the same transport and storage infrastructure. This is most easily done through clustering projects together at emissions hubs.

Emissions hubs can be defined as geographical areas where many high emitters exist near one another. These emissions hubs can be ideal locations for large-scale implementation of CCUS technologies because the individual emitters can share transport and storage costs, reducing the overall cost of each project. Focusing on emissions hubs also allows land impacts from the buildout of necessary transport and storage infrastructure to be minimized.

In Texas, the Eastern half of the state has the largest number of large point source emitters, with over 400 facilities reporting to the EPA.[8] Many of the plants with the highest emission rates in Texas are located in the state, and even if some of these plants have multiple emissions streams, some of which may not be candidates for CCUS, the identification of hubs of point sources is critical to this analysis. There are four potential sub-areas of high emissions point sources in Eastern Texas. First, the areas of high emissions density in the Southeast portion of Texas provide an ideal opportunity for utilizing both existing CO_2 pipelines and easy access to permanent saline storage in the Gulf of Mexico. Other areas of high emissions density are in the Permian Basin and the Northeast portion of the state. The Permian basin cluster or hub is situated in an area where utilization of CO_2 for EOR or storage is readily available. Further CO_2 pipelines used for EOR for decades are already present in the area and could be utilized for both EOR and storage opportunities. Figure 2 shows these clusters with individual plants visible in each area.

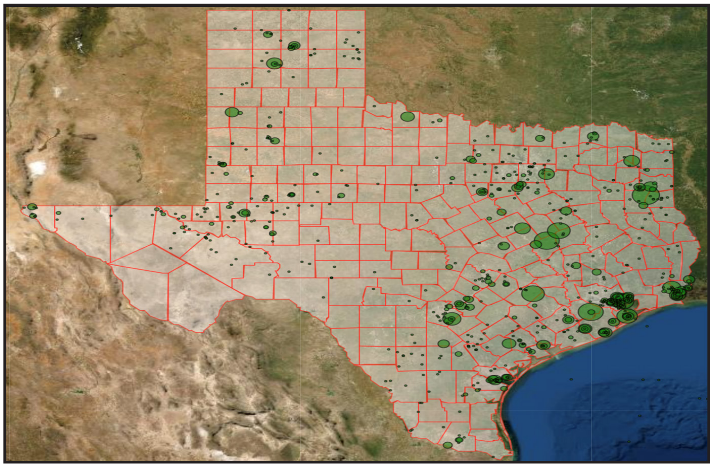


Figure 2: Clusters of point sources.

Based on this clustering of emissions sources, we estimate that more than 50% of overall CO_2 emissions in the state have the potential to be captured and either stored or utilized within the previously proposed locations for Texas emissions hubs or ~372 million metric tons of CO_2 emissions.

1.3 Geological Attributes

While geology is not a consideration for nature-based solutions to carbon removal, geology is critical in considering where to locate DAC and CCUS operations. Once captured, the CO_2 must either be permanently stored or utilized. For storage, the economics of capture and storage require that the distances between capture and storage sites be as short as possible. If the site is not proximal to storage or pipelines transporting CO_2 from multiple sources, the CO_2 needs to be utilized. As mentioned above, the utilization market is small. Today, around 230 million metric tons of CO_2 (5% of the total CO_2 produced in the U.S.) are used each year, with 130 million metric tons used in urea manufacturing and another 70 to 80 million metric tons used for EOR.[9] The primary path for large-scale utilization in Texas today is the usage of CO_2 in EOR operations where an estimated 90-95% of CO_2 injected can be expected to be permanently stored.[10] Additionally, estimates have suggested that EOR operations in Texas alone can result in up to 4.9 billion metric tons of CO_2 being stored. Beyond utilization through EOR, Texas is home to unmatched geologic resources for permanent storage through sequestration. Some estimate that 1.4 trillion metric tons may be stored in saline formations, three times the amount from EOR alone.[11] The combination of EOR and storage opportunities positions the state to store more than two times the CO_2 of any other state. The geology in Texas and the location of point source emissions – depicted in Figure 2 above – position the state as an ideal candidate for large-scale carbon removal.

The capacity of these reservoirs could exceed the total emissions generated by the state for centuries – providing the opportunity to also create a market for storing and utilizing significant amounts of CO_2 from other neighboring states. Figure 3 shows existing or planned CCUS projects in Texas overlaying the geology capable of CO_2 storage.

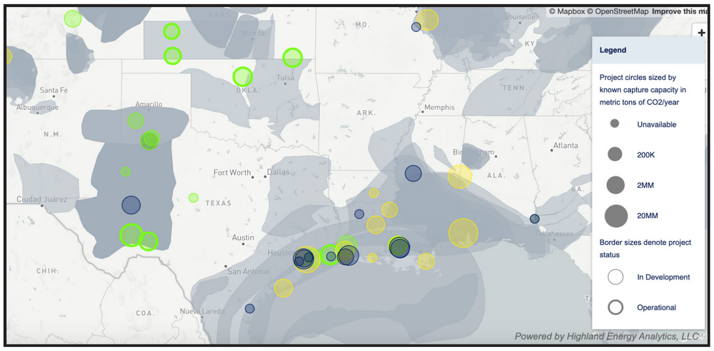


Figure 3: CO_2 storage sites are in grey with CCUS projects represented by circles. Source: Clean Air Task Force (CATF).

1.4 Infrastructure in Place and Potential for Development

For carbon removal hubs to be successful at a broad commercial scale, infrastructure enabling the transport and storage of CO_2 from multiple sources is needed. Currently, such infrastructure exists on a sufficient scale to meet the needs of some early adopters of CCUS and DAC technologies but will need to be expanded for large-scale commercialization. The ability to access CO_2 transport can be critical for project economics as CO_2 pipelines can cost up to $2 million per mile to construct.[12] Table 1 shows the existing CO_2 pipeline capacity. Figures 4a and 4b show maps of existing pipelines.

Table 1: Existing CO_2 pipeline infrastructure in Texas. Source: U.S. DOE and NETL.

CO_2 Pipeline Infrastructure in Texas

Large Scale Trunk-lines

Pipeline	Operator	Location	Length (miles)	Diameter (in)	Estimated Flow Capacity (MMcfd)
Bravo	Oxy Permian	NM, TX	218	20	380
Canyon Reef Carriers	Kinder Morgan	TX	139	16	220
Centerline	Kinder Morgan	TX	113	16	220
Central Basin	Kinder Morgan	TX	143	16	220
Cortez	Kinder Morgan	TX	502	30	1300
Green Line	Denbury Resources	LA, TX	314	24	930
Sheep Mountain	Oxy Permian	TX	408	24	590

Smaller Scale Distribution Systems

Pipeline	Operator	Location	Length (miles)	Diameter (in)	Estimated Flow Capacity (MMcfd)
Adair	Apache	TX	15	4	50
Anton Irish	Oxy Permian	TX	40	8	80
Borger	Chaparral Energy	TX, OK	86	4	50
Comanche-Burbank	Oxy Permian	TX	120	6	70
Cordona Lake	XTO	TX	7	6	70
Dollarhide	Chevron	TX	23	8	80
El Mar	Kinder Morgan	TX	35	6	70
Este I - to Eelch, TX	ExxonMobil, et al.	TX	40	14	180
Este II - to Salt Crk Field	Oxy Permian	TX	45	12	130
Ford	Kinder Morgan	TX	12	4	50
Mabee Lateral	Chevron	TX	18	10	110
Means	ExxonMobil	TX	35	12	130
North Cowden	Oxy Permian	TX	8	8	80
North Ward Estes	Whiting	TX	26	12	130
Pikes Peak	Oxy Permian	TX	40	8	80
Slaughter	Oxy Permian	TX	35	12	130
TransPetco	TransPetco	TX, OK	110	8	80
Val Verde	Oxy Permian	TX	83	10	110
W. Texas	Trinity CO_2	TX	60	12	80
Wellman	Trinity CO_2	TX	25	6	70

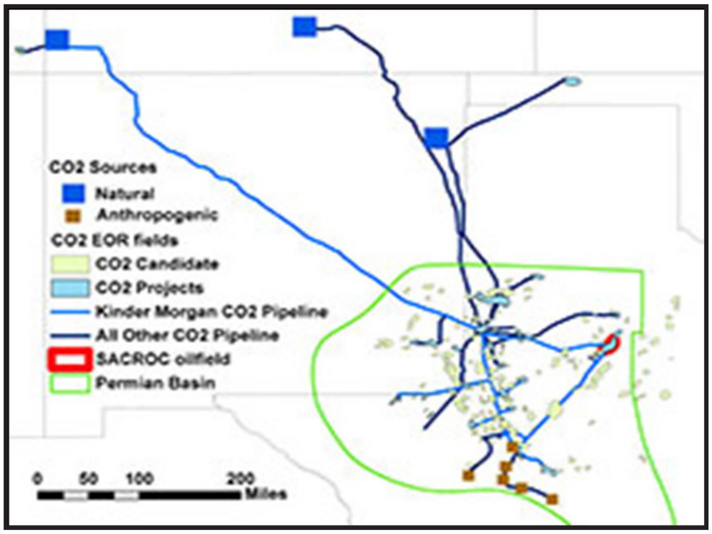


Figure 4a: Existing CO_2 pipelines in the Permian Basin depicting Texas, Oklahoma, Colorado, and New Mexico. Source: Bureau of Economic Geology.

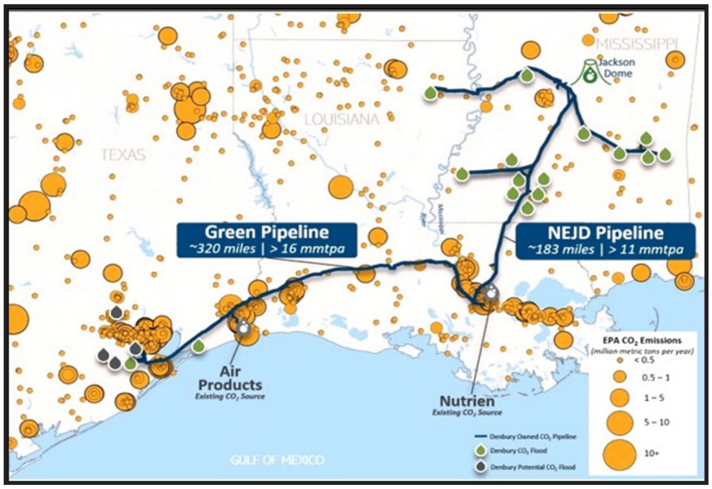


Figure 4b: Existing CO_2 pipelines in the Gulf Coast depicting Texas, Louisiana, and Mississippi. Source: Denbury.

Figure 4a shows there is a complex network of existing CO_2 pipelines in the Permian basin. These pipelines help enable EOR operations in the area, which have been ongoing since the 1970s using naturally occurring CO_2 primarily from Wyoming and Colorado.

In addition to the EOR CO_2 pipelines in West Texas, there are additional pipelines on the Gulf Coast. Figure 4b demonstrates the density of emissions within a short distance of the existing Denbury Green Line. The three-county area around Houston, including Harris, Galveston, and Chambers counties emits 52 million tons of CO_2 annually. Companies in Houston and the surrounding region who are first adopters of DAC and CCUS may be able to utilize the existing unused capacity of the Green Line. The Green Line can move about 16 million tons per year and is currently only operating at about 25% capacity.[13] This means there are about 12 million tons of existing storage or EOR transport capacity that is readily accessible. However, as can be seen from Figure 4b, there are other point sources along the line, particularly in Louisiana, which may compete with Texas capturers for capacity. This is particularly important because as discussed below (Section 1.5.2 d), Louisiana has been granted state primacy to regulate Class VI injection wells, and Texas' application is still pending, meaning Louisiana could begin utilizing Green Line capacity before Texas can establish a robust CCUS industry. If there is large-scale adoption of carbon removal technologies in Texas, more pipelines and capacity will certainly need to be built to connect those point sources to other EOR or storage opportunities

1.5 Incentives and Liabilities

1.5.1 Federal Financial and Economic Incentives for CCUS and DAC

The primary economic driver for the implementation of DAC and CCUS projects today is the 45Q tax credits, which allow companies or investors to claim credits for each ton of CO_2 they capture and utilize or store. The Bipartisan Budget Act of 2018 included in its entirety the FUTURE Act introduced in the U.S. Senate in 2017 to extend and reform the 45Q tax credit. The 2018 legislation increased the 45Q credit value incrementally over ten years from \$10 to \$35 per metric ton of CO_2 utilized in EOR operations and from \$20 to \$50 per ton for saline and other forms of permanent geologic storage. The legislation also provided \$35 per ton for CO_2 captured and put to beneficial uses beyond EOR that reduce lifecycle emissions. The law authorized projects beginning construction within 7 years after enactment to claim the credit for 12 years after being placed in service. The 2018 legislation also reduced the minimum eligibility threshold for qualified facilities from 500,000 metric tons of CO_2 captured annually to 100,000 tons for industrial facilities and 25,000 tons for CO_2 captured and put to beneficial uses other than EOR.

However, the legislation retained the 500,000-ton eligibility threshold for electric generating units. Later guidance clarified that although the credit is awarded to the owner of the carbon capture equipment, it could be transferred to entities in the value chain to provide greater flexibility for companies with different business models to utilize the tax credit effectively, including cooperatives and municipal utilities. The legislation also clarified projects that involve carbon monoxide capture and DAC may qualify for the credit as well.

The changes to the legislation have encouraged additional project announcements. From the time the credits were amended in 2018 through the end of 2021, 76 projects were announced and are at various initial stages of development.[14],[15] Despite all the newly announced projects and additional incentives, only one new project utilizing 45Q incentives has been completed and put into operation since the changes were announced in 2018.[16]

To further encourage CCUS and DAC adoption across the economy, Congress recently enacted even further changes to the 45Q credits. The Inflation Reduction Act of 2022 (IRA) has again increased the credit from $35/ton for EOR and other utilization applications to $60/ton, and from $50 to $85 for permanent storage. The IRA also extends the period to begin the construction of CCUS projects from 2026 to 2033. Further, and arguably most importantly, the IRA reduces the previous qualifying capture threshold from 500,000 metric tons annually for power plants and 100,000 metric tons annually for industrial sources to 18,750 and 12,500 metric tons per year for each respective source. This change will increase the number of potential projects that qualify for the 45Q tax credit. These smaller projects may present opportunities for lower capital cost projects to be built in the near term, lowering the cost curve for larger projects in the future.

The IRA also treats DAC technologies differently than post-combustion capture. To qualify for 45Q credits, DAC projects must capture at least 1,000 metric tons per year. The IRA also significantly increases the value of the 45Q tax credit for DAC. DAC projects may now receive $130/ton for CO_2 captured and utilized for EOR or other purposes and $180/ton for CO_2 captured and permanently stored.

1.5.2 State of Texas Regulatory Issues

a) Pore Space

Texas currently has a well-defined policy around land and mineral rights when it comes to the exploration and production of hydrocarbons from a reservoir. The Railroad Commission oversees and governs the exploration and production of these reservoirs. However, when it comes to the storage of CO_2, Texas is unique from other states hoping to attract carbon removal projects in that it has not statutorily defined who owns the rights to subsurface pore space in which CO_2 is injected and stored. In the 2023 legislative session, SB 2107 and a companion HB 4484 sought to address pore space ownership in Texas. Both bills would have followed other states and declared by statute that the surface owner owns pore space. However, neither bill passed through to the Governor.

Case law on pore space ownership from most states holds that surface owners retain the rights to everything that they do not explicitly convey. Accordingly, the conveyance of mineral rights does not convey pore space, and therefore the surface owner would retain the rights to utilize pore space. However, some see case law in Texas as being split on this issue and there has not been a case that is directly on point in the state. As mentioned above, each state taking legislative action to address the issue has affirmed the holdings of courts in most states by passing statutes in favor of the surface owner. Resolving ownership of pore space is not simply a legal issue. States like North Dakota and Wyoming, which have resolved pore space ownership through laws and regulations, have benefited from new CCUS projects being announced in those states, giving them experience and an advantage to attract more projects in the future. Accordingly, clearly defining pore space ownership may help Texas attract CCUS investment.

b) Right of Way

Before moving forward with plans to construct new pipelines, a right-of-way (ROW) must be obtained from private and public landowners or eminent domain must be exercised. Pipeline companies and landowners negotiate ROWs. The pipeline business and the landowner agree to and sign a ROW, which allows pipeline operators to proceed with constructing and maintaining pipelines on that land. If pipeline operators cannot acquire the ROW by paying for the right, they may obtain an ROW through exercising eminent domain, a court-ordered process. ROW can be acquired permanently or only temporarily. For interstate pipelines – which cross from one state to another – Federal Energy Regulatory Commission (FERC) approval is required. Various federal or state agencies have authority over the regulatory affairs of pipelines, depending on the type of pipeline, what it is transporting, what it is made of, and where it runs, and this can impact whether the owner may proceed with the construction of the pipeline or not.

In Texas, pipeline operators may obtain common carrier status and exercise eminent domain for CO_2 pipelines. However, this right is restricted to those common carriers where a reasonable probability exists that the pipeline will at some point serve the public by transporting gas for one or more customers who will either retain ownership of their gas or sell it to parties other than the carrier.[17] Accordingly, eminent domain cannot be used by an owner who constructs a pipeline to transport CO_2 captured at their facility to a sequestration or utilization site at another location. In such a situation, ROW would need to be granted by landowners. This, in turn, emphasizes the inherent importance of identifying CO_2 hubs where several point sources can be aggregated, and CO_2 transferred and sold from multiple parties.

c) Tax Incentives

Texas has incentivized investment in economic development projects through the passage of the Texas Economic Development Act in 2001.[18] The Act provides school districts with the power to enter into agreements with entities making large, qualified investments in a community for a reduced property assessment over ten years which in turn reduces the entity's ad valorem tax obligation to the school district through Chapter 313.[19] The credits are available for investments in manufacturing, research and development, clean coal projects, and advanced clean energy projects which include the capture of at least 50% of CO_2 emissions, renewable electric generation, electric generation using integrated gasification combined cycle technology, nuclear power generation, computing centers, and Texas priority projects.[20]

The Texas Comptroller publishes a biannual report showing estimates of the status of the Chapter 313 program. The 2021

Summary Data showed that the program has resulted in 193 active manufacturing projects, 4 research and development projects, 210 wind renewable projects, and 102 non-wind renewable projects.[21] Of note, although there are 9 categories of projects that qualify for the tax reductions, only four categories are reported to have entered into agreements for such reductions with a majority of those agreements going to renewables developers. The Comptroller estimates that the program has resulted in $2.71 billion in total gross tax benefits to companies investing in renewables in the program.[22] The Chapter 313 program is set to expire on December 31, 2022. However, projects entering into agreements before the deadline for the program will be eligible to receive the reduced ad valorem taxes for the next ten years. Additionally, a more tailored economic incentive package as outlined in HB 5, was approved by the Legislature during the 2023 session. Under the new revised tax incentive, which is expected to become active on January 1, 2024, wind and solar projects will not be eligible. However, dispatchable generation facilities, manufacturing plants, development of natural resources, and technology research and development facilities will remain eligible, making CCUS projects eligible.[23]

d) Class VI Wells and Primacy

Class VI injection wells play a crucial role in the permanent sequestration of CO_2 for both CCUS and DAC projects. The EPA developed a Class VI rule that involves the following requirements to develop permanent sequestration in geological reservoirs:

- Geologic characterization to ensure that geological sequestration wells are appropriately sited.

- Requirements for the development and operation of the wells include the construction with injectate compatible materials and automatic shutoff systems to prevent fluid movement into unintended zones.

- Requirements for the development, implementation, and periodic update of a series of project-specific plans to guide the management of sequestration projects.

- Periodic re-evaluation of the area of review around the injection well to incorporate monitoring and operational data and verify that the CO_2 is moving as predicted within the subsurface.

- Rigorous testing and monitoring of each project that includes testing of the mechanical integrity of the injection well, groundwater monitoring, and tracking of the location of the injected CO_2 using direct and indirect methods.

- Extended post-injection monitoring and site care to track the location of the injected CO_2 and monitor subsurface pressures until it can be demonstrated that U.S. Drinking Waters (USDW) are not endangered.

- Clarified and expanded fiscal responsibility requirements to ensure that funds will be available for corrective action, well-plugging, post-injection site care, closure, and emergency and remedial response.

- A process to address injection depth on a site-specific basis and accommodate injection into various formation types while ensuring that USDWs at all depths are protected.

The application and approval process when submitting to the EPA for a single project may take 6-7 years. This permit timeline poses risks to projects that may no longer be eligible for the 45Q tax credits if construction does not begin before the statutory deadline. It also poses risks that the project may struggle to obtain and retain financial support from private or public investors.

To address these issues, the EPA allows individual states to apply for primacy to process applications at the state level. The EPA works with States that are considering applying for Class VI primacy to ensure that state Class VI rules and permitting are consistent with the requirements of the EPA. A state may, at any time in the future, apply for Class VI Program primacy following the establishment of a Federal Class VI UIC Program. Once a State receives Class VI Program primacy approval, the EPA will publish a subsequent Federal Register notice that codifies the State Class VI Program in 40 CFR part 147. At that point, the State, rather than the EPA, will implement the Class VI Program allowing companies to be regulated at a state level, decreasing the time to approval. To date, only three states, Louisiana, North Dakota, and Wyoming have been granted Class VI primacy. The increased efficiency gained by obtaining primacy is most evident in North Dakota, where four permit applications have been approved in the last few years. Notably, the now-operational Red Trail Energy project took less than five months after submitting its permit to have the permit approved.

In 2021, the Texas legislature passed a bill consolidating Class VI authority with the Texas Railroad Commission and mandating that the state apply for primacy. The Texas Railroad Commission issued its proposed Class VI on May 16, 2022, changing Chapter 5 rules on CO_2 injection. These rules were approved and became effective on September 19, 2022. The state has now officially requested Class VI primacy from the EPA. If granted primacy, operators will be able to apply directly with the Railroad Commission for Class VI permits to store CO_2, which should allow for more efficient and timely permitting.

e) Long-Term Liability

Another issue that many states interested in attracting DAC and CCUS investment and projects face is that of long-term liability. Under the EPA Class VI UIC program, storage operators are liable for damages from CO_2 migration to US Drinking Waters and can be subject to 45Q tax credits being recaptured if CO_2 escapes to the atmosphere. Several states, including Indiana, Montana, Nebraska, North Dakota, Utah, and Wyoming have passed statutes that allow storage owners to file for a certificate of completion after the injection has ceased and the CO_2 plume has stabilized or ceased movement. If granted, ownership of the CO_2 and some or all associated liabilities is then transferred to the state. This transfer of ownership and liability after the statutory period is another regulatory mechanism that can further encourage carbon removal projects.

Texas has a split approach to addressing the issue of long-term ownership and liability. Current Texas law allows the General Land Office to lease permanent school fund lands – or lands owned by the state – for CO_2 storage.[25] Once injected, the state acquires title to the CO_2 in storage and assumes liability for the stored CO_2.[26] This statutory structure applies only to state lands. The state lands contemplated for this use are offshore and therefore in practice apply primarily to offshore storage of CO_2. In 2021, leases to submerged lands were awarded to two companies that may become the first storage operators to utilize this option.[27] However, for other CO_2 injection projects, timelines, ownership rules, and liability would all be determined by the EPA rules and cannot at this time be transferred to the state.

f) Legislation Impacting Nature-based Solutions

During the 2023 legislative session, HB 4018 was proposed and passed through the House and Senate and is awaiting signature by Governor Abbott. The bill allows for the Texas Parks and Wildlife Department to enter into agreements with public or private entities to develop nature-based carbon sequestration projects. The department is authorized to plan, operate, and maintain approximately 1.4 million acres of public lands across the state. The impact of this bill remains unknown but will provide an opportunity for testing and assessing nature-based solutions on public lands throughout Texas.

1.6 Project Economics and Cost Drivers

Project economics are one of the primary prohibiting factors when considering the construction of CCUS and DAC projects. Alternatively, nature-based solutions are far less capital intensive but do require a complex system of verifying the CO_2 sequestered and are inherently slow. However, standards and companies are quickly arising to address this cost driver for nature-based solutions. Accordingly, this section focused on economic and cost factors impacting CCUS and DAC projects.

1.6.1 Available Technology

There are several types of carbon capture technologies at various stages of maturity. The available technologies often take years to develop before they are ready for deployment in the commercial context. The efficiency and degree to which different technologies can be applied often depend on the source of emissions and the concentration of CO_2 in an emissions stream. Whether CO_2 capture can be economically adopted also depends on temperature and pressure constraints. The combination of both determines the initial investment that a plant requires to effectively apply a carbon capture solution to its emission source. The maturity and readiness of these technologies vary, and most are not currently commercially available. To date, projects like Petra Nova, have primarily focused on decarbonizing the power generation system. More recently, companies producing hydrogen, chemicals, ethanol, concrete, steel, and other products have announced plans to capture CO_2. IEA breaks down available capture technologies into the following categories:

Table 2: Available Carbon Capture Technologies. Source: IEA.

Capture Technology	Overview
Chemical Absorption	Common process operation based on the reaction between CO_2 and a chemical solvent. Amine-based solvents are the most advanced and common.
Physical Separation	Based on adsorption, absorption, cryogenic separation or dehydration and compression.
Oxy-fuel Separation	Involves the combustion of fuel using pure oxygen and the subsequent capture of CO_2 emitted. Flue gas is almost exclusively CO_2 and water vapor, with dehydration pure CO_2 can be obtained.
Membrane Separation	Based on polymeric or inorganic devices with high CO_2 selectivity, which let CO_2 pass through but act as barriers to retain the other gases in the gas stream.
Calcium Looping	Two-reactor technology. The first reactor, where metal particles are used to bind oxygen from the air into metal oxide, then transported into a second reactor where it reacts with fuel producing CO_2 and regenerating metal particles back to their origin, then reused in the first reactor
Direct Separation	Involves the capture of CO_2 process emissions from cement production by heating limestone using a special calciner. The process strips CO_2 from the limestone without mixing it with other combustion gases.
Supercritical CO_2 Power Cycles (Oxy-combustion)	CO_2 above its critical temperature and pressure is used to drive one or multiple turbines. These turbines use pure oxygen to combust the fuel that will combust with the fuel obtaining CO_2 and water vapor only.

1.6.2 Source of Emissions

Evaluation of CCUS projects is not only dependent on the technology used to capture CO_2, but also on the type of plant the CO_2 is captured from and whether that project is proximal to transport and storage. For example, ethanol plants often have high concentrations of CO_2 in their emissions streams. This high concentration of CO_2 can make capture of that CO_2 easier as CO_2 in high concentrations does not need to be separated from other gases. This is simpler than DAC because CO_2 exists at a low concentration of approximately 414 ppm in ambient air.[28] Such low concentrations make DAC more difficult and costly. The following average costs for CCUS come from a 2018 sample of 37 different plants located in Texas where capital costs and operating costs were evaluated together for a total result of USD / tCO_2eq. [29]

Table 3: Average Costs of CCUS Projects at Different Plants. Source: NPC Dual Challenge.

	Average Nominal Capture Cost	**Average Real Capture Cost**
Total	$71.41	$56.68
Hydrogen production	$39.33	$31.18
Refinery FCC	$78.97	$62.29
Industrial furnaces	$77.00	$61.12
Natural gas power plant	$65.34	$51.85

The study assessing the costs in Table 3 was completed by the National Petroleum Council (NPC) in concert with dozens of entities.[30] That work suggests that adopting CCUS in hydrogen production presents the lowest cost opportunities for carbon capture. Hydrogen plants contribute about 2% of overall emissions in Texas. The second lowest cost opportunity identified by the NPC study is for natural gas power plants. Such plants contribute a much larger share of the overall emissions in the state, considering 47% of electricity produced in the state comes from natural gas power plants. For our analysis, we seek to apply a similar methodology as the NPC study – which looked at CCUS nationally – to evaluate a broad range of potential projects in Texas. Further, we seek to evaluate changes to project feasibility based on current information regarding project costs and increases to the 45Q tax credits and how these changes will impact carbon removal technologies and the carbon removal market more generally.

For DAC, the cost drivers are different. Unlike the point-source CCUS value chain, which is driven in part by transport costs, DAC plants can be located at or near sequestration sites. Despite this flexibility, DAC plants are more costly than CCUS, in large part due to the need to separate CO_2 from ambient air, which is far more dilute than CO_2 in a flue gas. Estimates for DAC technologies range from $94-$600 per ton depending on the technology.

Chapter 2: Methodology

2.1 Defining Scenarios

To begin our analysis, we defined five potential scenarios for growth within Texas. This analysis included the growth of emissions and electricity demand and generation. Under each scenario, different technologies are expected to improve in cost and performance at varying rates and therefore can be expected to have varying availability to contribute to generation and capacity. The growth rates represent high growth rates for all technologies fueled by federal incentives. For technologies not currently operating within the state, including DAC, we assume that at least 0.1 tons will be captured utilizing DAC by the end of 2025.

After 2025, these innovative technologies are assumed to begin increasing in their utilization due in large part to federal policy incentives such as tax credits and zero emissions goals as well as state policies incentivizing EOR and the development of the CCUS and DAC industries. Such incentives have previously contributed to the substantial growth of onshore wind (Figure 5). We assume that the federal and state governments will support, incentivize, and encourage the growth of CCUS and DAC in a comparable manner moving forward to achieve state and national decarbonization goals and therefore we assume a best-case scenario for technologies with broad state and federal support.

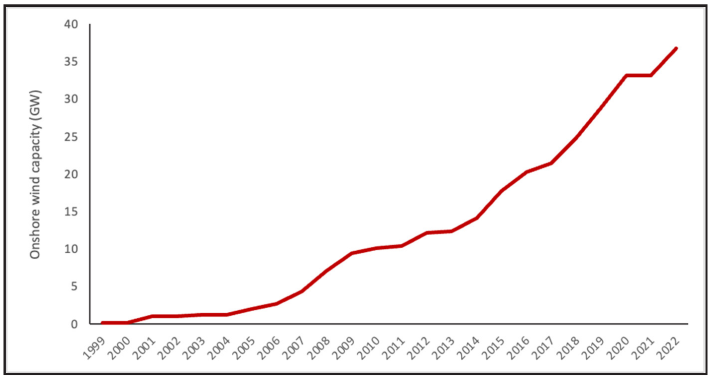


Figure 5: Capacity addition from onshore wind energy in Texas from 1999 to 2022. Data source: ERCOT.

We define our scenarios as Business as Usual (BAU; Scenario 1), High End-Use Electrification, Unconstrained Energy Supply (Scenario 2), High End-Use Electrification, Constrained Renewables and Storage (Scenario 3), High End-Use Electrification, Unconstrained Renewables and Storage (Scenario 4), and Low End-Use Electrification, Constrained Energy Supply (Scenario 5). The Business-as-usual scenario is based on the National Energy Modeling System used in the U.S. EIA's 2022 Energy Outlook scenarios. The remaining scenarios were growth scenarios relative to the Business-as-usual. For all scenarios, it was assumed that capacity additions of innovative technologies would become available beginning in 2026 and therefore the scenarios would begin to diverge from the base case at the growth rate outlined below in Table 4.

Table 4: Technology penetration and energy supply scenarios, year-on-year growth rates relative to the Business-as-usual scenario of the U.S. EIA's 2022 Energy Outlook.

	CCUS	CDR
Scenario 1	Reference	Reference
Scenario 2	-1.70%	-2.00%
Scenario 3	Same as wind	Same as wind
Scenario 4	-2.30%	-2.30%
Scenario 5	+3.00%	+3.00%

Assumptions made in formulating the scenarios are based on EIA predictions and current national energy policy. The variations in each scenario are intended to differentiate between the scenarios based on the growth trajectory of wind in Texas from 1999-2022. The results of CCUS and DAC growth along these trend lines are shown in Figures 6 and 7.

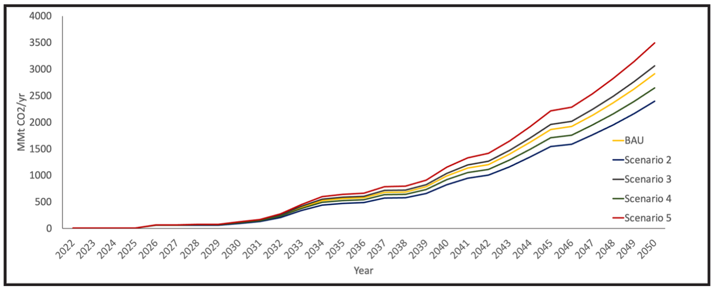


Figure 6: Potential Growth of CCUS through 2050.

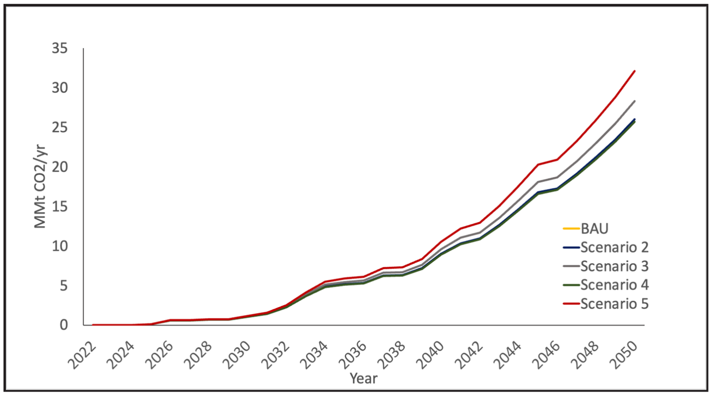
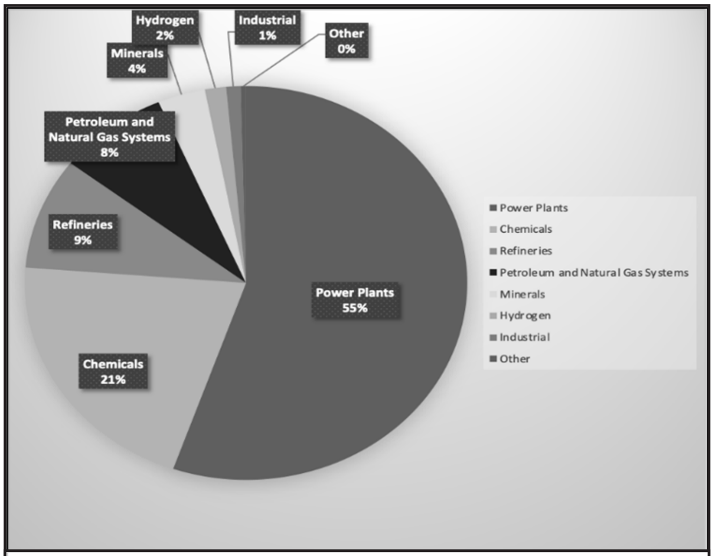


Figure 7: Potential Growth of DAC in Texas through 2050.

In each scenario, the potential growth of CCUS may result in 2,645.1-3,495.5 MMt CO_2 captured annually by 2050. In the four scenarios analyzed, the potential growth of DAC may result in 25.7-32.1 MMt CO_2 captured annually. To assess the economic viability of such expansion, we further analyzed the economics of CCUS and DAC to assess whether such potential growth is viable.

2.2 Point Sources with Potential for CCUS

To evaluate the impacts of the Inflation Reduction Act on CCUS and DAC, we began by identifying point sources near one another and geology that would be suitable for technological carbon removal and storage. Figure 8 shows a breakdown by industry of emissions that could be abated from plants located near potential CCUS pipeline pathways identified below. Additionally, "low-hanging fruit" – or low-cost, high-return projects – can be identified from the breakdown and will be discussed below. Some of these low-cost, high-return projects include steam methane reformers (SMR) which are used to produce hydrogen. Additionally, some petrochemicals and refineries present low-cost opportunities for CCUS adoption.



Category	Sum of Emission (CO2e Metric Tons)
Power Plants	205,918,528
Chemicals	77,759,860
Refineries	34,058,122
Petroleum and Natural Gas Systems	30,216,496
Minerals	12,945,756
Hydrogen	5,761,575
Industrial	3,882,250
Other	1,479,019
Grand Total	**372,021,605**

Figure 8: Potential annual CO_2 emissions reductions by industry category from plants located near potential CO_2 pipeline infrastructure.

We further sought to identify point sources near existing CO_2 transport infrastructure and geology capable of large-scale storage. While we did not exclude point sources that were not immediately proximal to transport and storage, we did account for additional costs that might be incurred by such projects by estimating the distance from the project to the nearest transport or storage opportunity and applied a cost of $60,026 per inch-mile that might be incurred in constructing transport pipelines to connect with large trunk lines.[32] We also assumed that at least 10 miles of trunk line would need to be built for CCUS projects while we assumed DAC projects would likely be sited at storage locations and require little to no transport infrastructure.

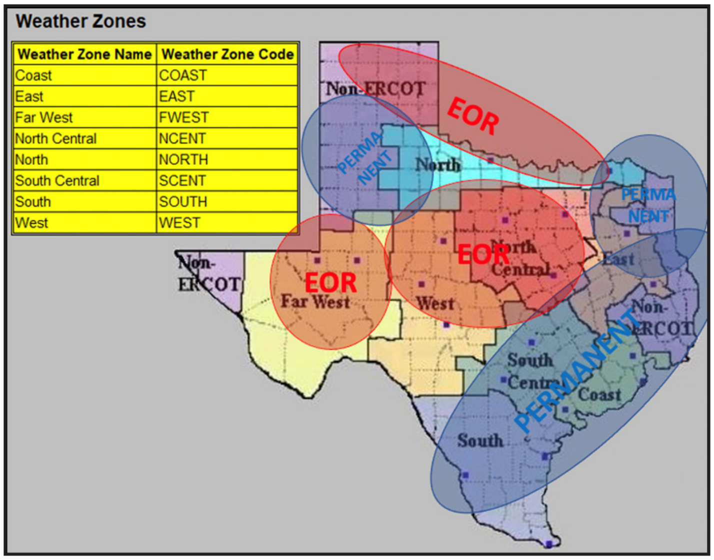


Figure 9: EOR and Permanent storage zones are used in the model. Point sources were identified by ZIP code and the nearest storage or EOR zone was identified to calculate transport costs.

2.3 Texas Cost Curve Methodology for CCUS Projects

After identifying potential candidate plants for CCUS, we sought to create a cost curve for Texas plants to evaluate the economics of such projects. The methodology applied to build the Texas CCUS cost curve was completed using the following data:

- EIA Data reported from 2019 for point source emissions in Texas provide the location of the point source, the type of plant from which the emissions come, and the quantity of CO_2 emitted annually.

- CATF storage information and reservoir location for identifying EOR or permanent storage opportunities.

- NETL Carbon Capture Retrofit Database, National Petroleum Council, and IEA estimations for costs associated with different CCUS type projects including Natural Gas Power Plant combined cycle carbon capture retrofit, Pulverized Coal Power Plant carbon capture retrofit, and other industrial sources carbon capture retrofit such as Steam Methane Refiners, Ethanol Plants, LNG powered plants as well as refineries and petrochemicals. IEA cost estimations are shown in Figure 10.

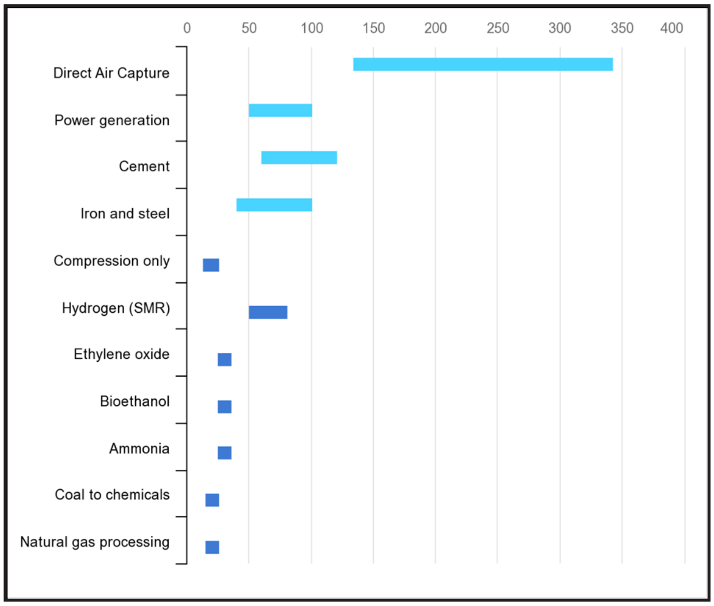


Figure 10: Range of Cost of Capture for CCUS projects in $USD/metric ton. Image source: IEA

The steps taken to model Texas CCUS costs are described in the following flow chart. Based on the selection criteria described above, we analyzed point sources comprising 83% of current emissions in the state of Texas from the power generation and industrial sectors. This includes more than 290 data points, and results are presented in USD per tCO_2eq.

2.4 CCUS Model Inputs

Inputs for the model were divided by industry type and further subdivided to account for a variety of factors that are known to drive costs for carbon removal projects. The following summarizes the most relevant inputs that are included in the development of the economic analysis:

- Capacity factor for each plant.
- Carbon capture rates based on solvent absorption method.
- Macroeconomic factors, including inflation.
- Financial factors include tax rates, project discount rate, project evaluation time, investment straight-line depreciation periods, CCUS implementation period.
- Incentive such as 45Q over 12-year time horizon.
- Commodity prices involved in the carbon capture process and utilization of CO_2 captured.
- Estimates of alternative revenue sources from utilization including cement aggregates, CO_2 sold for EOR operations and CO_2 used for synthetic fuels.
- Estimate of permanent storage cost in $/ton.
- Estimate of midstream transportation cost in $/ton.
- Estimates in natural gas and electricity usage for CCUS processes.
- Capture capacity per unit.
- Additional NETL estimates on labor, tax & insurance, chemical waste, and maintenance costs from operations.

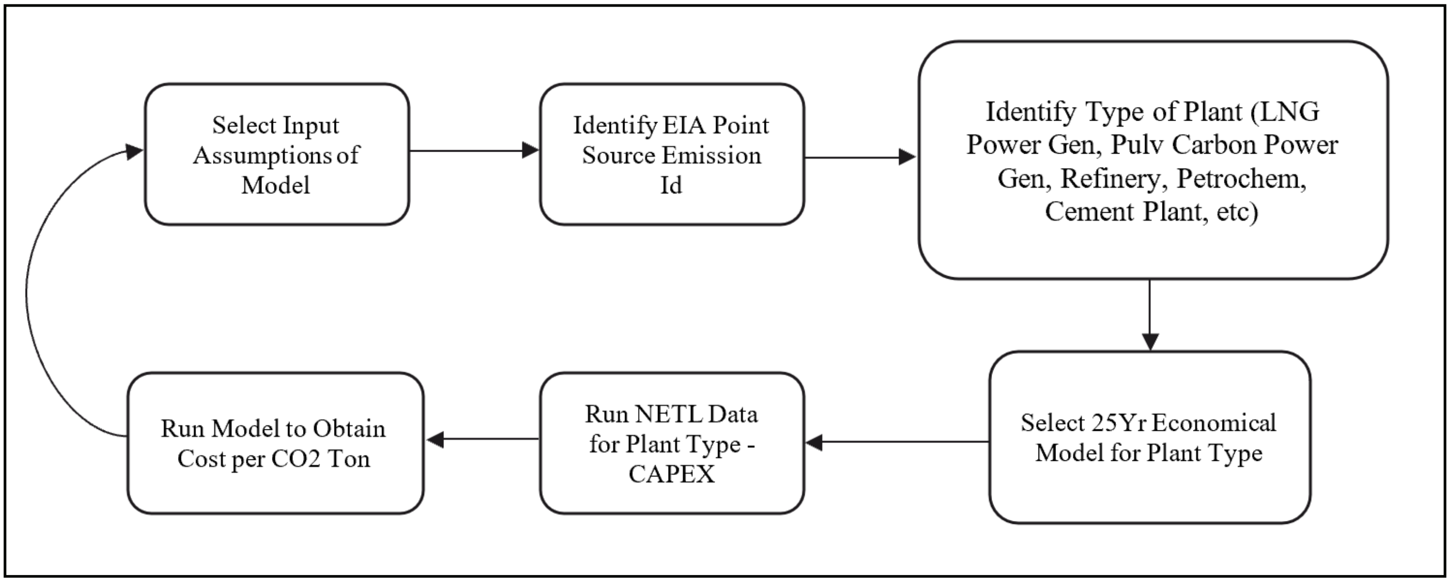


Figure 11: Flow chart describing the methodology of estimating costs per ton of CO_2 captured for potential CCUS projects.

2.5 CCUS Assumptions and Considerations

To model the economics of CCUS projects in Texas, we defined certain boundaries and limited our scope to assess first the costs associated with retrofitting existing plants for capture. We next assessed the capital expenditures associated with constructing a trunk pipeline to reach existing CO_2 pipelines, minimizing distance, and not necessarily accounting for routing concerns that may make a pipeline longer. The construction and operation of a permanent storage well or an EOR field development is not part of the scope, instead, it is included as a fee for every ton stored. Additional assumptions and considerations are described below:

- We have accounted for capacity factors for power generation plants based on the capacity reported.

- All other plants are assumed to operate at a 90% capacity.

- Permanent storage, EOR, and utilization locations have been selected based on first evaluating the zip code of the plant and then identifying the closest reservoir (EOR or permanent storage).

- 45Q incentives for CCUS are benchmarked at $60/Ton for EOR and $80/Ton for permanent storage.

- Financial considerations are fixed for every scenario and are shown below.

- Costs of CO_2 trunk lines are estimated at $480,000 per mile for an 8-inch line.[33]

Table 5: Financial Assumptions for CCUS Cost Curve.

Financial Factors

Tax Rate	**21%**
Discount Rate	**12%**
Project Evaluation (yr.)	**23**
Investment Depreciation	**20**
Timeline to Implement CCUS Project (yr.)	**3**
CAPEX Distribution	**Straight Line**

We further used the principles from our scenarios to adjust the CCUS cost curve to assess the deployment of CCUS under five different scenarios. We adjust the capital cost parameters according to Table 5. Further, we adjusted input costs accounting for operational and maintenance factors as follows in Table 6 based on historical costs of inputs. In our business-as-usual scenario, natural gas, coal, oil, and electricity prices are based on current market prices. For transport and storage, our estimates are based on work recently done showing low-cost areas – like Texas – have transport costs of $3.78 and storage costs of $9.40 adjusted for inflation per ton of CO_2.[34]

Table 6: Adjustments to Input Cost Parameters for CCUS Cost Curve.

	Cost of Oil (EOR)	$/kWh	$/MMBtu Natural Gas	$ tariff for storage	$ tariff for transport	$/Ton Coal
BAU	$66.00	$0.05	$3.50	$9.40	$3.78	$60.00
Scenario 2	$50.00	$0.09	$4.50	$11.00	$6.00	$75.00
Scenario 3	$70.00	$0.04	$3.00	$8.50	$3.22	$55.00
Scenario 4	$40.00	$0.12	$6.50	$15.00	$15.00	$100.00
Scenario 5	$80.00	$0.02	$2.20	$5.00	$2.50	$35.00

In addition to running an analysis given the parameters described above, we also analyze the impacts that certain policy or marketplace incentives may have on carbon removal implementation. One such policy may involve allowing low-carbon electric generators to charge a premium for providing low-carbon electricity. To model this scenario, we ran the business-as-usual scenario but increased revenue for power plants by $0.1/kWh.

We next sought to quantify the impact on the cost curve by adding additional 45Q benefits either administered by the federal government or provided through a state-funded program that would credit an additional amount for CO_2 captured in the same way that 45Q is administered. We measured the impacts of increasing 45Q by $5, $10, $15, $20, $25, and $30. The NPC study estimated that a 45Q value of $115/ton would enable a significant increase in the number of projects constructed and CO_2 captured.

In our third scenario, we sought to evaluate the impacts of certain policies that enable low-carbon power and goods to be sold at a premium. To do so, we increased the amount paid by end-use customers on their bill by $0.1/kWh for low-carbon dispatchable power. We also estimated that low-carbon fuels from refineries could be sold at a premium and $10 could be charged per ton captured. Finally, we estimated steel, concrete, and other producers of goods could charge $5 per ton captured.

2.6 Modeling DAC Economics and Expansion

There are currently no operational DAC projects within Texas. However, Occidental has announced plans to open the first DAC plant in the Permian Basin in 2024, and the largest plant worldwide, which is designed to capture more CO_2 than the 20 currently operating plants around the globe combined.[35] Accordingly, it is anticipated that a baseline level of approximately 400,000 metric tons will begin to be captured in 2024 from the Oxy DAC plant in the Permian Basin. Additionally, the company has entered into an agreement to build out additional DAC plants on over 100,000 acres on the King Ranch capable of supporting up to 20 additional DAC plants.[36]

The economics of DAC are still in question, especially for large-scale projects like those being planned in Texas as no projects of that size are currently operational. DAC falls into one of two categories, much like CCUS. DAC can utilize liquid or solid sorbents that selectively capture the CO_2 and then use heat to release the gas from the sorbent to be compressed and stored or utilized. Alternatively, CO_2 can be captured utilizing a series of membranes and subsequently released via temperature swings. As a result, estimates of costs for DAC range from \$100-\$1000/ton captured depending on circumstances, including the technology used.[37] Further, recent work suggests that of the available technologies, membrane DAC with or without utilization via EOR may be profitable now or in the near term.[38] However, commercial operations utilizing this technique have not been proven. Therefore, we assume that DAC technologies fall somewhere within the cost range estimated using a liquid sorbent-based technology by Climate Engineering, who estimated their levelized cost of capture fell within the \$107-\$249/t-CO_2 captured.[39] At those cost levels, it is anticipated that DAC may be commercially viable today with the assistance of 45Q tax credits which are set at \$120/ton and \$180/ton of CO_2 captured for EOR and sequestration, respectively. To model potential DAC expansion within our scenarios, we utilized the ReEDS model.[40] The ReEDS model is a grid capacity expansion model that is also capable of modeling the growth of technology-specific additions such as DAC and CCUS. Inputs for the ReEDS model were tailored to closely approximate those defined in our scenarios for growth as discussed in Table 4.

2.7 Modeling Nature-based Solutions

Agriculture, forestry, and anthropogenic land-use activities accounted for ~ 23% of total net anthropogenic emissions of GHGs globally (including CO_2, CH4, and N2O) from 2007–2016 (12 ± 3 Gt CO_{2_e} per yr.). Terrestrial carbon sequestration by increasing the amount and maintenance over time of organic carbon in biological stocks through changing land use practices presents a powerful opportunity to sequester carbon. Forest-focused nature-based carbon storage routes such as afforestation and reforestation have the potential to affect climate via several biophysical mechanisms (modified surface albedo, evapotranspiration, and surface roughness, as well as effects on atmospheric circulation and cloud characteristics) in addition to the effect of carbon sequestration. The IPCC suggests a mitigation potential range of 0.4–5.8 Gt CO_2 per yr. from avoided deforestation and land degradation at a global scale, as well as a carbon sequestration potential of 0.5–10.1 Gt CO_2 per yr. in vegetation and soils from afforestation/reforestation across the globe.

The balance of carbon stocks is determined by the difference between carbon inputs usually by assimilation through photosynthesis and carbon losses to the atmosphere via biological degradation or combustion. With total global terrestrial carbon stocks of ~ 600 gigatons (Gt) carbon in biomass and ~1500 Gt / ~2600 Gt of carbon in the soil to a depth of 1 m / 2m, respectively, the terrestrial ecosystem provides a massive opportunity, especially in the subsurface soil, for biological sequestration of carbon.

Separately, the National Academy of Sciences recently estimated that annual rates of coastal carbon sequestration are significant – globally, the total carbon sequestration rates are estimated at 31-34 Mt C per year for mangroves, 5-87 Mt C per year for salt marshes, and 48 – 112 Mt C per year for seagrass beds – summing up to a global annual rate of 0.84 Gt CO_2 per year. Issues associated with the terrestrial carbon sinks include the potential impermanence of these storage sites as well as the potential for feedback from climate change that could result in the erosion of these stored sites through floods and removal of soil as well as fire-induced loss of biomass.

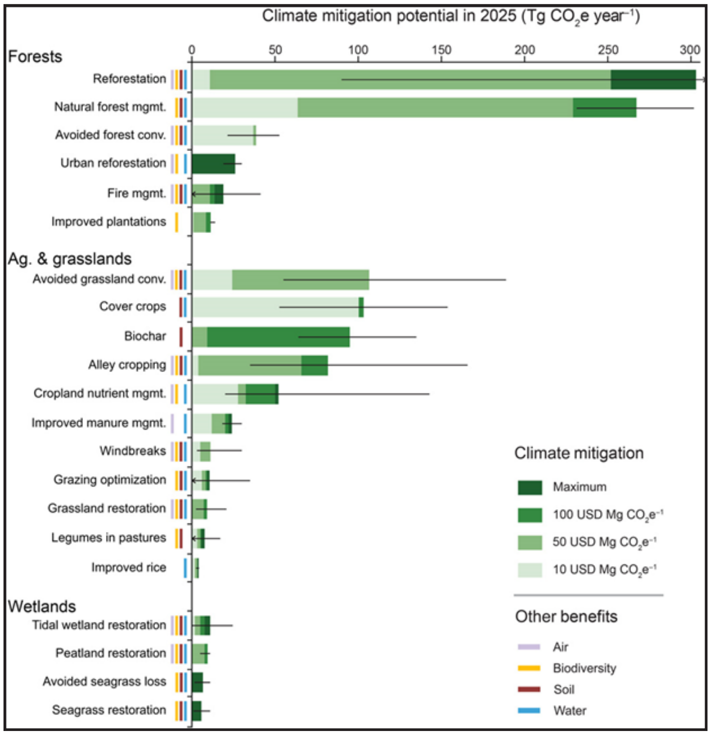


Figure 12: Climate mitigation potential of 21 NCS in the United States. Black lines indicate the 95% CI or reported range. Ecosystem service benefits linked with each NCS are indicated by colored bars for air (filtration), biodiversity (habitat protection or restoration), soil (enrichment), and water (filtration and flood control). Source: Natural climate solutions for the United States | Science Advances.

To assess the potential role that nature-based solutions might play in carbon sequestration in Texas, we focused in large part on agriculture. However, methods such as enhanced rock weathering, creation and utilization of biochar, algae farming, and other techniques and technologies will undoubtedly play a role in sequestering carbon in the future. Within agriculture, one of the largest opportunities for sequestering carbon is through changes in grazing practices. Previous research has suggested that 0.11-2.53 additional tons of CO_2 can be sequestered per acre by implementing multi-paddock grazing practices in Texas.[41] The mean sequestration potential is 1.32 tons per acre. According to the 2017 Census of Agriculture, nearly 88 million acres in Texas are used as permanent pasture and rangeland.[42]

Chapter 3: Results

The results of our modeling suggest that a robust carbon sequestration industry in Texas is possible. We estimate that in the near term, several plants present profitable opportunities for the commercialization of CCUS. Further, we estimate that DAC in Texas can play a leading role in reducing atmospheric CO_2 and that land use practices can likewise contribute significant decreases.

3.1 Texas CCUS Cost Curve

The results from the cost curve model are illustrated in Figure 13. It projects the cost per ton CO_2eq for each of the point source emitters assessed. Each bar on the figure represents a single-point source and presents data for more than 700 plants.

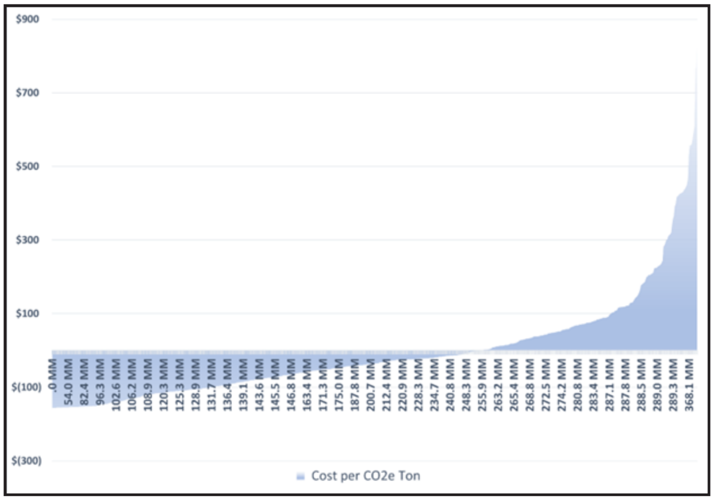


Figure 13: Business as Usual Texas CCUS Cost Curve.

Under our BAU scenario, we estimate that 255.8 MMT/CO_2eq can be captured without costs to the emitter given the current levels of 45Q, capital costs, and input costs. This represents 62.81% of emissions analyzed in the state and 459 projects. While these projects may be economically feasible now, obstacles such as access to larger transport pipelines, storage fields, storage permitting, labor, and capital may all mean that the level of projects possible today is built over a 10-to-15-year time horizon.

The results of all five baseline scenarios are shown in Table 7 The results show that given current policy, a considerable number of CCUS projects are economically viable in Texas today resulting in the company breaking even on the project. Given higher capital costs and input costs in Scenario 4, the outcomes will be worse than BAU with approximately 35% of emissions captured. With favorable capital and input costs in Scenario 5, more than 65% of emissions can be captured.

Table 7: Results of Defined Scenarios Impacting Capital and Input Costs.

	BAU	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Emissions Captured below $0/ton (MMT CO_2eq)	255.8	232.6	262.9	143.3	265.9
Percent of Emissions Analyzed (%)	62.81	57.10	64.56	35.19	65.27
Number of Projects	459	406	472	252	502

3.2 Increasing 45Q

We next sought to quantify the impact on the cost curve from doubling 45Q benefits. To do this we increased the 45Q credit by increments of $5. For example, point source storage amounts were increased from $85 to $115 in $5 increments. Figure 14 demonstrates the impact of increasing 45Q by $5, or to $65 for utilization and $90 for storage. Doing so results in 263.2 MMT/CO_2eq captured without costs to the emitter. This represents 64.61% of emissions analyzed in the state and 481 projects. The results of all incremental increases are shown in Table 8.

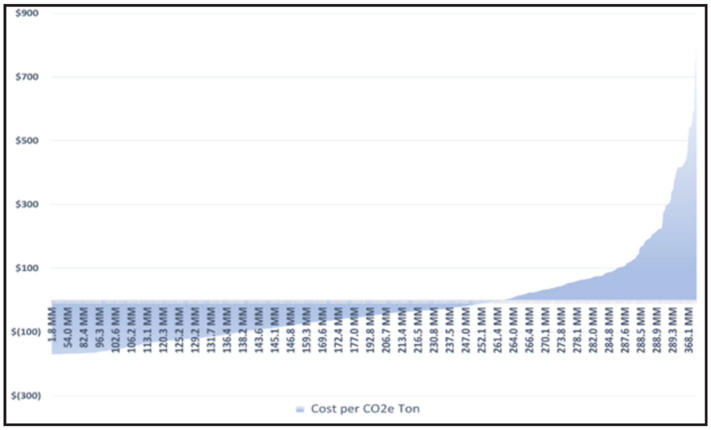


Figure 14: Texas Cost Curve With $5 Increase to 45Q.

Table 8: Results of Defined Scenarios with an Increase to 45Q.

	BAU	$5	$10	$15	$20	$25	$30
Emissions Captured below $0/ton (MMT$CO_2$eq)	255.8	263.2	264.2	265.4	267.0	267.3	268.0
Percent of Emissions Analyzed (%)	62.81	64.61	64.86	65.15	65.55	65.62	65.79
Number of Projects	459	481	497	514	529	537	547

3.3 Results of Increasing Revenue from Low-Carbon Products for Companies Using CCUS

In addition to increasing 45Q, we assessed the impacts of increasing the price of low-carbon goods. To do so, we modeled low-carbon electricity selling at a premium of $0.1 kWh and goods from the low-carbon industry selling at a $10 premium. The results are shown in Figure 15. The results show incremental increases over the BAU scenario to 256.1 MMT/CO_2eq representing 62.87% of emissions.

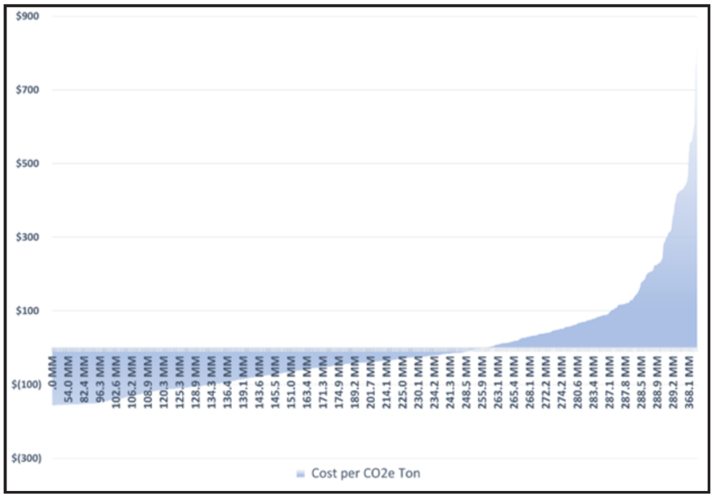


Figure 15: CCUS Cost Curve with Increased Revenue for Low Carbon Products.

3.4 Decreasing Transportation and Storage Costs

We further sought to analyze the impacts of reduced costs of transport and storage. This might occur through state investment into transportation and storage to move the CO_2 from emissions sources to where they need to be. To do this, we reduced transportation costs by decreasing the tariff rate to $2 per ton and reduced the trunk line capital costs by 50%. We similarly reduced storage costs to $3 per ton. The results are shown in Figure 16. The results show incremental increases over the BAU scenario to 269.3 MMT/CO_2eq representing 66.12% of emissions.

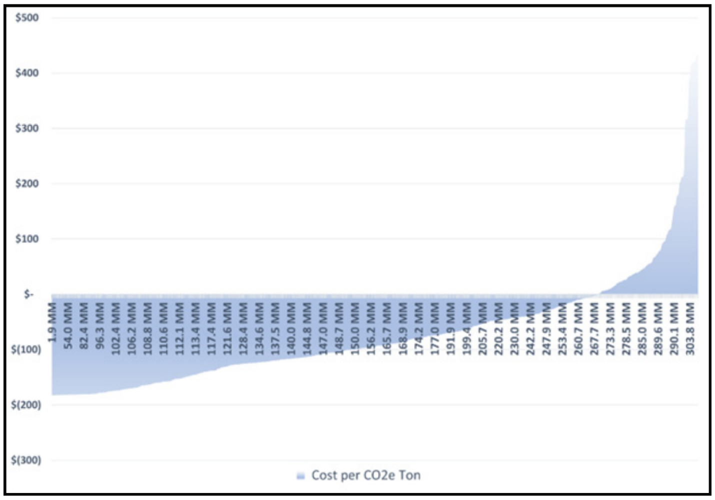


Figure 16: Reduced Transportation and Storage Costs.

3.5 Results of DAC Modeling

To model the impact that DAC might have on the Texas grid, we used the ReEDS model produced by NETL. We ran five scenarios meant to reflect our five defined scenarios outlined in this paper. In each of the alternative scenarios, DAC was modeled to play a significant role in Texas, specifically for the ERCOT grid. Table 9 shows the anticipated TWh used for DAC by 2050 with the corresponding tons captured using a range of 5.6 GJ to 10 GJ per ton captured.

Table 9: Results of ReEDS Model Projecting DAC.

	TWh Consumed for DAC	Tons of CO_2 Captured at 5.6 GJ/T	Tons of CO_2 Captured at 10 GJ/T
BAU	-	-	-
Scenario 2	26.94	17,318,571	9,698,400
Scenario 3	38.94	25,032,857	14,018,400
Scenario 4	51.18	32,901,428	18,424,800
Scenario 5	24.80	15,942,857	8,928,000

In each of these scenarios, the ReEDS model also models for the required capacity additions needed to accommodate the increased load required to operate DAC plants. The values vary depending on the generation mix of the grid and how much each mix is anticipated to be available. For example, if the grid contains more natural gas generators with CCUS, fewer GW of capacity would have to be built than if the grid is comprised mostly of renewables operating variably which would not always be available. For Scenario 2, it is estimated that 5.48 GW of additional capacity would be needed. Scenario 3 would require 6.64 GW of additional capacity. Scenario 4 requires 6.49 GW of additional capacity. Finally, Scenario 5 would require 3.96 GW of additional capacity. Also of note, only Scenario 3 at 5.6 GJ/T of CO_2 captured falls within the range of expected outcomes as defined in our expected growth scenarios.

3.6 Results of Nature-based Solutions

We began by assuming that at least half of the 88 million acres of land used for grazing and pasture could be transitioned to multi-paddock grazing. Using the estimates in the literature of increased carbon storage from this practice, an estimated 58 million additional tons of CO_2 could be stored annually. Similarly, there are 8.7 million acres of Texas cropland that utilize intensive tillage practices.[44] Studies have shown that in the first 20 years of switching from tilling to no-till, soil organic carbon – or carbon sequestered in the soils – can increase from 0.11 to 0.22 additional tons of carbon per acre per year.[45] While carbon storage in soils is heavily dependent on the crops raised, the types of soils, and climate factors such as precipitation, we assume the value per acre to be the mean value of 0.16 tons of CO_2 per acre. Using this assumption, we estimate that switching to no-till practices on acres currently being heavily tilled could store an additional 1.4 million tons of CO_2 annually in the state.

Chapter 4: Policy Implications

The results from our analysis show with CCUS, DAC, and changes to agriculture practices, an estimated 212 to 362 million tons of CO_2 can be sequestered annually in Texas. The results from the CCUS model show that hundreds of projects are commercially viable today, given the updated 45Q incentives. Our analysis of DAC shows that DAC may continue to grow in Texas, but not as much as nature-based solutions or CCUS. Nature-based solutions show great promise for what is the lowest-cost alternative and present an opportunity to grow carbon markets for nature-based carbon sequestration. Our analysis further shows that the number of commercially viable CCUS projects and subsequently the amount of CO_2 that can be captured via CCUS technologies increases significantly with additional 45Q benefits and reduced transportation and storage costs. However, for CCUS, DAC, and nature-based solutions to play a significant role in decarbonizing the economy, a favorable policy environment must be in place.

4.1. Policy Implications for CCUS and DAC

Our analysis suggests that significant reductions in annual emissions can be achieved today by implementing CCUS on commercially viable projects. Those projects can break even or possibly profit from the existing 45Q incentives that exist. Our analysis also suggests that over the next two decades, DAC will play a smaller, but key role in decarbonizing Texas. However, our analysis also suggests that state or federal incentives can significantly increase the number of commercially viable CCUS projects and the same holds true for DAC given that the cost of many DAC projects may still be above the 45Q levels.

The most impactful policy change analyzed for CCUS suggests that meaningfully decreasing transportation and storage costs may result in 14 million additional tons of CO_2 being captured annually. Our analysis similarly suggests that supplying $5 in additional 45Q type credits, either through the state or federal government may have significant impacts. Interestingly, the magnitude of the increase in tons captured with a $5 increase in credits is not seen with corresponding increases, meaning this is the most effective increase of our analysis. Additionally, it is anticipated that efficiency in planning projects, efficiencies gained from building additional projects, and improvements in technology will bring down the costs of CCUS. While these same policy changes were not analyzed in a DAC-specific cost curve, we assume that increasing 45Q credits may significantly assist DAC projects. However, because DAC projects are more flexible in locating plants, transport costs may be less impactful in incentivizing DAC, but storage costs, especially those associated with permitting, characterizing, and drilling storage wells may significantly impact DAC projects and therefore we anticipate reducing storage costs or reducing capture thresholds may also have substantial impacts for DAC.

To meaningfully impact the costs of transportation and storage, the state might implement policy changes that mirror the incentives provided to the wind industry in the late 1990s and early 2000s. Such a policy might include state-funded transportation and planning. This is not unprecedented in Texas history. Texas has previously taken legislative action to incentivize renewable projects through the buildout of transmission from Competitive Renewable Energy Zones (CREZs) in the wind-rich Panhandle and West Texas to population centers in East Texas. Legislation mandating the construction of the lines was passed in 2005. Completion of the CREZ lines cost approximately $6.9 billion. Like the legislation enabling the CREZ projects, the state could invest in transportation pipelines to move CO_2 for the public good. This CO_2 can be permanently stored, helping to reduce global warming and it can be utilized to support important Texas industries – including EOR, cement production, and others. Additionally, state-owned storage sites might reduce the costs of storage and help to address public concerns regarding long-term liability. Payments from those seeking to utilize the storage reservoirs would go first to pay the capital, operational and maintenance expenses of storage and then towards insuring against potential leaks. Alternatively, tax breaks in the form of credits specifically for transporters and storage operators might help to offset the costs enough to have a similar effect as state-owned infrastructure.

Texas might also incentivize CCUS by allowing power generators to charge a premium for providing low-carbon electricity. Such a premium may be allowable if the Texas renewable portfolio standard were revitalized and amended so that low-carbon electricity from generators with CCUS could qualify as generators able to sell credits to meet the standard. Alternatively, the state could consider implementing a low-carbon baseload portfolio standard. Such a standard would operate similarly to a renewable portfolio standard but only non-variable generators like nuclear, gas, and coal could qualify to provide the power to meet the standard. Such a standard could help address carbon emissions from the power sector while at the same time may aid in addressing concerns within the state about whether the state has enough baseload power to meet rising energy demands. While this analysis specifically looked at how such a mechanism could impact CCUS projects, such a mechanism could be applied to any number of new low-carbon baseload technologies like utilizing hydrogen for power generation, new small modular nuclear reactors, and others which might supply reliable baseload power.

Alternatively, Texas could pass a low carbon portfolio standard. Wyoming recently implemented a low-carbon electricity standard which is meant to incentivize the use of CCUS. While a low-carbon electricity standard does not need to be limited to incentivizing CCUS, such standards are garnering attention as reliability concerns have arisen in the power industry following natural disasters like Winter Storm Uri in February 2021, and populations are becoming increasingly aware of the need for diversity in power generation sources.

The same type of policy can also create market incentives for low-carbon synthetic fuels and low-carbon incentives to produce aggregate. Such marketplaces have been incentivized before. The California low carbon fuel standards have incentivized investment in reducing carbon emissions in fuel production. Today, companies are seeking to utilize captured CO_2 from CCUS and DAC projects to synthesize low-carbon fuels, and allowing a premium for these fuels through a credit mechanism like California's might further incentivize innovation in this space.

If Texas chooses to heavily incentivize CCUS and DAC through the above-mentioned mechanisms, the state will also need to consider how to meet the energy demands of CCUS and DAC projects. As mentioned, CCUS and DAC each require lots of energy to separate, compress, and transport CO_2. Estimates for CCUS on coal and natural gas-fired plants suggest the CCUS plant may require 25-33% of the power produced at the plant to operate. Our models also suggest that by 2050 DAC may consume 6.5 GW of energy – or over 8% of the peak demand on the ERCOT grid historically. To meet this demand through solar for instance would take an estimated 65,000 acres of new solar panels – and even then, additional build-out of storage, wind, or other low-carbon resources would be needed for when solar is not available.[47]

This demand is incredible and will require careful planning and additional generation. More pointedly, if these plants are to meaningfully reduce carbon emissions, more low-carbon generators will need to be built to meet the demand Texas already has for electricity and to meet the growing demand of these projects. Orderly planning of this increased need for generators would be wise and should be started now so that the state can understand the land requirements.

4.2. Implications for Nature-based Solutions

Our analysis suggests that nature-based solutions in agriculture have significant potential to reduce atmospheric CO_2. However, it is also clear from the literature, that more work needs to be done in this space to fully characterize the potential of different soils under different conditions. Accordingly, a first policy step may be to fund additional research into nature-based solutions. The General Land Office manages 13 million acres and the submerged lands out to 10.3 miles from the Coast.[48] These lands offer a prime opportunity to add carbon sequestration projects within the multiple uses currently taking place on that land.

Additionally, market-based incentives are needed to incentivize nature-based solutions. While voluntary carbon markets already exist, there have been concerns about the efficacy of these markets and the amount of carbon being stored. State-funded research into the various methods of nature-based solutions can help to inform uniform methods for measuring and accounting for carbon storage and may even be an area where the state might set up a centralized marketplace for brokers, landowners, and purchasers to interact based on that research. Carbon offsets today are typically verified via one of three mechanisms:

- Voluntary carbon registries, such as the Verified Carbon Standard or Gold Standard.

- National or regional carbon offset schemes, such as California's offset program or Australia's Emissions Reduction Fund.

- International crediting mechanisms. such as the Clean Development Mechanism (CDM).

However, concerns persist and there is space in the marketplace for Texas to help refine and reform verification methods. Particularly because carbon sequestration via nature-based solutions is often heavily dependent on geographical variations in soils, climate, and land use practices. Having Texas-specific verification standards could therefore go a long way in incentivizing and growing the nature-based carbon market in Texas, adding revenue to Texas landowners and the state.

In sum, Texas has an unmatched opportunity to lead not only the country but the world in carbon removal. However, there are current hurdles that may hinder broad industry enthusiasm and investment in Texas if not resolved. State primacy is one such hurdle that will hopefully be resolved soon. However, as our analysis shows, additional state incentives, like those seen in Wyoming, could certainly go a long way in increasing the number of projects, investments, and jobs in this growing industry. Further, clear guidelines on carbon markets for CCUS, DAC, and nature-based solutions could similarly fuel investment and protect buyers by ensuring that their investment in carbon offsets or credits is durable and permanent. By carefully thinking and planning carbon capture, storage, and utilization hubs along with planning for the infrastructure associated with both CCUS and DAC, Texas can lead the world in this emerging industry and reach net-zero in the industrial and power generation sectors by 2050.

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