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CCUS Infrastructure

Preparing for the Future of Houston

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McConnell previously served as vice president of carbon management at Battelle Energy Technology in Columbus, Ohio, and with Praxair, Inc., where he was global vice president of energy and hydrogen. He is currently a board member of the Energy & Environmental Research Center (EERC) Foundation in North Dakota, a member of the National Coal Council, and has held a number of board positions for the Gasification & Syngas Technologies Council and the Clean Carbon Technology Foundation of Texas. He earned a bachelor's degree in chemical engineering from Carnegie Mellon University (1977) and an MBA in finance from Cleveland State University (1984).

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The University of Houston thanks the Houston CCS Alliance, the Greater Houston Partnership, and the Houston Energy Transition Initiative for commissioning this study. We are grateful for the input of the broader CCUS ecosystem and stakeholders, as well as the companies and organizations who worked to develop a shared vision for Houston's infrastructure assets and opportunities to deploy CCUS at scale. The authors of this report would especially like to thank the following organizations and their members:

Houston CCS Alliance
The Houston CCS Alliance was formed to advance one of the most significant carbon capture and storage opportunities in the world. The companies that are a part of this effort believe now is the time for ambitious collaboration among industry, non-governmental organizations, academia, and local communities to significantly reduce carbon dioxide and other greenhouse gas emissions while simultaneously meeting America's growing energy and industrial needs. The Alliance unites the city's respected industrial community with diverse organizations, community leaders, and residents in Houston and Southeast Texas who share a vision to advance carbon capture technology and secure a lower emissions future.

Houston Energy Transition Initiative
The Houston Energy Transition Initiative (HETI) is a strategic initiative led by the Greater Houston Partnership, the principal business association for the 12-county Greater Houston region. HETI works alongside and on behalf of its industry members, academia, nongovernmental organizations, and community stakeholders to strengthen Houston's leadership as the energy capital of the world.And finally, this document is the result of a three-month research effort by graduate students at the University of Houston. I extend my personal appreciation for the collaboration with research associates **Gautam Kakati** and **Zhiyuan Li**, without whom this paper could not have been completed. Their work has been not only tireless but professional.

Executive Summary

Carbon capture, utilization, and storage, known as CCUS, is increasingly recognized as one key to the energy transition, allowing the United States, and the world, to lower climate-changing carbon dioxide emissions while continuing to provide an energy-hungry world with the electricity, fuels, and other sources of energy it demands. The eight-county Houston Gulf Coast region is at the center of efforts to launch CCUS at commercial scale, taking advantage of the region's enormous volume of industrial emissions – estimated at between 90 and 110 million metric tons annually – as well as existing carbon dioxide (CO_2) pipelines and right of way access options, as well as nearby geologic formations suited to CO_2 sequestration that are unmatched globally in terms of potential capacity both onshore and offshore.

Interest is high, with six announced projects anticipated to come onstream over the next decade. Business development is currently very active, and marketplace enthusiasm is high for making these initial projects a reality.

If CCUS cannot advance as a commercially viable operation in this region, which reaches from Freeport to Beaumont, it will be hard pressed to do so elsewhere. However, more will be required beyond investments in these early projects. The infrastructure – a category which includes pipelines, storage, electricity, and water – needed for these initial projects, and especially for future projects is a critical piece, which has not previously been assessed and analyzed in detail.

CCUS has been recognized as one necessary component of achieving climate targets by a number of notable organizations, including the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC), and the U.S. Energy Information Administration (EIA). Beyond the direct reduction in carbon emissions, CCUS and the required infrastructure can also provide a foundation for other key steps toward the future clean-energy economy, including hydrogen, a lower-carbon petrochemicals circular economy, and a decarbonized electric power grid.

This recognition of the importance of CCUS, and even the growing number of announced projects signaling industry interest, are just the first step. Getting there will not be easy and will require both significant private investment and conscious market changes, driven by both government and industry to ensure the advance of CCUS from its current status as a largely government-funded set of institutionalized research projects to a serious commercial player in the energy transition. We do not have the luxury of unlimited time – if we fail to meet our goals for the first decade, reaching any significant aspirational targets for emissions reduction by 2050 will become much harder, if not impossible. Every month that passes without measurable progress puts us further behind.

Our previous white paper, CCUS – Lynchpin for the Energy Transition, addressed CCUS-specific investment economics in a scenarios-based set of analyses and outlined a 20-year cashflow set of investment returns in the Greater Houston area. We did not consider the necessary accompanying investment in infrastructure. This paper does that.

Investment in infrastructure goes beyond hardware and equipment. It also involves business development, including technical, commercial, legal, and policy issues, all of which must be addressed if the nascent CCUS industry is to become a successful regional entity. It will require not just new projects coming online, but strategic thinking about how to integrate those new projects into a cohesive whole. The region has a number of small regional industrial clusters and a strong cadre of major companies with both the ability and the will to advance CCUS. This analysis is intended to provide a framework for that strategic path forward to enable the integration of those clusters into a functioning regional CCUS hub for decarbonization.

The Houston region is considered the energy capital of the world, and the U.S. and the world will continue to demand the energy produced here. Increasingly, however, there will also be a market for lower-carbon products. If Houston is to remain the energy capital, it must expand its focus to lead not just in energy production and conversion, but also the energy transition. As one part of that, the region must lead in making CCUS a viable commercial enterprise, building on our current advantages and ensuring we can meet future challenges:

- The Denbury Green Line CO_2 pipeline carries about 16 million metric tons per annum (MMTPA) for enhanced oil recovery (EOR), and ranges from 20%-30% of its capacity at any given time. Future projects will require both leveraging existing CO_2 pipeline capacity and building new pipelines.

- The eight-county region is a net importer of electricity. Power-intensive CCUS operations will require strategic planning to ensure we are able to increase available generation and transmission to provide the resilient and reliable 24/7 electricity this expansion will demand.

- Existing facilities are adequate to meet water supply and treatment needs for current operations, but aggressive expansion of water supplies, potentially including new desalination plants, will be required for future growth.

- Five onshore CCUS projects have been announced for the Gulf Coast region, as well as an offshore geologic storage repository. The onshore projects are expected to come online by 2030. Final investment decisions will require a deep understanding of the risks and economics, as well as of the adequacy of infrastructure to support long-term investment.

• Current onshore storage capacity is adequate to meet initial needs, but high growth will require the future utilization of offshore storage, as well. The long-term effectiveness of storage will require the aggregation of captured emissions at storage sites that are able to handle large, long-term volumes from multiple capture projects.

• The region's energy workforce is strong and skilled, but fast expansion of CCUS operations will raise questions about whether we can provide the necessary human capital in terms of both capability and capacity. Additional questions about the supply chain's ability to support the new investments must be answered.

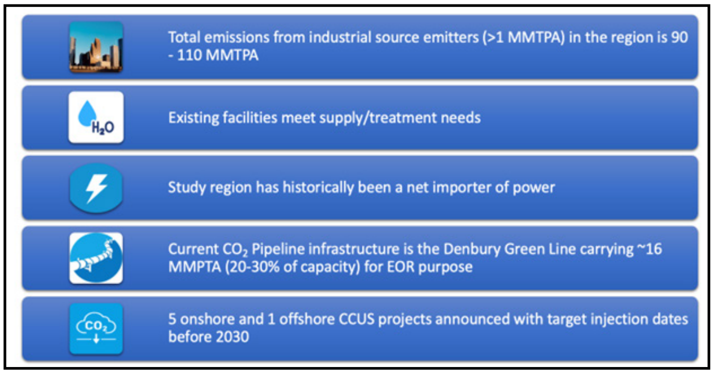

Figure 1. Current CCUS enabling attributes in the Greater Houston region

This status analysis is supported by data from the Greater Houston Partnership (GHP), the Electric Reliability Council of Texas (ERCOT), industry and state geologic survey data, and municipal water supply projections. Our analysis also incorporated the fact that the region's population is growing, and that CCUS will be just one focus for investment in the energy transition. Hydrogen, liquified natural gas, and decarbonized electricity and industries will also play large roles in the future, shaping the scope of our study and this paper.

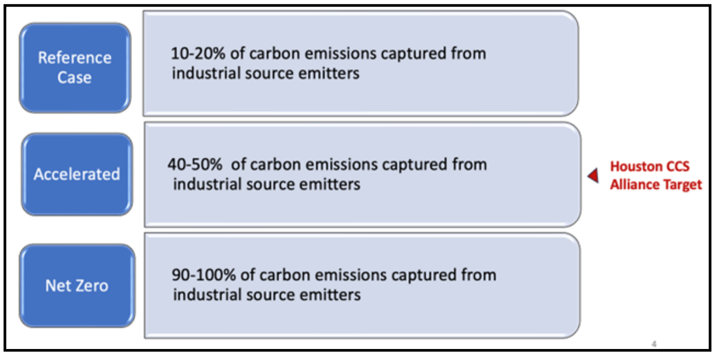

Figure 2. Scenario Framework for CO2 capture by 2050

To determine future needs for the infrastructure, workforce, and supply chain investment needed for CCUS development, we developed three scenarios, based on different emission reduction targets for 2050: capturing 10% to 20% of industrial carbon emissions; capturing 40% to 50% of industrial emissions; and capturing 90% to 100% of industrial emissions. For each scenario, we then determined what will be required to achieve that goal at three stages – between 2023 and 2030, between 2031 and 2040, and between 2041 and 2050. We did not choose a "most probable" case but instead focused on true scenario planning. For each scenario, we considered the four infrastructure areas – pipelines, storage, water, and electricity – along with workforce and supply chain impacts. In addition, we looked at the risks, consequences (including potential unintended consequences), and the reality of what must happen quickly for development to grow sustainably over the longer term.

This work yielded key observations about each of the major infrastructure areas, as well as the steps that must be taken to reach the necessary ends – what will it take to realize the full promise of CCUS, and how will the workforce and supply chain be mobilized to support those steps? Upskilling and reskilling of workers will be required in all but the lowest capture scenario, for example, suggesting a need to work with both education institutions and employers to ensure retraining is available. Similarly, steps must be taken to ensure high-need equipment, ranging from pumps and compressors to steel pipes, is available not just for CCUS projects but also for other clean-energy projects expected to come online in coming years.

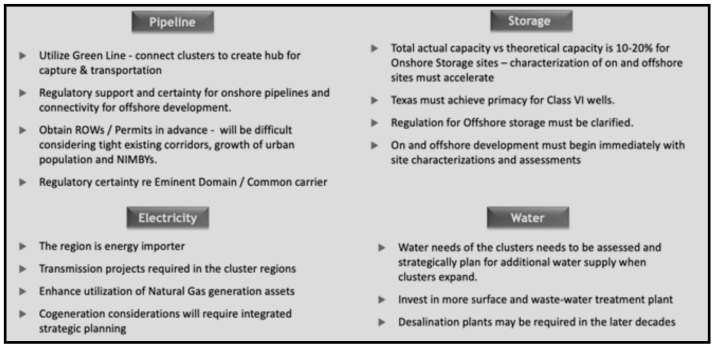

Figure 3. Pathway enablers for CCUS adoption

Among our findings for each infrastructure area:

Pipelines
• The Denbury Green Line (now part of the recently completed ExxonMobil acquisition) should be leveraged to connect the initial clusters of emission sources, creating hubs for capture and transportation. Multiple pipelines will be required in any build out scenario.

• Regulatory certainty is critical for common carriers and eminent domain. This certainty extends to right of way acquisition, construction permitting, and the associated community engagement processes to ensure a successful outcome for the community and for the project investors.

• Additionally, regulations must support and provide certainty for onshore pipelines and connectivity for offshore storage.

• Permitting and right-of-way will be complicated by urban population growth, tight existing corridors, and pockets of "not-in-my-backyard" or NIMBY sentiment. This will drive optionality for routing and the optimization of schedule and cost for investment.

Storage
• Characterization of offshore and onshore storage sites must be accelerated to accurately assess the permeability and porosity of the geology and to assure adequate long-term capacity.

• Texas must achieve EPA-approved primary enforcement authority (primacy) for Class VI wells.

• Regulation for offshore storage must be clarified.

• Onshore and offshore characterization and development must begin immediately in any expansion scenario. Optionality will be critical and will require multiple site development that can yield the most effective solutions. Aggregated captured CO_2 delivered to sites that can accept multiple capture streams will be a desired outcome.

Water
• Water needs for each emission cluster must be assessed to allow for long-term planning as the clusters grow. Large facilities serving multiple clusters in the hub will likely not be the most feasible solution given the planning and investment sequencing of local authorities. Cluster investments will grow to serve local municipalities.

• Investments must be made in surface water and wastewater treatment plants to ensure adequate availability. New surface water reservoirs would be required by the mid-2030s under the mid-capture scenario.

• Caution will be required removing subsurface water as subsidence issues in the region can present challenges. Planning and strategic assessments will be necessary to anticipate required growth.

• Desalination plants may be needed in future decades. Individual industry sites can become effective desalinization investments to serve large-scale capture as well as large-scale cogeneration electricity and steam needs for CO_2 capture.

Electricity
• Transmission projects will be required at emission clusters. Regulatory and permitting assurances must precede large investments and electricity demands.

• Utilization of natural gas generation plants' existing capacity should be increased, with additional natural gas plants added to the grid by the mid-2030s if we are to achieve accelerated capture targets.

• Regulatory support for baseload 24/7 electricity supply investments in generation and storage will be required, including market incentives on the ERCOT grid to encourage natural gas baseload generation in order to take advantage of increased capacity and ensure the around-the-clock reliability required for CCUS.

• Cogeneration facilities may be needed by 2040 under the mid-capture scenario.

This paper then uses each of the time horizons as outlined and produces a series of key findings for each time horizon at the conclusion of each section. The impacts of investing, positioning, market maturity, and regulatory and policy support will greatly affect the next decade, as these developments will take time and test the will of the investors.

The findings and pathways outlined here are not designed to choose what investments the region or companies should make. Our objective is to detail the complexities, trade-offs, and risks, and the consequences both intended and unintended. These are choices, but they are not the only choices. However, choosing to not pursue infrastructure expansions and other actions now will have consequences for what we are able to achieve or even aspire to later. Each scenario has choices built into the pathway, determining actions for investment but also for positioning for the next 10-year horizon.

Many of these choices are individual company and investor decisions. Others will require action on the part of regional and state leaders as they determine the importance of the CCUS industry. The stakes are high – jobs, revenues and tax base, technology leadership, and the ability to create a long-term construct that would allow Texas to continue as the energy center of the U.S. and the world. CCUS can be a platform for the state to advance game-changing economic activity over the next 25 years. We can proceed with caution or with enthusiasm, but we must be guided by a full understanding of the landscape. That understanding is what we bring to this analysis.

The Houston Gulf Coast region starts the CCUS race with tremendous advantages, from the clustering of emission sources to existing infrastructure and suitable geology. We are home to companies that are eager to enter the field, and our technical workforce is capable of making the transition.

Industry has shown it is willing to lead on these issues, and it must do more, including increasing capital investment. But industry can't operate in a vacuum, and it won't operate indefinitely without a reasonable return on investment. A strong market structure – including regulatory changes, the assurance that federal tax incentives will remain in place, and new state incentives – is not yet in place to enable rapid commercial investment and deployment of CCUS. There isn't time to wait around; if we are to make a meaningful dent in rising carbon emissions and meet the net-zero goals that have been set by governments and industry alike, we must jumpstart carbon capture, utilization, and storage at scale, as it underlies other components of the energy transition.

It will be a difficult needle to thread, and our hope is that this paper will inform the debate and a strategic approach from industry, from the regional marketplace, and from the state and federal policy makers.

Introduction

Amid growing concern about the impact of climate-changing carbon emissions – spurred by record heat, drought, wildfires, and deadly storms – efforts to reduce emissions using carbon capture, utilization, and storage (CCUS) are gaining traction. Houston and the Texas Gulf Coast are positioned to play a leading role, capitalizing on the growing interest in CCUS technologies and the region's natural advantages, including emissions-producing industrial facilities, a corporate base that is interested in solving the problem, and a workforce with transferrable skills. The region is in a strong position for the future.

But the real work begins now. Key to creating a successful industry around CCUS, the supporting infrastructure must be designed and built out, including pipelines, storage sites, and projects to ensure adequate supplies of electricity and water. That won't happen on its own, and incremental growth won't be enough to support CCUS at the levels we will need to be successful. Projects must be developed with significant forethought and collaborative planning, as each piece will affect the next.

In the following pages, we offer a detailed look at how to get there, broken down by decade between now and 2050. The choices are different, depending on how aggressively we choose to target emissions. The least ambitious target won't reduce CO_2 levels enough to make a serious dent in efforts to mitigate the impacts of greenhouse gas emissions. The most ambitious, which offers the promise of decarbonizing the industries that are synonymous with the Gulf Coast while capturing 100 percent of industrial emissions by 2050, demands dramatic action, starting within the next few years.

The First Decade (2023 to 2030)

Decisions made over the next seven years will be critical to position the region for the following two decades. Important investment and regulatory milestones – especially in the pipeline and storage segments – will determine the pace and effectiveness of CCUS adoption across the region. Action in the electricity and water segments will also be decisive in future positioning because while current capacity is sufficient for initial projects, longer-term expansion will require investment.

For companies aspiring to reach mid-level and Net Zero emission targets – capturing between 40% and 50% of industrial emissions, or between 90% and 100% of industrial emissions – the next seven years will prove especially consequential for beginning the infrastructure development needed to achieve those goals by 2050. Maintaining this momentum will require a full understanding of the future infrastructure landscape, and decisions to move forward or delay will shape the future possibilities.

Adding to the challenge, the choices will not be made in a linear manner but often will require simultaneous advancement across multiple fronts. Conventional methods of decision-making will be challenged.

Infrastructure investment today is often considered to be already in place, and project economics incorporate only incremental variable costs to access existing infrastructure. The most effective means of infrastructure expansion will be for projects to collectively share and utilize access, yet there may not be a clearly shared vision by all parties as to the pace or need for CCUS deployment in the region. This dynamic may be the most challenging to address.

Industry groups such as the Houston CCS Alliance and the Greater Houston Partnership's Houston Energy Transition Initiative (HETI) collectively support the advancement of CCUS in the region, but we cannot assume all individual companies and other entities that support the expansion of CCUS will employ uniform strategies. Supportive policies and legislative support at the local and state level will be required, as will the necessary permitting and economic policy support. The commercial uncertainty of such policies and potential changes are producing headwinds for investment, and while companies currently are investing strongly in developing CCUS projects, commercial certainty remains a challenging target. In this paper we will call out the needs and the required pace, but we cannot assign investment or first movers in the marketplace, as that will be tactically unveiled with project and investment needs.

Building a Hub for Capture and Storage

Two main categories of industrial source emitters were chosen for the study: hydrogen facilities that will utilize natural gas as a feedstock, and other industrial source emitters with CO_2 emissions greater than one million metric tons per year (MMTPA). These segments were chosen as the most economically feasible to jumpstart capture investments, with the site locations serving as a set of base cluster areas that over time could be connected to create a synergized hub for capture and storage. This strategy would require industry and cluster locations to collectively plan and execute in order to maximize infrastructure investment in all four of our areas of study.

According to the U.S. Environmental Protection Agency's Facility Level Information on Greenhouse gases Tool (FLIGHT)[1], there are 12 hydrogen facilities and 34 other industrial source emitters with CO_2 emissions greater than 1 MMTPA in our study area (Beaumont to Freeport). Total emissions from these 46 facilities are approximately

[1] https://ghgdata.epa.gov/ghgp/main.do?site_preference=normal

90 to 110 MMTPA. These source emitters are grouped into six clusters: 1) Baytown-Pasadena, 2) Beaumont-Port Arthur, 3) Freeport, 4) Texas City, 5) Sweeney, and 6) Thompson (the W.A. Parish Plant). The Denbury Green Pipeline running across the region is approximately 90 miles long and currently carries 16 MMTPA of CO2, which is about 25% of pipeline capacity[2]. CO_2 is supplied from this line and used for enhanced oil recovery (EOR) at oil fields in Hastings, Webster, and Oyster Bayou. A detailed map of these existing facilities is shown in Figure 4 below.

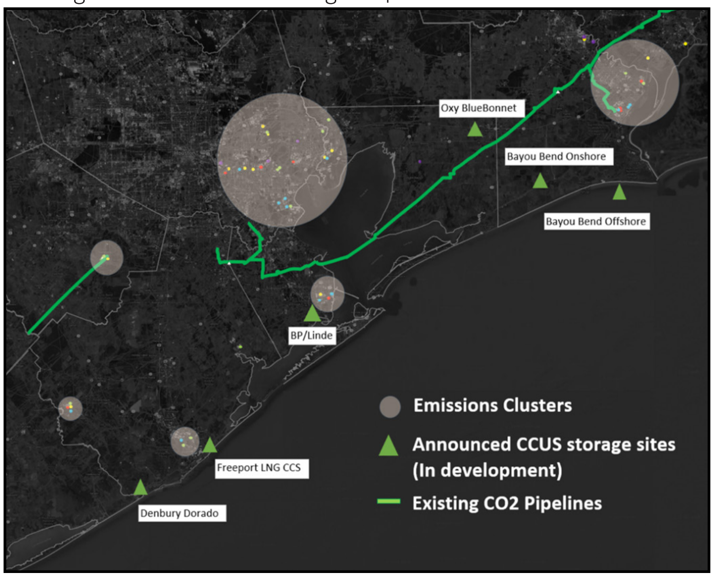

Figure 4. Industrial emitters and existing infrastructure map.

For this study, three scenarios were developed: Reference case (10%-20% of regional industrial CO_2 emissions captured), Accelerated case (40%-50 % CO_2 captured), and the Net Zero case (90%-100 % CO_2 captured). We then organized the efforts necessary within each scenario and applied the analysis for each of the next three decades – 2023-2030, 2031-2040, and 2041-2050.

In the Reference case, between 5 and 10 MMTPA of CO_2 is expected to be captured and sequestered in the 2023-2030 time period, with six announced projects anticipated to come online before 2030. That will require specific actions, including retrofitting capture technologies at the source emitters, acquiring right-of-way (ROW) and permits for pipeline projects, building pipelines to connect the emitters and storage sites, well characterization at proposed sequestration sites, and obtaining Class VI permits to allow actual sequestration. Executing these projects will be unprecedented and require enormous skills, capabilities, and capacity to build and operate. As a datapoint, the Decatur CCS project in Illinois is the only active pure storage project in United States, injecting around 1 MMTPA into a single well. The National Petroleum Council (NPC) forecasts that total industrial source emissions for the Gulf Coast region is expected to grow to approximately 225 MMTPA by 2050, more than double current levels.

Assuming a range approximating 1+MMTPA CO_2 capture per project, we extrapolated the forecast for the other scenarios and the following two decades. The chart below illustrates the decades and ranges of capture using the appropriate scenario lens. As Figure 5 illustrates, a steep ascent is required for the Accelerated and Net Zero scenarios. It further shows the dramatic gap between the Reference and Net Zero cases. (Note: Net Zero 2050 is anchored at 225 MMTPA, based on the NPC 2019 study[3] emissions forecast for the Gulf Coast region).

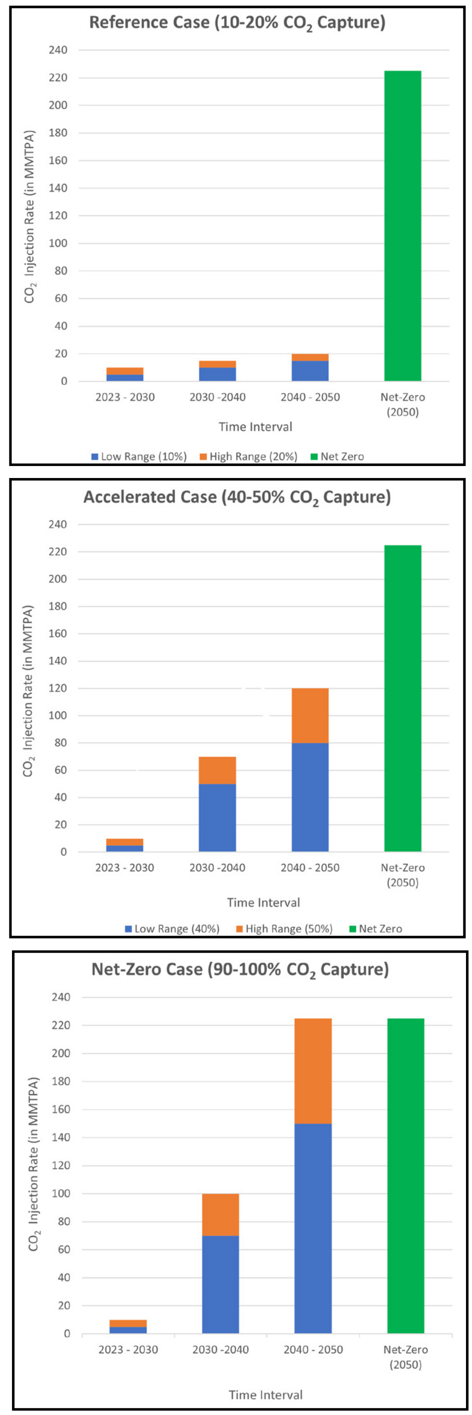

Figure 5. CO_2 Injection Rate Vs Time

[2] https://www.denbury.com/operations/pipeline-network/
[3] https://dualchallenge.npc.org/

Considerations for the Four Infrastructure Sectors

Advancing carbon capture projects across the region will require more than just coordination among industry and government policymakers. The four identified critical infrastructure sectors must develop in each of the decades as per the scenarios to achieve the carbon capture targets. Infrastructure development – in each of the four critical sectors – will be a fundamental building block upon which broad commercial deployment will be based, and the pace of development will dictate the acceleration or cadence of CCUS adoption in the region.

In addition to the analysis of the infrastructure investment requirements to spur that adoption, we assessed two rate limiting externalities that would be critical to realizing the impact and will challenge the aspirational targets:

1) How will we ensure an adequate supply chain to not only construct but to operate these facilities?
2)How will we ensure the regional workforce has the necessary skills and capacity to meet the demand?

Pipelines: Pipelines play a critical role in connecting source emitters to proposed sequestration sites. The first decade will require the utilization of the existing infrastructure (the Denbury Green Line) to connect industrial source emitters and planned CCUS onshore projects. This would serve as a framework for eventually connecting all emitters in the region, transitioning from a collection of emitter clusters to an inclusive Gulf Coast hub. The hub would provide the most efficient economics, reliability and redundancy, and operational synergies, and would enable long-term network growth as opposed to individual project economics for each discrete project. In this study, the National Pipeline Mapping System (NPMS) public viewer[4] and the National Energy Technology Laboratory (NETL)[5] website was used as a tool for pipeline proposals and pipeline mileage estimations.

In the Reference case (capturing 10%-20% of regional CO_2 emissions), between 5 and 10 MMTPA of CO_2 would be captured by 2030. Due to the limited number of projects and feasible injection rates, as well as timing of obtaining Class VI permits, no additional amounts of CO_2 can be expected to be captured and injected underground in the region initially. And that rate limiting fact affects all three scenarios for the first seven years as essentially no projects beyond those already in process could possibly be realized. The initial decade will not only challenge project execution and often first-time investment in CCUS sites, but also the positioning of the CCUS marketplace for projects in the next time horizon.

Considering the modest initial CO_2 capture target, onshore infrastructure would be sufficient for the first decade, and offshore storage development won't be required until future decades. However, it is important to note that strategies for future pipeline development will be driven, in part, by decisions about geologic storage, including the necessary characterization and selection of future geologic sites, both onshore and offshore.

The key infrastructure development needed for this initial decade will be connecting source emitters to the Green Line through laterals and proceeding to connect with the announced CCUS onshore projects. Given that existing hydrogen facilities in Greater Houston account for approximately 10 MMTPA of CO_2 emissions, connecting these facilities to the Green Line and transporting the CO2 to storage sites may be the compelling purely economic choice for all three scenarios during this first decade.

Looking at the CO_2 pipeline map 2050 for the Reference case (Figure 6), we can see that even during the first decade, with a low injection rate target, connecting emitters to the storage location(s) would require between 80 miles and 150 miles of new pipelines, depending on the emitters selected for connection. The pipeline mileage is similar for the Accelerated case and Net Zero case in the first decade, since the primary objective is to connect a few large emitters to all storage sites announced. Even though infrastructure development is the same for all three scenarios and involves land-based storage sites, industries aspiring to reach Accelerated and Net Zero targets should consider moving to offshore storage in the following decades. Hence, business decisions and infrastructure buildout need to be planned in such a way to allow for offshore storage should the need arise. That is about more than just capacity – the optionality is critical so that advancement is not bottlenecked by any singular occurrence or circumstance.

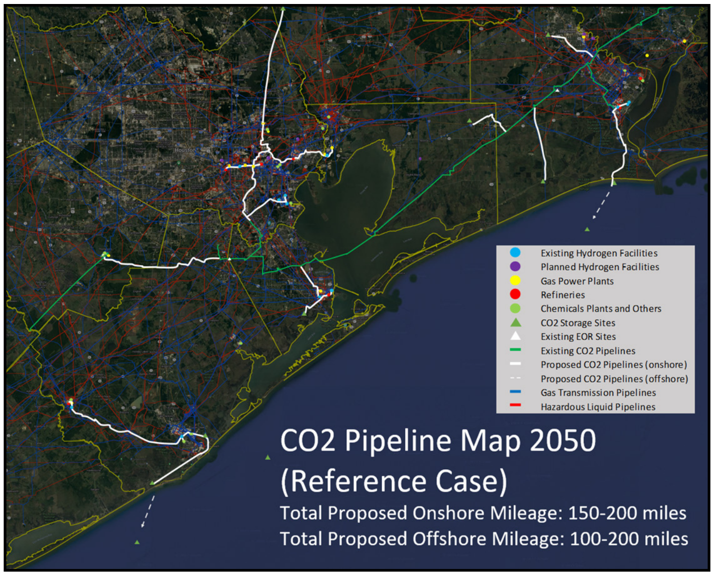

Figure 6. Proposed CO_2 pipeline map 2050

[4] https://pvnpms.phmsa.dot.gov/PublicViewer/
[5] https://www.netl.doe.gov/

Storage: The Greater Houston area has significant theoretical storage capacity, which has been quantified using traditional static volumetric analysis with available subsurface data gathered for oil and gas exploration in the area over time. The U.S. Department of Energy estimates the Gulf Coast area, including Greater Houston, can store up to 500 billion metric tons of CO_2 offshore. This is, at least theoretically, equivalent to over 700 years of emissions of all the industry emitters along the Texas Gulf Coast.

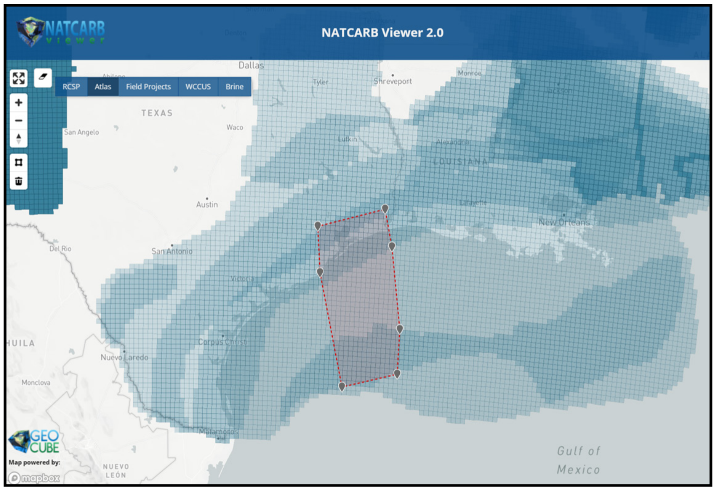

Figure 7. NATCARB CO_2 onshore and offshore storage capacity for Greater Houston region - context

Figure 7 is a snapshot of the storage capacity for Texas, with the red box highlighting the region of our study including state and federal waters.

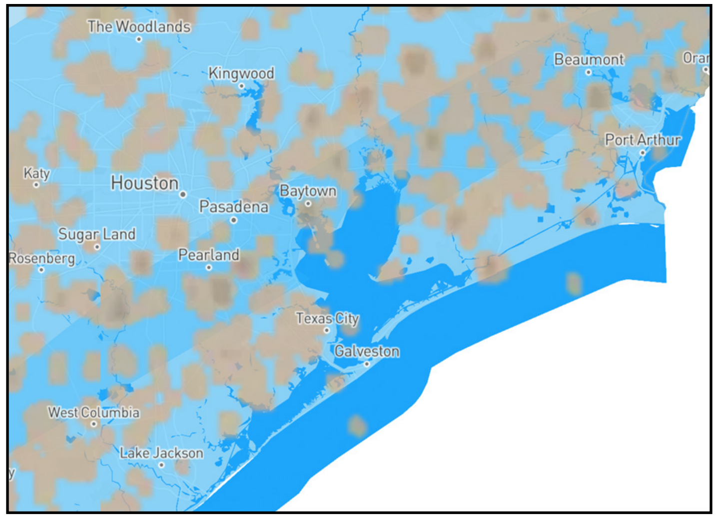

Figure 8. Saline formations and active oil and gas wells[6]

Figure 8 highlights the saline formations suitable for carbon storage, as well as the active oil and gas wells in the Greater Houston region. Legacy wells, including abandoned oil and gas wells, may occupy potential storage formations and reduce the available space for CO_2 injection. The presence of these wells can complicate site characterization, well construction, and monitoring efforts, as well as increase the risk of permitting and monitoring challenges long term[7]. The need for thorough well integrity assessments and remediation measures adds complexity and potential costs to onshore storage projects. Consideration of the legacy well inventory when planning for onshore CO_2 storage is a necessity.

The major short-term conclusion here is that although we have great potential along the Gulf Coast, we must follow through with thorough site characterizations and confirmation of storage that is safe and permanent. We strongly believe, based on previously conducted technical assessments, that such storage exists, but final characterizations will provide confidence and specificity about exactly where such sites are located.

At the time of this study, there is no pure carbon sequestration in the state of Texas. Enhanced oil recovery (EOR) has been practiced for nearly 70 years and has in fact resulted in the storage of great volumes of CO_2. Nationally, about 11 trillion cubic feet (560 million metric tons) has to date been used for EOR. Regulatory requirements for EOR fall under Class II conditions, while pure storage is regulated under Class VI. Class VI requirements are more rigorous and include long-term liability responsibilities but also include the necessary elements of tax treatment qualifications under 45Q of the tax code. The path forward for CCUS must include pure storage.

There have been six major CCUS projects announced in the region

[6] https://www.bakerinstitute.org/texas-ccus-map
[7] https://netl.doe.gov/sites/default/files/2018-10/BPM-SiteScreening.pdf

with start-up targets before 2030: Bayou Bend (Offshore and Onshore), Talos Freeport LNG, Oxy-Bluebonnet, BP-Linde (location yet to be determined) and Denbury Dorado CCUS project.

The EPA, through the Underground Injection Control (UIC) Program[8], regulates injection wells. Pursuant to the UIC program, EPA has promulgated regulations and established minimum federal requirements for six classes of injection wells (Class I to Class VI). Class VI wells are used to inject CO_2 into deep geologic formations solely for the purpose of permanent storage, often referred to as dedicated storage. Currently, the permitting approval for Class VI wells in Texas lies with EPA, and the approval process can take up to six years. Hence, Texas achieving primary permitting authority for Class VI wells, known as primacy and expected between now and 2026), would be the determining factor for the announced projects coming online before 2030.

Further infrastructure development during this initial decade will be similar for all three scenarios, but for the Accelerated and Net Zero cases, it will nonetheless be a critical time in positioning for the next decade. Also, with a growing urban population, NIMBY sentiments against building new projects, and a permitting and approval process that requires obtaining rights of way for pipelines, it can be anticipated that onshore CCUS projects in coming decades will become increasingly difficult. Thus, industries must consider and think strategically about having a full suite of options – with the choice to move to offshore storage in state or federal waters in coming decades.

To conclude, the period 2023 to 2030 will be extremely significant as the first carbon sequestration is expected to begin within this period and key long-term business decisions will set the tone for infrastructure growth in storage – both onshore and offshore – over the following two decades.

It is imperative for industries aspiring to Accelerated and Net-Zero targets to begin preliminary work now, pushing to establish offshore storage regulations, acquire offshore sites, and perform well characterization studies. In August 2023, the Texas General Land Office awarded six leases for offshore carbon storage, signaling a trend for offshore storage in coming decades. A comparison of strengths of weaknesses for both onshore and offshore is provided on the right.

Onshore Storage

Strength	Weakness
Proximity to emission sources - reduced cost of transportation	Limited to lightly populated rural localities
Ability to leverage existing infrastructure – Pipelines being the most important	High density of legacy oil and gas wells
Easy access to selected sites for monitoring and remediation	Ownership profile for surface, pore space, and minerals vested with multiple parties. Long-term liability remains a question, and insurability will be tested in individual circumstances. Site owners will be challenged to provide insurability
Enhanced accuracy for site characterization through existing onshore best practices established throughout the Regional Storage Partnerships over the past 10+ years	Management of contamination risk to Underground source of drinking water (USDW)
	Public acceptance and environmental justice impact

Offshore Storage

Strength	Weakness
Vast theoretical storage capacity with geologic capability	Farther removed from emission sources – high cost of transportation
Single owner for storage sites	Elevated costs – new infrastructure requirements
No constraints due to population	Complicated access to sites for monitoring and remediation
No risk to USDW due to lack of access	Environmental impact on marine ecosystem
Finalizing Bureau of Ocean Energy Management and Bureau of Safety and Environmental Enforcement guidelines to propel offshore considerations	Lack of established best practices

[8]https://www.epa.gov/sites/default/files/2015-07/documents/epa816r13004.pdf
https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-146

Electricity: The eight-county region is a net importer of electricity; five of those counties are served by the Electric Reliability Council of Texas (ERCOT), which oversees the state's electricity grid. While three regional counties are outside ERCOT, there are not major differences in the characteristics of the ERCOT vs non-ERCOT counties in terms of supply and adequacy; the specifics of the initial cluster areas drove the assessment to focus on the five ERCOT-supplied regions.

From a detailed review of existing literature analyzing power demand for the capture and transportation of CO_2 emissions, we found that using current MEA (monoethanolamine) solvent-based post combustion capture technology, energy requirements for capture facilities would be in the range of 0.8 to 1.9 megawatt hours (MWh) per metric ton of captured CO_2. (This calculation does not include the parasitic load reduction that would impact a gas-fired electricity generator.)

Given the announced CCUS projects in the study region, carbon capture and storage in the period up to 2030 for all three scenarios is expected to range from 5 to 10 MMTPA, requiring that counties have the capacity to provide an additional 19 million MWh to 29 million MWh[9] of delivered energy on top of existing requirements. Looking at existing power infrastructure, the eight counties included in our study have a total actual generation of 81.5 million MWh, while the current demand is 106 million MWh. Meeting that excess demand requires importing electricity from neighboring counties or elsewhere in the state.

It is crucial to note that installed capacity does not equal delivered electricity. CCUS requires reliable 24/7 delivery of electricity.

Clearly, the region has a deficit of approximately 23% in self-sufficiency, leading to the question of available capacity. Solar and storage assets aren't feasible for efficiently powering capture facilities that require an around-the-clock electricity supply. For that reason, from an electro-economic point of view we considered only coal and natural gas power plants. Among existing assets, 3% of power plants in the region are coal-fired, 7% natural gas–steam turbine (NG-ST), 35% natural gas–combined cycle (NG-CC), and 55% natural gas–gas turbine (NG-GT).

Coal plants run at an average capacity factor of 0.7, the equivalent of 100% output for 70% of the time, although more often that equates to running below full capacity for longer periods of time. There is not much room for enhancement through increased utilization of coal plants; therefore, it makes sense to focus on natural gas power plants.

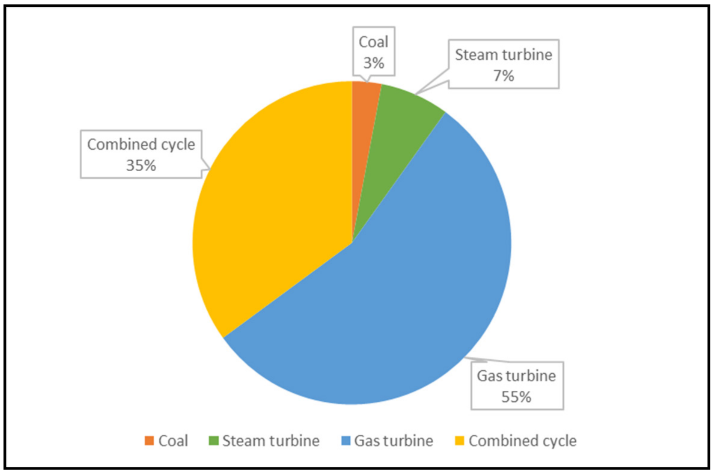

Figure 9. Power production distribution in the Greater Houston region in 2022 (ERCOT CRD Report 2022).

Among the various classes of natural gas plants in the region covered by this study, there is an opportunity to increase the capacity factors of the combined cycle and the simple cycle turbines to as much as 85%, based upon the understanding that the combined cycle facilities would be the most energy efficient and deliver the lowest cost energy in a market demanding uninterrupted delivery.

At present most combined cycle and gas turbine plants run at an average capacity factor of 0.45. Increasing that to 0.85 will increase regional energy capacity to 110 million MWh. However, this would also increase the need for natural gas to fuel the plants. At present, power generation in these eight counties requires around 1.8 billion cubic feet per day (bcfd). If the capacity is enhanced, demand will rise to as much as 5 bcfd by 2050. Given the latest price of natural gas has ranged from $2.80 to more than $3 per thousand cubic feet, this would require an additional $3 billion-$4 billion investment.

But the capacity of existing plants isn't the only issue; equally important is ensuring that the market structure encourages existing plants to provide as much power as they are capable of producing. Natural gas-simple cycle power plants, especially, are able to ramp quickly up and down in response to demand and market conditions on the ERCOT grid. For baseload 24/7, NGCC will be the facilities of choice. In ERCOT's energy-only market, generators are paid only when they provide power, not for being in stand-by mode. That encourages producers to offer power only when market conditions are favorable, ramping production down when rates are low, as often happens when solar and wind power produce large amounts of electricity.

This market-driven start-and-stop generation conflicts with the reliability needed to run CCUS operations. Policies authorizing a new market mechanism that would allow these plants to meet

[1] https://www.ercot.com/files/docs/2023/05/05/CapacityDemandandReservesReport_May2023_Revised2.pdf

the 24/7 appetite of CCUS operations, separate from the minute-by-minute market fluctuations driven by low-cost renewable producers, could do much to meet the increased demand for power.

Increasing the utilization of fossil fuel-powered generating facilities would create an additional concern – higher rates of utilization would add to regional CO_2 emissions and thus the plants would also become candidates for CCUS. (A prime example of this approach is at the W.A. Parish Plant in Fort Bend County, where CCUS has been retrofitted onto a coal-fired facility. The project was a DOE demonstration project that has recently re-started, with a 1.4 MMTPA CO2 capture target – roughly 10% of the plant's emissions (13.8 MMTPA as per 2021 emissions data). Further CO_2 capture will be accessible to investment over time.

Assuming, as we have noted, that sequestration of CO_2 for the period between 2023 and 2030 will be in the range of 5 to 10 MMTPA for each of the scenarios, the focus of the next seven years should be on enhancing the utilization rate of existing power plants, especially natural gas-gas turbine plants, and ensuring policies are in place to encourage that enhanced utilization. Large transmission projects take on average 10 years to develop, including obtaining licenses from local, state, and federal agencies as well as negotiations with private landowners, community organizations, and other stakeholders. Hence, in order to achieve the Accelerated and Net Zero scenarios in the coming decades, key strategic decisions must be made now, including transmission projects, cogeneration facilities, and the construction of new power plants.

Water: Water consumption will be a key factor in determining whether CCUS projects will be implemented at the level needed to achieve Net Zero. In this study, estimated water needs are based on the post-combustion amine technology requirement for CCUS. This consists of the water in the amine solvent used for breaking down the gas, the makeup water that is required to help replenish that water and avoid corrosion, as well as the condenser water used to reduce water loss due to evaporation. For coal-fired power plants and natural gas power plants shown in Figure 11, water requirements for post combustion CO2 capture can range from 0.5 to 3.16 m^3/tonnes of CO2 (equivalent to 900 to 6000 ft3/MMSCF CO_2). Freshwater, rather than brine, is needed for this process due to the requirements for the amine solvent.

As shown in Figure 10, most water usage in the eight counties falls under the municipal category. As we have a growing regional population, this category will be on the increase, necessitating allocating funds to either increasing the water supply or improving transmission to the counties. The available supply from existing water sources was approximately 3.35 million acre-feet/year as of 2020[10]. About two-thirds of that comes from surface water, predominantly Lake Conroe and Lake Houston within the San Jacinto River Basin and Lake Livingston within the lower Trinity River Basin. The remainder comes from groundwater and run-of-river sources in the region.

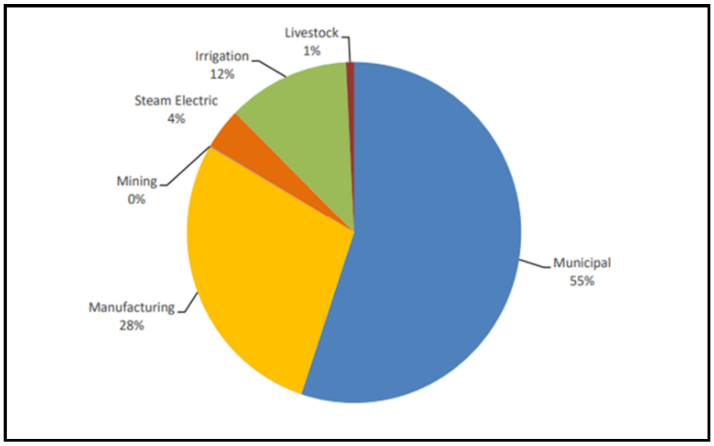

Figure 10. Water usage by industry (Water Planning Group 2020)

However, in the long run, the available supply will shrink to approximately 3 million acre-feet/year. The anticipated reduction reflects restrictions on the Gulf Coast Aquifer, instituted to combat subsidence in a large part of the region. Reduced reservoir yields due to sedimentation also will contribute to the reduction in supply over time. Considering this, it is necessary to get approval for new surface water reservoirs as early as possible in order to maintain water supply for CCUS.

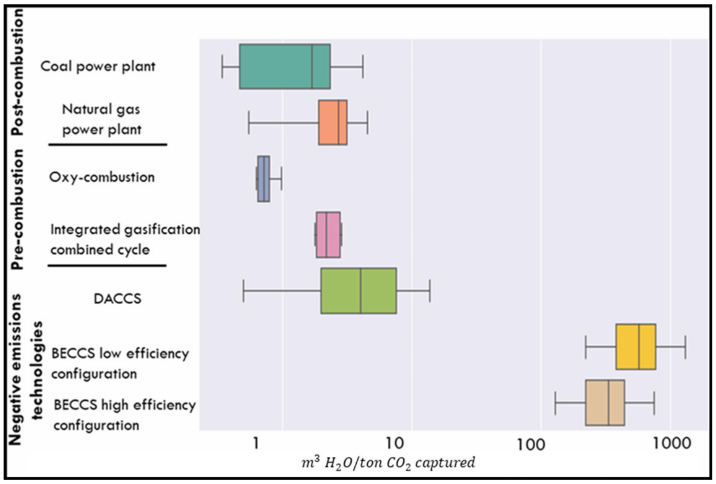

Figure 11. Water use intensity on amount of CO_2 captured.[11]

Looking at the water use intensity on CO_2 capture in Figure 11, the highest targeted CO_2 injection rate in the first decade (10 MMTPA) will only require about 1%-2% of the current regional water supply.

Presently, around 500 water projects are being completed, with 90% of them conservation projects. For the Reference case (10%-20% CO_2 capture) delay in approval of new surface water reservoirs will likely have no impact. Both the Accelerated case (40%-50% CO_2 capture) and Net Zero case (90%-100% capture) likewise can be satisfied without additional water projects during the current

[10] https://www.twdb.texas.gov/waterplanning/rwp/plans/2021/H/RegionH_2021RWP_V1.pdf

[11] https://www.sciencedirect.com/science/article/abs/pii/S1364032120307978

decade; however, approval for new surface water reservoirs needed in future decades must be granted within the next few years to meet future demands.

According to our estimates, water supplies won't be significantly affected by proposed CCUS projects in the short term. Nevertheless, key factors need to be considered for the longer term. Future capture and storage projects, especially under the more aggressive scenarios, will require more water, just as Texas' growing population is also demanding more. Planning – for new reservoirs, for transmission projects, and for enhanced opportunities for conservation and reuse – must begin well before the water is needed.

Conclusions

Current conditions accompanied by relatively limited infrastructure expansions will allow CCUS to begin operations in the Gulf Coast region over the next few years. But as we have outlined, substantive work must begin immediately to prepare for the coming decades if we are to realize the promise of CCUS and the potential of the Houston region to lead in advancing this technology.

Key pathway enablers for this decade include:

Pipelines:

- Utilization of Green Line to connect cluster sources to storage.
- Regulatory support and certainty for onshore and offshore pipeline development.
- Obtain right of way and permits well in advance for construction projects.
- Regulatory certainty for CO_2 private and common carrier systems – especially for the extensive pipeline network that will need to be built in the following decades.

Storage:

- Texas achieving primacy for Class VI wells.
- Well characterization of announced CCUS projects to determine actual capacity.
- Clarity for offshore storage regulations.
- Acquisition of offshore land for potential future storage
- Key investment decisions and strategic planning for future decades

Electricity:

- Enhanced utilization of current assets.
- Key investment decisions and strategic planning for future decades – transmission projects take up to 10 years from concept to reality.
- Preliminary work for new power plant construction in the next decade.
- Cogeneration facilities may be necessary in the 2040s, but development must be considered within this decade.

Water:

- Existing water supply should suffice for CCUS deployment during the first decade.
- New water resources, especially surface water reservoirs, required in future decades will need to be approved early.
- Water needs of the clusters must be assessed and planned as clusters expand in the following decades.

The degree and pace of positioning and the advancement of the market, policy, and the regulatory framework over the next seven years will determine the trajectory and possibilities for what happens with CCUS over the following two decades.

We must recognize that business as usual is not meeting, in significant ways, any emissions reductions goals. Failing to move now will lead only to stagnation and delay.

The Second Decade (2031 to 2040)

In many ways, the decade between 2031 and 2040 will determine where we stand in terms of capturing carbon emissions in 2050. It will be a pivotal time for infrastructure development, and our ability to reach – or even come close – to Net Zero by mid-century will depend upon completing a tremendous amount of infrastructure work in all four relevant sectors during these years.

But as noted above, infrastructure development for CCUS in 2031-2040 will also depend on the planning and early development work that happens between 2023 and 2030. The work must be effectively integrated and built upon in the second decade to ensure the promise of CCUS is realized, along with the Houston region's leadership in the field.

Pipelines: The requirements for actual new installed pipeline infrastructure will be relatively low in the years before 2030, a function of the limited number of announced regional CCUS projects and the fact that Texas has not yet been granted primacy on Class VI wells, limiting the potential for CO_2 storage under all three scenarios. That stands to change in the second decade, and demand for pipeline infrastructure development will differ dramatically depending on capture targets.

Primacy in Texas over Class VI well permits is essential for aggressive CCUS project development, and our assumptions for this second decade are based in part on the expectation that Texas will be granted primacy before 2030. Total regional CO_2 emissions are projected to be between 120 and 160 MMTPA in the decade between 2031 and 2040, rising to around 225 MMTPA by 2050. In the second decade it is necessary to gradually include pipeline connections to more industrial facilities with annual CO_2 emissions greater than 1 million metric tons.

In the lower-capture Reference case, we project that between 10 to 15 MMTPA of CO_2 will be captured and stored underground in the Greater Houston area from 2031-2040, due to slower project development and limited injection rates. This would require connecting an additional five to 10 industrial source emitters, and a total of 80 miles to 150 miles of CO_2 pipelines. While onshore storage capacity will be temporarily sufficient, development of offshore storage capacity would need to start by the end of the second decade.

The Accelerated case, with a target of capturing between 40% and 50% of regional carbon emissions, calls for between 50 and 70 MMTPA of carbon dioxide to be captured and stored underground during the second decade, and for offshore development to start by early in the decade. This would require connecting an additional 20 or 30 industrial source emitters and a total onshore CO_2 pipeline network of 150 miles to 200 miles.

The Net Zero case, capturing 90% to 100% of regional carbon emissions by 2050, would require the capture and storage of between 80-120 MMTPA of CO2 and assumes that offshore development started in 2026. This would require connecting all 34 regional industrial source emitters and a total CO_2 pipeline mileage of between 250 miles and 300 miles. In the second decade, connecting industrial facilities emitting more than 1 MMPTA of CO_2 would be sufficient to meet the storage requirements for all three scenarios, given that all the CO_2 emissions from those emitters are effectively captured and stored.

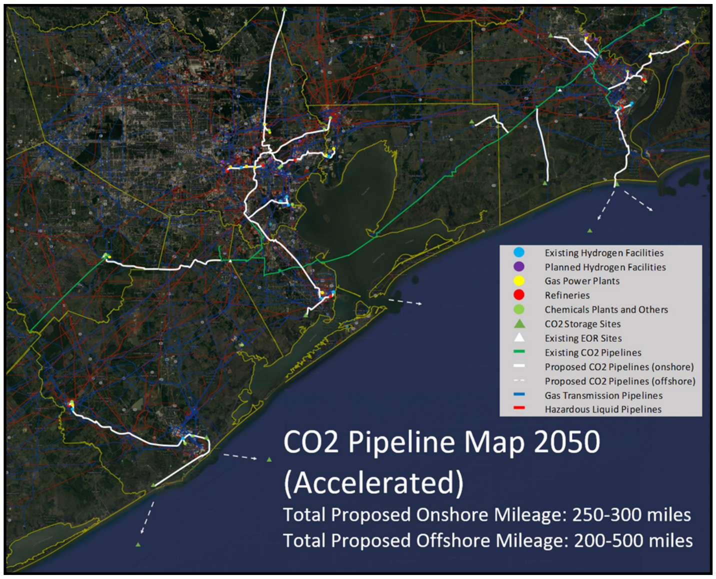

Figure 12. CO2 pipeline map 2050 (Accelerated case)

Storage: While the first decade will focus on initial projects coming online and key decisions that must be made by industry, the second decade will be the most consequential for storage in terms of the actual buildout of the necessary infrastructure. Lessons learned from the first wave of projects will ease the learning curve for future projects, leading to smoother execution.

Relatively little work to meet the targets of the Reference case will be required during this decade, but assuming Texas obtains primacy by the late 2020s, infrastructure needed to achieve the Accelerated and Net Zero targets must begin to take shape in 2031-2040.

The Accelerated case: With the expectation that only 5-10 MMTPA of emissions will be captured and stored by 2030, meeting the target of capturing 50-70 MMTPA will require a steep ascent. In addition to increased injection rates at existing projects, it will require the rapid construction of new storage sites, both onshore and offshore. Permits for Class VI wells should be granted more quickly if the state obtains primacy; however, with a growing urban population along the Gulf Coast and the possibility of neighboring residents' concerns of the growth of the CCUS footprint, onshore projects could face greater resistance from neighboring communities. As such, it may be prudent or even compulsory to move offshore by the mid-2030s. To achieve this, permitting and offshore leasing must begin in the early 2030s.

As we noted in the section dealing with 2023-2030, offshore leasing for storage began in August 2023. By 2031, we expect additional auctions and leasing in preparation for offshore geologic storage. Industry needs to start infrastructure buildout and well characterization by the early 2030s.

The Net Zero case: Reaching the target of removing between 70 and 100 MMTPA during the second decade will be a gigantic step from the 10 MMTPA levels that can be achieved in the early years of this effort. It will require an exponential three-pronged effort – increasing the capacity of existing CCUS projects and adding additional projects both onshore and offshore.

An important caveat is the complexity and cost of offshore storage projects. Preliminary investigation suggests the cost of offshore storage will be five or even 10 times that of onshore projects. Meanwhile, site characterization for announced projects is ongoing, even for sites previously determined to be geologically suitable. To put it into perspective, announced CCUS projects call for storing 1 MMTPA per project. Ramping that up tenfold will not be an easy task, hence, the need to characterize offshore sites to assess possible storage capacity.

Electricity: The second decade – especially for Accelerated and Net Zero scenarios – would focus on building upon the key decisions made in the first decade. Enhancing imports, continued increased utilization of existing natural gas combined cycle power plants, improving grid reliability and flexibility, and retrofitting existing power plants with CCUS technologies, allowing them to continue providing electricity while also reducing emissions – all would be expected in this decade. Also, the development of onshore solar in our region of study must be complemented by significant increases in storage capacity – if it is to be an adequate solution.

Integrated resource planning (IRP) will require a thorough techno-economic analysis and the potential of technology improvements and the growth of storage capability. In addition, offshore renewable energy – both wind and solar – may become effective solutions through the development of advanced technologies and further integration improvements.

The Reference case: The additional electricity required to meet Reference case targets for 2031-40, an estimated 10-20 MMPTA, could be provided by enhancing the utilization of existing power assets. Beginning in the mid to late 2030s, preliminary work for the construction of new power plants is expected to start.

The Accelerated case: Meeting the mid-level targets of the Accelerated case – up to 10 times the amount of emissions captured during the first decade – will require building new power plants fitted with CCUS technologies, while continuing increased utilization of existing power plants, as well as additional renewable energy generation. Counties where these projects are located will also need to increase the amount of electricity they import from elsewhere in the state. As the infrastructure continues to build out, the emission clusters will start to look like a hub – and hence, transmission projects in these hubs will be necessary. Preliminary construction work on cogeneration facilities should also begin within this decade in preparation for beginning operations in the following decade.

The Net Zero case: Achieving Net Zero targets will be even more challenging as we look to capture 14 times the emissions from the first decade. In addition to the requirements of the Accelerated case – enhanced utilization of existing natural gas combined cycle power plants, CCUS-fitted new power plants, and transmission projects near clusters – achieving Net Zero targets will require aggressive development of cogenerating facilities for all projects, along with increased levels of imported electricity.

Water: Water requirements will become more demanding in the second decade due to the dramatic increase in CCUS projects needed to meet the Accelerated and Net Zero targets. However, it is important to note that CCUS will not be the only factor driving water demand. Due to projected population growth, demand for water in virtually all categories, including municipal water systems, manufacturing, irrigation, and livestock, will also increase. As referenced in Figure 11., depending on the number of projects and the volume of CO_2 that is actually being captured at any given time, the required amount of water can be estimated for each of the scenarios.

CCUS water requirements during the second decade will vary greatly depending on the targeted capture projects. The Reference case requires a relatively low number of CCUS projects, hence related water needs would likely be met as projects already proposed come online. Growth will require additional capacity as well as treatment.

That changes for the Accelerated case (40%-50% capture), which calls for rapid growth in the number of CCUS projects and, as a result, additional water and wastewater capacity. In addition to projects required for the Reference case, the Accelerated case would require additional water and wastewater projects.

For Net Zero case, strategy and planning will be important in the beginning of the 2nd decade. The Net Zero case (90%-100% capture) would require far more water infrastructure – roughly double the projects in the Accelerated case - to increase water and wastewater capacity. The Net Zero scenario will also require the use of desalination to bolster the state's freshwater supplies, with the first desalination plant needed by the late 2030s. Also worth noting is that by the end of the second decade, there will be additional water required to meet the needs for cogeneration in the electricity workstream. Figure 13 shows the approximate capital cost of water projects in each decade for the Reference case, indicating more than $13 billion in capital costs from 2030 to 2040.

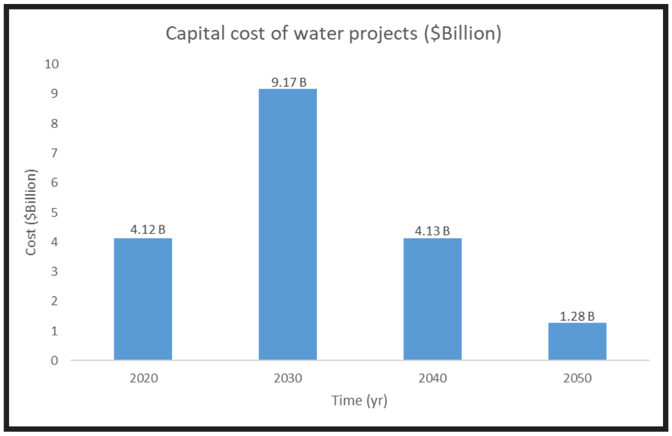

Figure 13. Capital cost of water projects (Reference Case)

Conclusions

Pipelines

• Pipeline infrastructure installations are required with clusters to hub strategies employed.

• Offshore pipeline and storage must both come online during this decade.

• Regulatory certainly for private and common carrier must be advanced and provide investment certainty.

• Rights of way and well permits must be obtained well in advance for projects.

Storage

• Completion of onshore and offshore site acquisitions and well characterization.

• Rapid construction of additional onshore projects to accommodate capture targets.

• Development of offshore projects and investment confidence displayed.

• Extension of 45Q tax credits beyond 2032.

Electricity

• Continued enhanced utilization of existing power projects and reliable imports.

• Retrofitting existing NG generation assets with CCUS technologies.

• Transmission projects will supply emission clusters as well.

• Storage is developed to integrate renewable sources for grid stability.

• Developmental work of cogeneration facilities for Net Zero case – aggressive development required to meet target operation dates by late 2030s.

Water

• Current water supply becomes insufficient to meet water needs for CCUS.

• New water projects must be continuously developed to provide additional supplies.

• New surface water reservoirs must be approved and online early in this decade to provide additional water sources.

• The majority of capital cost for water project development would be in this decade.

The Third Decade (2041 to 2050)

Infrastructure development in the third decade (2041-2050) would be a continuation of the first two decades. However, if we are to rely mainly on CCUS to reduce CO2 emissions, the Reference case, representing current progress on CCUS project development, will prove insufficient. For the Accelerated and Net Zero scenarios, which have the potential to provide far more substantial results, the third decade will be a continuation of the trajectory and momentum set during the years between 2031 and 2040, with a vision of capturing most or all emissions from industrial sources by 2050.

Pipelines: Comparing Figures 6, 12, and 14, it is clear that in 2050, pipeline infrastructure for the Reference case focuses primarily onshore, connecting every storage site available to selective source emitters in the region. For the Accelerated case, offshore pipeline requirements increase, as all source emitters with greater than 1 MMTPA CO_2 emissions need to be connected to storage sites. For the Net Zero case, in addition to everything required to meet the Accelerated case, extensive offshore pipeline development is required, selective emitters below 1 MMTPA CO_2 emissions need to be connected, and additional pipelines are needed to increase CO_2 capacity, as well as connecting the various clusters to form a hub.

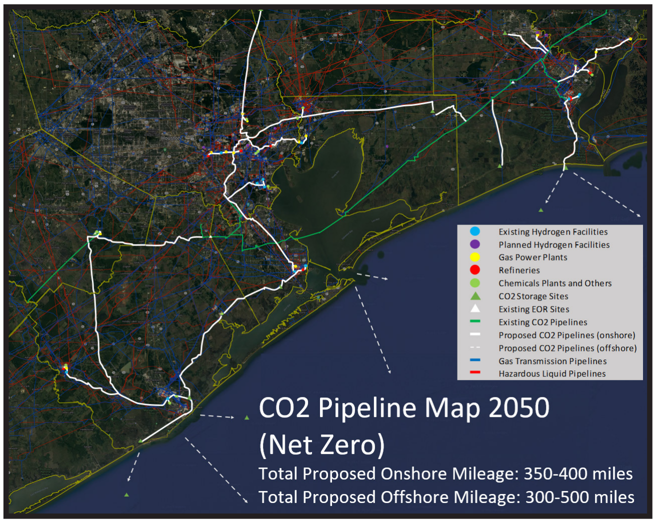

Figure 14. CO_2 pipeline map 2050 (Net Zero case)

Based on total projected CO_2 emissions of 225 MMTPA in the third decade, in the Reference case (10%-20% CO_2 capture), with an assumed growth rate of five projects per decade, only 15-20 MMTPA of CO_2 would be captured and injected underground, requiring connecting 10-15 industrial source emitters. Onshore storage capacity would become limited by this point, and offshore development should have started in the beginning of this decade.

In the Accelerated case (40%-50% CO_2 capture), given that CCUS projects will continue to be rapidly developed, around 80-120 MMTPA of CO_2 would be captured and stored underground between 2041 and 2050, and offshore development would have started by early in the preceding decade. To meet the target injection rate for the Accelerated case, all industrial source emitters considered in this study, including existing and planned hydrogen facilities, need to be connected to storage sites, and all CO_2 emissions from those facilities need to be effectively captured and stored. Realistically, however, effectively capturing CO_2 emissions from all facilities is unlikely, and thus meeting the Accelerated case requirements would require connecting to smaller industrial source emitters, those with CO_2 emissions of less than 1 MMTPA. For the Net Zero case (90%-100% CO_2 capture), 225 MMTPA of CO_2 would be captured and stored in 2041-2050, with offshore development started in 2026. The number of industrial source emitters fitted with CCUS technologies required to meet this target is likely beyond the number of facilities included in this study, and achieving economic targets for smaller industrial source emitters will require additional effort.

Storage: Entering the final decade covered by this study, the primary task in expanding geologic storage would be development and construction of offshore storage. In addition, permitting and regulatory maturity would be required by this time for maximum utilization of both onshore and offshore storage. For the Reference case, the amount of CO_2 captured during the third decade would be in the range of 15-20 MMTPA, built upon the development of additional storage in the preceding decades. As discussed in the detailed analysis covering 2023-2030, with population growth and NIMBY concerns, industries would want to consider offshore storage beginning in the 2040s even for the Reference case.

The Accelerated case, with a capture target of 80-120 MMTPA, would continue the trajectory from previous decades, requiring multiple onshore and offshore storage sites. The Net Zero case, with a capture target of 150-220 MMTPA, will require those storage sites along with a plan to connect all remaining industry emitters. Strategic planning in coordination with pipeline development would be key to achieving this goal.

Electricity: Continued work to increase the utilization of current natural gas power plants, along with new transmission project development, is essential to meeting Accelerated and Net Zero goals. The development and the integration of solar and wind renewable generation accompanied by storage, will greatly determine the mix of generation sources. The integrated resource planning (IRP) efforts will drive the size, location and storage requirements of any generation added. It is critical to recognize that baseload NG facilities would be required to have CCUS as part of the supply scheme.

Our analysis of 2050 emissions profile would require the assessment of the capturing of emissions from Natural Gas-Combined Cycle facilities. The development and integration of advancements of storage options for renewables, grid integration strategies, and other transformational advancements will be the determining factor in how the grid profile will be in 2050. An example of such transformational options in contrast to the preceding decades would be construction and operation of cogeneration facilities to meet the additional electricity demands of CCUS adoption, as well as the steam requirements for capture technology process regeneration.

Water: In the third decade, similar to the second decade, water infrastructure developments would proceed at a manageable pace for the Reference case; however, the Accelerated and Net Zero scenarios would require tremendous effort in water infrastructure development. For the Reference case, new surface reservoirs and other key surface water would need to come online in this decade. Additional water projects would be needed to keep up with municipal growth and repairing and replacing aging infrastructure. Municipal demand will drive water projects growth as compared to CCUS requirement.

Strategy and planning will be important for Accelerated case in the beginning of the third decade. To meet targets for the Accelerated case, desalination plants would need to come online early in the third decade, to accommodate more water usage. In addition to the projects required for the Reference case, additional projects would be needed to accommodate municipal growth, infrastructure decay, and an increasing number of CCUS projects. During this decade, blue hydrogen will assume an increasingly important role in the energy portfolio, along with cogeneration to help meet the energy demand for CCUS, both of which require additional water.

The Net Zero case would require multiple desalination plants to begin operations in this decade. Net Zero case will require far more projects compared to the Accelerated case to keep up with municipal growth, infrastructure decay, and increasing CCUS efforts. In this scenario, cogeneration, blue hydrogen generation, and fuel cell technology will all come into play to diversify the energy portfolio, increasing water demand. For both Accelerated and Net Zero scenarios – water requirements from multiple CCUS projects, rather than municipal requirements, will drive the planning and execution of water projects. Conservation and reuse will also become increasingly important as a low-cost strategy to help meet increased demand while allowing the delay or even elimination of some costly infrastructure projects included in regional water plans. Reuse could also be a key factor, as the ability to use brackish water for industrial needs or to treat wastewater to a level that would allow it to be used for other purposes would also help meet growing demands. This process is more expensive than conservation, as it requires the construction of additional sophisticated treatment plants.

Conclusions

Pipelines

- Extensive pipeline infrastructure required to transform clusters to a commercial functioning hub.
- Offshore pipeline development must be mature to accommodate storage targets.
- Regulatory certainty for private and common carrier must be known for investment.
- Rights of way and well permits must be obtained well in advance for projects.

Storage

- Maturity of permit and regulatory landscape.
- Ongoing regulatory support and development of regional hubs.
- Advancements to storage and measurement, monitoring, verification, and accounting will be required for broad-based commercial practice.

Electricity

- Diverse portfolio including renewables and integration of electricity storage options.
- Use of hydrogen as fuel for power and steam generation. (Full scope fuel substitution)
- Construction of cogeneration facilities.
- Construction of CCUS-fitted new power plants.

Water

- Current water supply becomes insufficient to meet water needs for CCUS.
- New water projects must be continuously developed to provide additional water supplies.
- New surface water reservoirs and desalination plants must be approved and online to accommodate water demands.
- Water conservation and reuse must be incorporated to increase efficiency.

The Regional Workforce

Houston is regarded as the energy capital of the world. Fifteen Fortune 500 energy companies have their headquarters in Houston. One-quarter of total oil refining production and 44% of total base chemical manufacturing in the U.S. is in the Greater Houston region. Not surprisingly, 40% of Houston's employment is tied directly or indirectly to the energy sector. Refineries, along with the steel and cement industries, are considered the most difficult to decarbonize. Thus, CCUS technology is vital – especially in the Houston region – for sustaining local job markets while also reducing emissions.

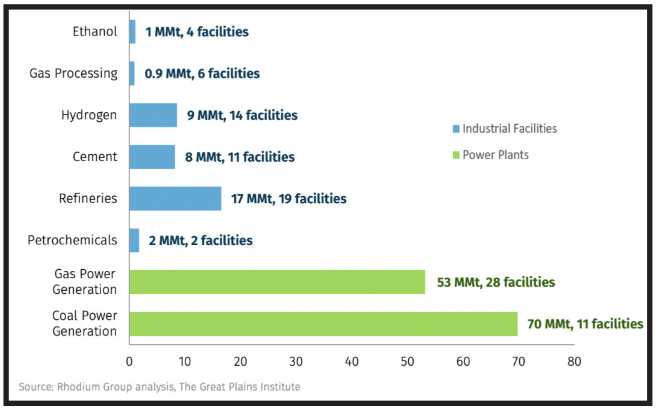

Figure 15. Facilities that can be retrofit with CCUS in Texas

Based on Great Plains Institute modeling of economically feasible capture projects, the Rhodium Group[12] has provided preliminary analysis of the jobs potential for a typical carbon capture facility across several industries. Houston, which has roughly 50% of all facilities listed in Figure 15, holds vast potential to create jobs and simultaneously reduce emissions by retrofitting existing facilities with carbon capture equipment. The range in job numbers reflects differences in project sizes in the Great Plains Institute project database (Figure 16).

			PROJECT JOBS	OPERATION JOBS
CARBON CAPTURE RETROFIT*	INDUSTRY	STEEL MILL	1,680 – 3,030	170 – 310
		REFINERY	440 – 760	40 – 70
		CEMENT PLANT	430 – 690	60 – 110
		HYDROGEN PLANT	175 – 300	20 – 30
		ETHANOL PLANT	30 – 50	5 – 10
	POWER	COAL POWER PLANT	1,800 – 3,350	160 – 300
		NATURAL GAS COMBINED-CYCLE POWER PLANT	1,140 – 2,090	100 – 180
CO_2 TRANSPORT INFRASTRUCTURE		TRUNK LINE (20" DIAMETER PIPELINE, 200 MILES LONG)	1,250 – 2,190	8 – 20
		FEEDER LINE (12" DIAMETER PIPELINE, 50 MILES LONG)	250 – 370	2 – 5

*By facility type

Figure 16. Associated workforce for retrofitting facilities.

The oil and gas industry is over 100 years old in this region, and the associated workforce has the required skills and experience to serve the different aspects of the CCUS project execution cycle, as illustrated below in Figure 17.

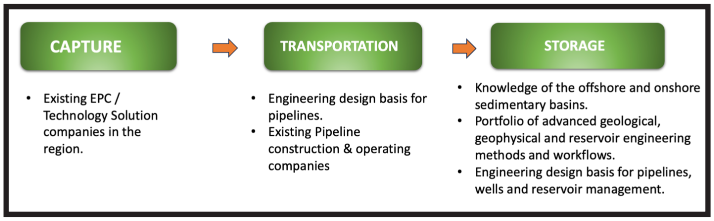

Figure 17. Skills and knowledge of the existing energy workforce translate to the requirements of the CCUS project cycle.

The existence of a knowledgeable workforce with transferable skills presents an opportunity to meet the employment requirement as CCUS adoption progresses in the coming years. New jobs will be created with CCUS deployment which in turn will require a larger workforce. Presently, an estimated 100,000 people are employed in the oil and gas and petrochemical sector, extending to 150,000 -170,000 if the steel and cement industries are included[13].

Reference case: With 10%-20% of carbon emissions captured per decade, we would be retrofitting between five and seven facilities per decade, which will require 5,000-7,000 workers. The employable workforce growth in the region should suffice to meet this requirement.

Accelerated case: There should be no workforce issues during the first decade. For the second decade, a capture target 10 times greater than that of the initial decade and close to 40 facilities connected translates to a CCUS workforce of 40,000-50,000. As noted earlier, there are roughly 150,000 people employed in the oil, gas, petrochemical, and related industries in the Texas Gulf coast region, suggesting a 30% growth in workforce requirements. Further, in the third decade, where the capture target is 15 times that of 2023-2030, the workforce requirement would be an additional 30%-40% over the previous decade. To meet these demands, significant upskilling and reskilling of workers will be required – including people who may lose jobs due to the energy transition.

Net Zero case: Workforce requirements would be similar to those for the Reference and Accelerated scenarios for the first decade. However, the exceptionally high target for CO2 capture in the following two decades will require a 70%-80% workforce growth in each decade. The current employment growth rate along with population growth would not be sufficient to meet the need. Upskilling and reskilling of workers is a necessity and would have to begin as early as the mid-2020s. More importantly, industries must collaborate with education institutions for early engagement to attract, train, and absorb talent to match the enormous workforce requirement.

12 https://rhg.com/research/state-ccs/

13 https://www.bls.gov/regions/southwest/news-release/areaemployment_houston.htm

Supply Chain

Based on data from the DOE Supply Chain Deep Dive Assessment report (2022)[14], we analyzed the supply chain in the U.S. energy sector industrial base to develop key findings.

- In aggressive infrastructure deployment scenarios, the United States' likely upper bound of CCUS capacity is 1.7 gigatons per year (Gtpa) by 2050. This report considers 2 Gtpa as the upper bound as a conservative approach.
- Among all the available technologies, solvent-based capture using Monoethanolamine (MEA), CO_2 drying using triethylene glycol (TEG), steel pipeline transportation, and geologic storage are most likely to meaningfully contribute to this infrastructure buildout.
- Through 2050, the United States will require 13.7 megatons (Mt) of MEA (833.96 kilotons (kt) in the year 2050), 632.1 kt of TEG (40.57 mt in the year 2050), 24–32 mt of steel, and 1.1 mt of cement yearly.

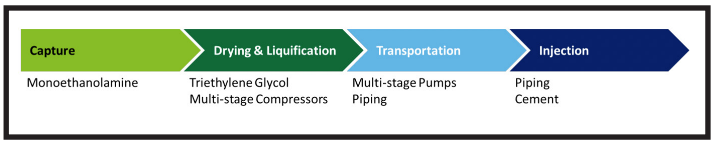

Figure 18. Schematic diagram of the carbon capture and sequestration process and associated material requirement.

As shown in Table 1, the Reference case does not pose any risks to supply chain material requirements. However, In the Accelerated and Net Zero scenarios, there is a potential risk of delayed receipt of materials, especially long-lead items (compressors, pumps) and steel pipes due to concurrent construction of CCUS projects, the growing LNG industry (industry experts forecast a global boom for the next 10 years) and announced blue hydrogen and ammonia plants (construction planned in the next 5-10 years).

Material		Production	Base Case	Accelerated	Net Zero
MEA		Produced from Ammonia and Ethylene Oxide, both are produced mostly in the Gulf coast (Texas and Louisiana)	● Low Risk	● Medium Risk	● High Risk
TEG		Global production is small with US (Gulf Coast) contributing 3%	● Low Risk	● Low Risk	● Low Risk
Steel	Pipeline Injection & Monitoring Wells	US is the 4th largest producer of steel. Global steel pipe capacity (80 Mt in 2020) . Ample opportunity for sourcing n the allied countries of Brazil, Germany, India, Italy, Japan, and Korea.	● Low Risk	● Medium Risk	● High Risk
	Pumps	Established domestic and international suppliers for O&G industry	● Low Risk	● Medium Risk	● High Risk
Cement (Injection & Monitoring Wells)		Texas, Missouri, California, and Florida led the United States in production, and accounted for about half of domestic production	● Low Risk	● Low Risk	● Low Risk
Pumps (Cast Iron)		US is also one of the largest producer for Cast Iron	● Low Risk	● Medium Risk	● High Risk
Compressors		Established domestic and international suppliers for O&G industry	● Low Risk	● Medium Risk	● High Risk

● Low Risk ● Medium Risk ● High Risk

Table 1.

Recommendations to mitigate supply chain risk include: (a) Identify suppliers and assess delivery capacity at early stage of projects and (b) develop alternate suppliers as a backup in case of disruptions posed by a Black Swan event such as the COVID pandemic or the Ukraine-Russia war.

As we have noted throughout this report, the Houston Gulf Coast region has tremendous advantages in efforts to establish CCUS at scale and, at the same time, position the region as the national and global leader in using carbon capture technologies to help reach Net Zero targets. The clustering of emission sources, existing infrastructure, and suitable geology all are important, as are the companies located here that are willing to invest in this new and growing field. Decisions about those investments must begin to take shape now, as we have outlined in the preceding pages.

But if we are to substantively address rising carbon emissions, industry cannot shoulder the burden alone. Local, state, and the federal government all must work together with supportive policies to guide the growth of the enabling infrastructure, to strengthen the nation's supply chains, and to prepare its workforce for the jobs of the future. That work must also begin concurrently with the investments discussed here.

FOOTNOTES

[1] U.S. Environmental Protection Agency's Facility Level Information on Greenhouse gases Tool (FLIGHT) (2021), retrieved from: https://ghg-data.epa.gov/ghgp/main.do?site_preference=normal

[2] Denbury Pipeline network (2023), retrieved from: https://www.denbury.com/operations/pipeline-network/

[3] National Petroleum Council (NPC) report (2019), retrieved from:
https://dualchallenge.npc.org/

[4] National Pipeline Mapping System (NPMS) public viewer (2023), retrieved from: https://pvnpms.phmsa.dot.gov/PublicViewer/

[5] National Energy Technology Laboratory (NETL) (2023), retrieved from:
https://www.netl.doe.gov/

[6] Baker Institute Texas CCUS Map (2021), retrieved from: https://www.bakerinstitute.org/texas-ccus-map

[7] National Energy Technology Laboratory (NETL) report "Best Practices: Site Screening, Site Selection and Site Characterization for Geologic Storage Projects (2017), retrieved from:
https://netl.doe.gov/sites/default/files/2018-10/BPM-SiteScreening.pdf

[8] U.S. Environmental Protection Agency (EPA) Underground Injection Control (UIC) Program Class VI Well Site Characterization Guidance (2013), retrieved from:
https://www.epa.gov/sites/default/files/2015-07/documents/epa816r13004.pdf

[9] Electric Reliability Council of Texas (ERCOT) Capacity, Demands and Reserves report (2023), retrieved from:
https://www.ercot.com/files/docs/2023/05/05/CapacityDemandandReservesReport_May2023_Revised2.pdf

[10] Region H Regional Water Planning Group Volume I (2021), retrieved from:
https://www.twdb.texas.gov/waterplanning/rwp/plans/2021/H/RegionH_2021RWP_V1.pdf

[11] The water footprint of carbon capture and storage technologies (2021), retrieved from:
https://www.sciencedirect.com/science/article/abs/pii/S1364032120307978

[12] Rhodium Group Report (2021), retrieved from:
https://rhg.com/research/state-ccs/

[13] U.S. Bureau of Labor Statistics (BLS) employment report (2023), retrieved from:
https://www.bls.gov/regions/southwest/news-release/areaemployment_houston.htm

[14] U.S. Department of Energy (DOE) Carbon capture, transport, and storage report (2022), retrieved from:
https://www.energy.gov/sites/default/files/2022-02/Carbon%20Capture%20Supply%20Chain%20Report%20-%20Final.pdf

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