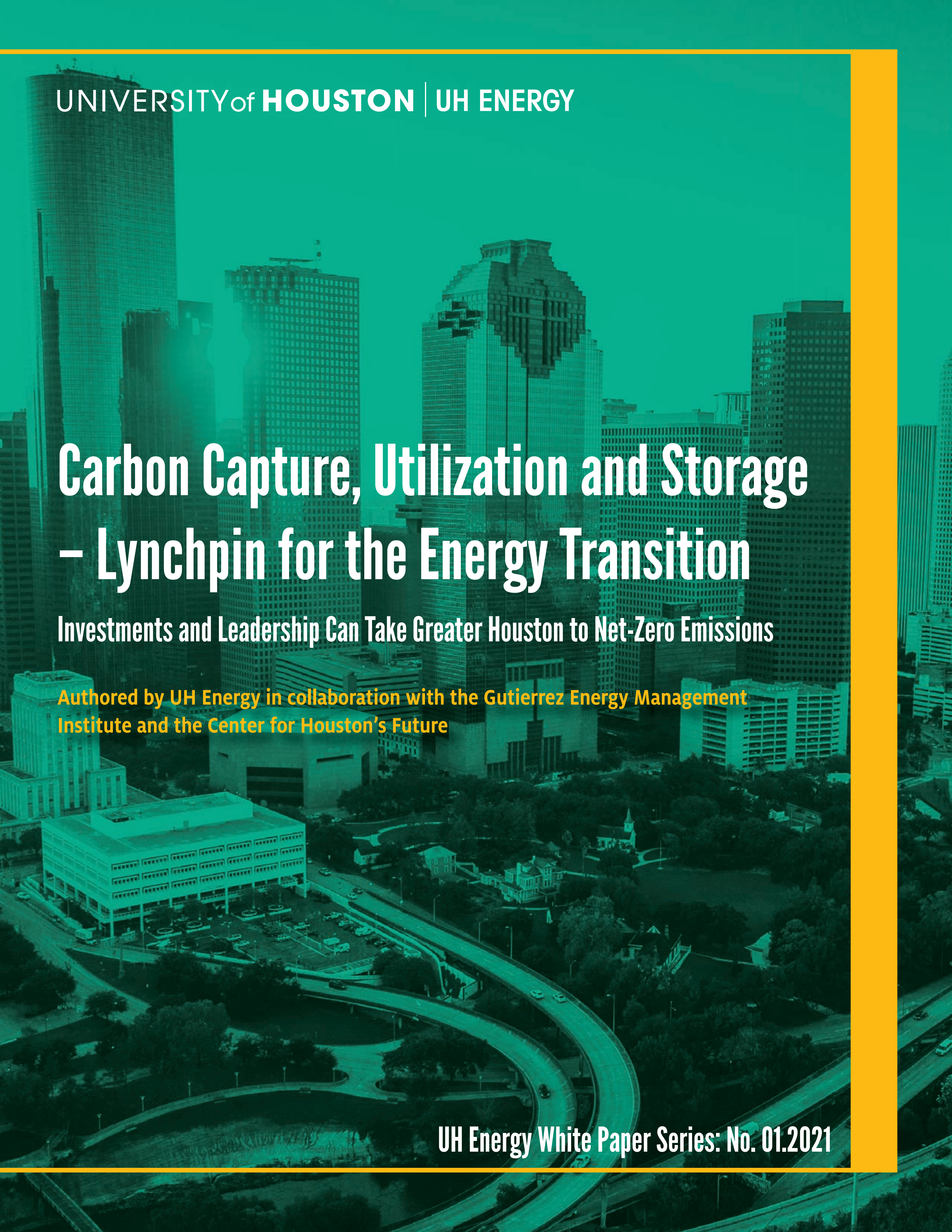

UNIVERSITY of HOUSTON | UH ENERGY

Carbon Capture, Utilization and Storage – Lynchpin for the Energy Transition

Investments and Leadership Can Take Greater Houston to Net-Zero Emissions

Authored by UH Energy in collaboration with the Gutierrez Energy Management Institute and the Center for Houston's Future

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McConnell is currently a board member of the Energy & Environmental Research Center (EERC) Foundation in North Dakota, is 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).

Executive Summary

The energy transition will require a number of new technologies, none more critical than the broad commercial deployment of carbon capture, utilization and storage, or CCUS. The ability to decarbonize the existing energy value chains in the oil and gas, petrochemical and electric power industries is essential both to immediately impact emissions and to create a commercially sound pathway to a sustainable energy future.

The International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Energy Information Administration (EIA) have all recognized CCUS as critical if we are to achieve the necessary climate targets through reduced emissions. CCUS and the required infrastructure will also provide the foundation for a future clean-energy hydrogen economy, a lower-carbon petrochemicals circular economy and a decarbonized electric power grid.

In order for Houston to remain the energy capital of the world, it must lead in several critical aspects of the energy transition, including CCUS. That leadership means ensuring the energy mix is sustainable not only in terms of providing reliable and affordable energy to meet growing global demand – the city's traditional role – but also ensuring that carbon emissions associated with that energy are dramatically lowered.

We have developed an analysis and created an investment thesis to illustrate what steps will be required in order for the Greater Houston region to expand the use of CCUS, building upon existing resources and dramatically lowering emissions from power plants, refining and other manufacturing operations while developing low-carbon products to meet demand over the coming decades. This model is our effort to build in capital and operations costs and necessary expansions and to drive out the business returns that the marketplace should expect with the scenarios of assumptions and the realities of return on investment.

Our goal was to define a pathway for the Greater Houston area to reach net-zero carbon emissions by 2050, amounting to a reduction of about 52 million tons/year from the various industry point sources of energy production and carbon emissions. It will be expensive, as required investment capital for carbon capture technologies, pipelines and geologic storage capacity development will be as much as $10 billion over the 30-year period, and the operations and development of a commercial business in CCUS will require ongoing expenditures. However, the cost of not developing CCUS in Houston is an existential threat to these industries and to global energy leadership.
But here is the most important consideration. The industries, infrastructure, geology and marketplace participants in Houston are positioned more favorably than anywhere else in the world to immediately jumpstart a regional CCUS hub and ecosystem to service Texas, the Gulf Coast and the extended U.S. energy system and to enable its businesses to export this capability internationally.
Our findings, and the necessary steps to get there, are explained here.

The Greater Houston region's geography and proximal geologic capacity for both permanent carbon storage and for use in enhanced oil recovery (EOR) is unmatched anywhere else in the world. The region's oil and gas, petrochemical and electric power industries produce significant CO_2 emissions in a geographic cluster ripe for capture. The region also has the backbone of the necessary pipeline infrastructure to start this work, providing connections between industries that produce the emissions and suitable storage. Industry players see the opportunity and understand why the Houston region should be the first mover.

The recent National Petroleum Council (NPC) study, "Meeting the Dual Challenge – A Roadmap to At-Scale Deployment of CCUS," made clear that Houston and Texas offer world-leading "hub and cluster" advantages that are key to accelerating deployment over the next decade and achieving broad market penetration by 2050. The NPC study created three phases, spanning 2020-2045, defined as Activation, Expansion and Broad Deployment. We incorporated this phased deployment construct for our Greater Houston analysis, outlining a three-phased plan to significantly reduce industrial emissions in the three-county region – Harris, Galveston and Chambers counties – and the expansion of CCUS along the Gulf Coast by 2050.

Perhaps our most meaningful discovery was that the use of Texas' and the Gulf Coast's geologic storage capacity (both onshore and offshore) would allow the region to play a far more significant role in reducing emissions from industrial sources throughout the United States.

In fact, the Greater Houston region alone could comfortably account for half or more of the total NPC study target, or 200 million tons/year of CO_2 emissions. Our key conclusion is simple: If CCUS cannot succeed in the Greater Houston region, it is unlikely to be effectively implemented anywhere.

Key regional assets include:

- A ranking of industry clusters with significant CO_2 emissions to determine the most impactful investments for reductions. These clusters can be linked to create a network connected with geologic storage sites, providing an established network that could be leveraged for future investment.
- Significant existing pipeline infrastructure that can be used immediately, with a favorable business ecosystem to expand pipeline access for both carbon dioxide and hydrogen, as well as for electric power line grid expansion and optimization. The region can not only accommodate but also optimize infrastructure investment in terms of right–of-way access and effective construction and project implementation.
- Leaders of the region's major energy operations are motivated by global market demand for decarbonized products and operations. Many of these companies have declared their intent to significantly reduce carbon emissions and in some cases have net-zero aspirations.
- The workforce is skilled and educational resources are in place to provide the constituent parts for both today's and tomorrow's workers, from technology and engineering to operations and maintenance. Supporting skills in legal, policy and business will also be essential, and Houston has the means and expertise to provide the necessary education for the future workforce.

Our research suggests the region can effectively use CCUS to remove the identified 52 million tons/year from current emissions sources by 2050, achieved through systematic steps over the next three decades. That will start with the initial 10-year Activation Phase, which goes through 2030, and continue with the Expansion and Broad Deployment Phases continuing through 2040 and 2050 respectively. (It should be noted that it is likely total emissions will be lower by 2050 due to other significant technology and optimization actions across the marketplace, but we used current data in order to ensure the region is prepared.)

Specific decade-by-decade targets include:
Activation, 2020-2030

- Existing natural gas electric power generating facilities and methane-based steam reforming hydrogen plants require lowest-cost capture investments and minimal connection investment to pipeline and geologic targets. Lowest-cost emissions sources were identified up to the point of filling existing transport infrastructure.
- The Denbury Greencore Pipeline, with nearly 13 million tons/year in existing capacity to transport CO_2, is positioned to receive captured CO_2 from identified Gulf Coast industries and to access geologic sinks east of Houston, both offshore and onshore.
- Geologic storage proximal to this pipeline is capable of receiving 1 billion tons of CO_2 for enhanced oil recovery and an additional 1 trillion tons into saline storage formations both on and offshore.

Existing infrastructure, coupled with adequate financing and incentives, will allow the region to demonstrate the practicality of large-scale CCUS commercialization, along with its ability to remove more than 12 million tons/year of carbon emissions during the coming decade.

Expansion, 2030-2040

- Expand carbon capture to include the remaining 6.4 million tons/year of CO_2 from natural gas-fired power plants and 13.5 million tons/year from refining, petrochemicals and other industrial processes.
- Expand the pipeline network for east and central Texas and into the Dallas-Fort Worth basin to provide as much as 30 million tons/year of capacity to reach additional geologic storage. Cost of a 250-mile pipeline expansion is estimated at $500 million.
- The Dallas-Fort Worth area is estimated to have 3.6 billion tons of available geologic storage for enhanced oil recovery and 500 billion tons of saline storage.
- The study used pipelines to expand the network of both pure storage and EOR, as well as a new pipeline network. Offshore capacity for CO_2 storage east of Houston may be a more attractive option for reasons related to surface and pore space rights and ownership and is sure to be explored in the Activation Phase through business development. In either case, investment in additional pipeline capacity will be necessary.

Broad Deployment, 2040-2050

Phase 3 was designed to take the Greater Houston region to net zero and will move efforts beyond the three-county region to stretch south

and east along the Gulf Coast.

- Expanding capture to include 11.4 million tons/year from industrial furnaces and 7.8 million tons/year from refinery catalytic cracker facilities, fully capturing the region's existing CO_2 emissions.
- Building a 500-mile CO_2 pipeline from Houston to the Permian Basin, capable of transporting 20 million tons/year and estimated to cost between $1 billion and $2 billion.
- The Permian Basin would provide an additional 4.8 billion tons of storage for EOR and 1 trillion tons of storage in saline formations; it would allow industry from across the United States to use the geological assets in Texas.

Substantial capital will be required to construct both capture facilities and pipelines, as well as to develop the geologic field infrastructure, but the payoff will benefit all of Texas in terms of jobs and a leadership position in the coming sustainable energy economy.
Long term, there will be global demand for the technology and intellectual capital related to CCUS that will be created here, as well as for the low-carbon products. Lower-carbon crude oil, natural gas, plastics and hydrogen would all be significantly impacted, along with decarbonized electricity used for energy production and the potential for other products produced from the utilization of CO_2 as a commodity feedstock.

It is widely recognized – by the marketplace, the U.S. Department of Energy (DOE) and the global community – that now is a critical time to accelerate the commercialization of CCUS. That will require a market-based approach, differentiated from current projects which have relied on government funding coupled with industry cost-share. Local and national government support will continue to be necessary, but successful commercialization will require a fully functioning commercial playing field of emitters and capture facilities, pipeline operators and infrastructure development, along with the geologic field operations for long-term safe and permanent storage of CO_2.

THE MODEL

In order to lay the groundwork for sustainable, commercially sound investment, we considered the investment required to make CCUS a commercial reality and the expected resulting business case scenarios. We then built an investment model using a full value-chain analysis to illustrate a variety of externalities. The business case model analyzes 20-year investment economics of the full value chain, as if the investment for the entire project was made by a single investor. This is, of course, not the reality, as projects will involve multiple investors, but it provides an analysis with a full value-chain view. The model identifies the most impactful assumptions and investment considerations and addresses potential policy and technology implications. It is not a tool to create a singular answer but a tool for the future, as the assumptions, inputs and scenarios, and individuals investing in discrete pieces of the value chain, will be continuously improved. Investors, emitters, operators and service providers all have their own view of risk, but from an overall perspective the model provides a tool to analyze discrete portions of the value chain.

The NPC study offered broad national findings and created cost curves and impacts. We regionalized costs for operations of world-scale facilities and capital costs based on Gulf Coast installed costs. Existing Internal Revenue Service incentives (the 45Q tax credit over the life of the project) were anticipated to extend beyond current 12-year horizons as part of our 20-year analysis. We did not assume technology cost advancements or significant cost improvements over time; as such, the costs we used should be considered conservative, incorporating no upside for cost reductions over time. In fact, the implications of significant cost improvements can be modeled and the impacts assessed. Policy considerations – such as carbon pricing mechanisms (e.g. emissions trading systems, taxation), significant changes to fuel standards or carbon intensity requirements for energy products – were not assumed as part of the model; they would also have significant long-term impacts.

We began with a base case of assumptions that mirrored the foundational set agreed by the participants in the NPC study. These assumptions on such critical factors such as the cost of capital, acceptable internal rate of return expectations, equity and debt financing, etc. are all variables for consideration and modeling. We do not advocate any position on such business thresholds, but simply recognize the impact to solving for investment scenarios and provide a tool for analysis.

Finally, we did not consider the end of the 20-year investment period and the long-term life cycle analysis of CCUS risk and cost vs. comparisons to alternative decarbonization value propositions. Our work instead provides a mechanism for making current-state comparisons and allows for the use of long-term externalities to model investment decision-making. The scenario evaluations should not be used to solve for the "most probable case" but to bracket the risks and impacts to such scenarios through the investors' lens. For policy-makers, it provides a mechanism to model policies for the consequences, intended or unintended.

As in the case of supply infrastructure development specifically in the gases industry, the first movers will be challenged by the first-investment original costs and returns, but it is widely accepted that those that follow will be advantaged by these initial investments and long-term returns will be considerably healthier.

ACKNOWLEDGEMENTS

We should recognize the concurrent work by other researchers from the University of Houston and Center for Houston's Future in the areas of the new hydrogen economy, the future decarbonized electricity grid and the circular plastics economy. Specifically Brett Perlman from the Center for Houston's Future as well as my colleagues at the University of Houston Greg Bean and Dr. Ramanan Krishnamoorti This focus on Greater Houston gave us a perspective into both the environmental impacts and the growth and economic impacts related to the energy transition. The other three areas also require CCUS as an enabling technology. We adopted the NPC structure, answering the high-level recommendations from that report with specifics to the Houston region and marketplace. We extend our gratitude to the GaffneyCline team and in particular, Nigel Jenvey, the Global Head of Carbon Management, for their expertise and

insights but also their engagement with our UH research team. Cost curve information for point source emitters and CO_2 removal investments was of immeasurable value in providing real-world numbers for our model. Jenvey also provided strong leadership to the overall NPC study team (2018-19) and in particular, the sub-groups in which this writer was a participant, and his guidance was critical for the regionalization of overall costs. Jenvey has reviewed this paper, and we are grateful for his contributions.

Also the geologic references and infrastructure details were graciously provided by Steve Melzer from Melzer Consulting and from Mike Godec from ARI. Their contributions and openness in the discussions with our research team made for strong experiential learning.

And finally my personal thanks to the team for the research and writing contributions of Makpal Sariyeva and Brad Peurifoy, as well as research provided by Paty Hernandez. All are recent UH graduates successfully working in the energy field and are committed to CCUS in their professional efforts going forward. It was a pleasure to have them on our team.

Why CCUS?

CCUS is effective for both the decarbonization of existing hydrocarbon-based energy processes and for the deployment of new low-carbon energy production. Where alternatives to hydrocarbon fuels and feedstocks are either not available, not practically deployed or are prohibitively expensive, CCUS provides a critical option. It allows the technology focus to be about reducing emissions and making a sustainable impact in terms of energy supply, reliability and cost. CCUS can enable a near net-zero CO_2 footprint for oil and gas in the upstream and downstream processes, as well as in the petrochemical sector. Electric power supply to customers and the integration of renewables such as wind and solar will continue to rely on the baseload 24/7 delivery of hydrocarbon-based electricity; CCUS enables such electricity to be carbon-free.

CCUS is a commercially proven and robust technology to reduce emissions and allow the sustainable use of all fuel sources to address

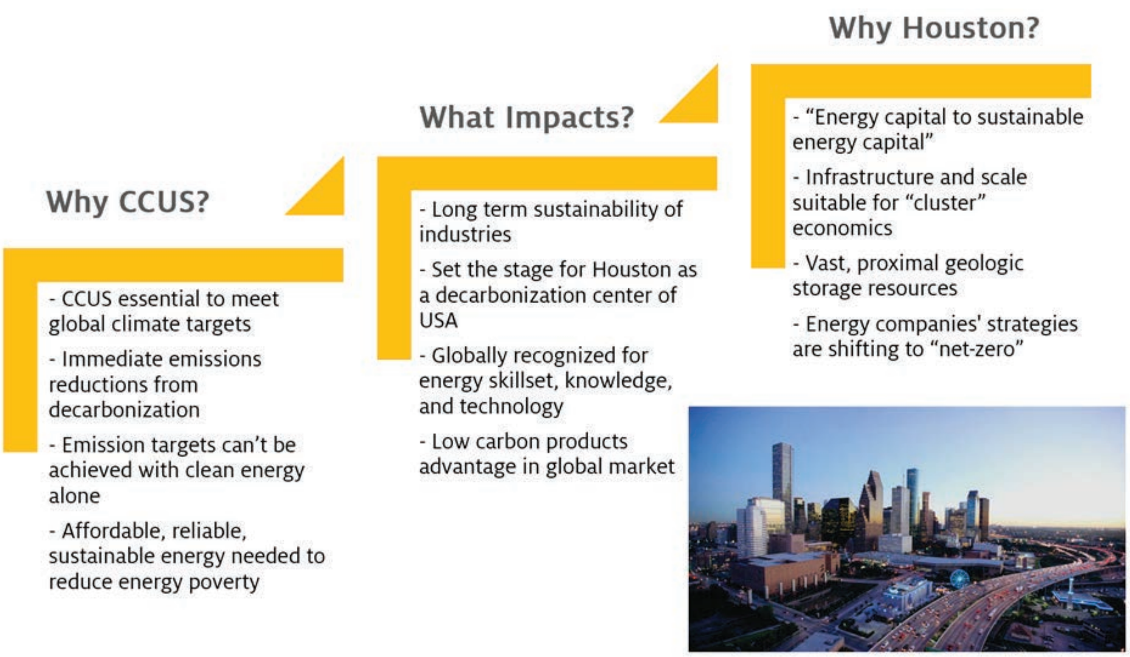

Figure 1. Roadmap process for the implementation of carbon capture, utilization and storage (CCUS) in the Houston Region.

global market demand. Broad deployment has lagged due to a lack of marketplace commercial support in the form of incentives and a cost structure that, without unique attributes, has made the risk and project investment hurdles unattractive. However, the marketplace landscape has changed many of the key drivers for investors, as has global awareness of the need to decarbonize.

The IEA, the IPCC, the U.S. EIA and the U.S. DOE have all concluded that without deployment of CCUS globally, the climate targets set by the Paris Accords and the emissions reductions required to meet them cannot be achieved. The IPCC has estimated that 10%-20% of global CO_2 emissions reductions must come from using CCUS on stationary emissions sources, largely from the industries heavily represented in Greater Houston and along the Gulf Coast, including oil and gas, petrochemicals and electric power. Other industries, such as cement and steel manufacturing, are also targets. Suffice it to say the technology is not only important but essential. The energy transition will succeed though a strategic approach to sustainable energy development, focused on satisfying what is known as the Energy Trilemma – energy supply that is reliable, affordable and environmentally sustainable.

Figure 2. The ENERGY TRILEMMA – the elements of true energy sustainability

As we view the energy landscape over the rest of this century and in particular from 2020-2050, there are major challenges as 80% of current global energy supply comes from hydrocarbon-based fuels. Renewables and other forms of alternative energy will be essential over the next 30 years, growing rapidly in market share and impact, but they will not be sufficient to address the global need to decarbonize. The best portfolio of energy options must allow choice, specific to the market. CCUS is not universally compelling; neither is wind, solar, hydroelectric or nuclear. The best choice will come from maximizing options for a low-carbon future and providing a long-term platform of decarbonized options.

What Impact Can CCUS Deliver?

There is a long-term existential threat to the industries that have positioned Houston as the energy capital of the world. To remain relevant and a major supplier of fuels, plastics and electricity, the region must decarbonize. Greater Houston currently hosts nearly 50% of U.S. crude oil refining capacity and 10% of global refining capacity. Regional petrochemical production is not only critical to meeting U.S. demand but is globally competitive, making a significant contribution to the U.S. balance of trade. And our energy system is underpinned with low-cost electricity, providing a production cost advantage.

All of this hydrocarbon-based energy production results in carbon emissions and an impact to long-term sustainability, but it also offers potential rewards. The region cannot, nor should it, abdicate its role in supplying affordable and reliable energy to the world. Instead, it must lead the transition to supplying energy that is both sustainable and affordable. The goal is lowering and eliminating carbon dioxide emissions and deploying technologies to create the most effective way to measure and index such impact.

Short-term, and longer term over the coming 50 years, that will require continuing to produce and use oil, natural gas and other hydrocarbons. CCUS can make that viable by reducing emissions from existing operations as we develop a scalable long-term sustainable model. Long-term emissions reduction will be a natural evolution of a system-wide approach. We have commercially practiced CO_2 EOR for over 70 years in Texas and

“CCUS is a commercially proven and robust technology to reduce emissions and allow the sustainable use of all fuel sources to address global market demand.”

have been a leader in national carbon storage demonstration efforts over the past 20 years, with projects supported by DOE and industry leadership, including projects in the power sector at NRG's W.A. Parish Plant in Fort Bend County; in the industrial sector with Air Products and Chemicals Inc. in Port Arthur; and enhanced EOR and storage in an around Greater Houston through the Southeast Regional Carbon Sequestration Partnership of the Southern States Energy Board. This work has validated not only that the regional geology can provide safe and effective permanent storage, but has demonstrated field and operational leadership. These projects have generated best practices by DOE and the National Energy Technology Laboratory (NETL).

The region has a number of existing and planned individual CO_2 capture projects in several market areas; a pipeline transportation grid currently in place with capacity for expansion; and a number of developed storage geologies that can be immediately used and leveraged for expansion and growth.

A longer-term impact will be the ability to create a suite of lower carbon products, technologies and knowhow that can be marketed globally, positioning the region to lead in the production and sale of cost-competitive, environmentally friendly energy technologies and projects. Examples include decarbonized refined fuels, petrochemicals, plastics and hydrogen.

Why Houston?

Greater Houston is the obvious place to jumpstart and rapidly accelerate CCUS. It offers:

- The potential for significant emissions reductions – an estimated 52 million tons per year in Harris, Galveston and Chambers counties alone.
- Proximal geology with the capacity to store billions of tons of carbon, providing a pathway for broad deployment and utilization well into this century.
- Available pipeline infrastructure and right of way access that provides an opportunity to leverage investment and to grow the infrastructure footprint.
- The workforce and expertise needed to expand CCUS, with regional capacity to educate both existing workers and the future energy workforce. There are opportunities for experiential learning in CCUS and strong university commitments to the development of the skills and talent needed for the future.
- Perhaps most importantly, industries in all energy segments have declared a willingness to participate, lead and invest in CCUS in response to global public opinion. Economic assumptions and scenario modeling suggest investments are not only doable but can create long-term strategic value as a backbone to the industrial base. (The IPCC report notes that achieving the same CO_2 emissions reduction targets by 2050

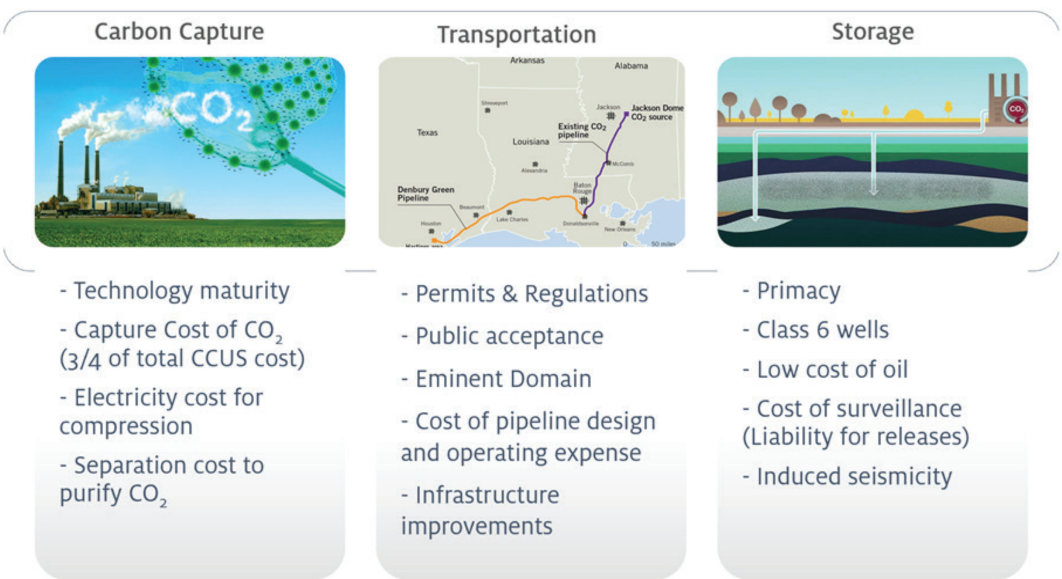

Figure 3. Key Challenges Ahead – The 3 key elements of the CCUS Value Chain

without CCUS is 139% more expensive in terms of overall global cost.)

Legal and policy challenges to accelerate the marketplace remain. A CCUS commercialization consortia made up of the full public-private stakeholder community would extend to the state(s) impacted, societal stakeholders, non-governmental organizations and the investment community. The leadership of carbon-emitting industries that have pledged to decarbonize is essential.

The Capture Challenge?

The DOE and NETL repository of global CCUS activities recognize the U.S. as the global leader in carbon capture investment as well as projects, responsible for 85% of the world's captured anthropogenic emissions. That is due significantly to the multi-year efforts of the Regional Carbon Sequestration Partnerships and geologic best practices, the advancement and deployment of CO_2 capture technology and project support from DOE to industry participants. The most expensive component of the CCUS technology value chain is the capture process, which includes the compression and purification of CO_2, making it "fit for purpose." Estimates range from 50%-75% of the total CCUS cost, depending on emissions sources, status of existing infrastructure and technology maturity. But while U.S. leadership in CCUS is noteworthy, today's volumes of captured CO_2 do not significantly impact global emissions. The sheer scale of energy-related carbon emissions in Greater Houston and across the United States suggests an ambitious slate of CCUS projects will be required for significant emissions reductions. The NPC reports that energy-related CO_2 emissions nationally reached 5.3 billion tons/year in 2017. Our investment model and analysis construct can be used in other hubs and clusters by using specific details for those areas to inform local results.

Three counties in the Greater Houston region – Harris, Galveston and Chambers – emit 52 million tons of CO_2 per year from point source industrial emissions sites. This three-county region provided a sub-segment that enabled the study to envision a Greater Houston region of point source emissions that could be assessed for 100% decarbonization, or net zero. The U.S. Gulf Coast would expand the study boundary substantially, providing a wealth of attractive point sources in terms of cost and investment. This would affect not only Texas but Louisiana and beyond. We are confident the U.S. Gulf Coast could account for at least half of the overall NPC goal, the capture of more than 400 million tons/year via broad commercial deployment.

By segregating the emission volumes in the three 10-year phases (Activation, Expansion, Broad Deployment), we created a more focused analysis process to rank the attractiveness for capture investment at the points of emission and for overall aggregation. Four unique facility types were considered:

- Hydrogen production from steam methane reformers (SMRs), known as gray hydrogen due to the CO_2 emissions from the shift reaction in the hydrogen generation process
- Industrial furnaces in process plants as energy production and sources of process heat
- Natural gas-fired electric power plants (combined and simple-cycle). There were no coal-fired electricity generating facilities in the three-county study area, but such facilities would be critical to decarbonization in a broader geographic assessment, especially in the U. S. Gulf Coast evaluation
- Refinery fluid catalytic crackers

  Industrial furnaces combusting methane or hydrocarbon fuel to create process heat and steam emit the highest levels of CO_2 of the four sources. Thus they offer the largest field of play to impact emissions, but they also are the most difficult and costly to address as they are dispersed throughout facilities, are replacement or electrification.

As such, these furnaces are not the best initial opportunities, as prioritizing impact for investment suggests the initial focus should be hydrogen production from SMRs and natural gas-fired electric power plants.

SMR hydrogen production equipped with carbon capture will be the most cost-effective investment, with an estimated average capture cost range of \$65/ton to \$85/ton at an 85% utilization rate. Capture costs for natural gas power plants and refinery fluidized catalytic crackers average \$117/ton and \$124/ton respectively. That rises to more

than $140/ton for industrial furnaces. These costs were normalized for investment using Gulf Coast installation costs and taking advantage of the region's world-scale facility size.

The cost of capture, purification and compression is a systems cost that can be customized and optimized as well. Scale-up, integration, process intensification and advanced controls are all potentially accretive to overall costs and will be an ongoing source of R&D and commercialization investment as the CCUS market evolves.

THE INFRASTRUCTURE CHALLENGE

Pipeline infrastructure is critical to the transport of CO_2 from emissions sources to geologic storage sites. Existing pipelines are available, but implementation will require expansion and investment. This will drive policy and regulatory action to further both the access and approval of right-of-way, as well as construction permitting. The existing Denbury CO_2 pipeline network, owned by Denbury Inc., extends into Houston and is proximal to the point source emitters targeted in Phase 1. The system currently carries only one-third of its available CO_2 capacity and can be leveraged to transport 12 million tons of CO_2 per year between 2020 and 2030.

For EOR and other storage alternatives considered for the study, the existing Permian Basin and Gulf Coast geological storage sites, both onshore and offshore, can be used based on economic and technical analysis. EOR and pure storage each have various criteria – the price of oil, capture costs, government policy, long-term liability, incentives, etc. – discussed elsewhere in this paper. Using existing oilfields where CO_2 is currently used for EOR and where the infrastructure is in place to enable incremental CO_2 delivery for additional oil production is a particularly attractive option from both an emissions reduction and cost standpoint. This approach cannot singularly meet the total emissions reductions targets but provides an opportunity to galvanize work with minimal field infrastructure investment. The Activation Phase can gain great advantage from this existing infrastructure.

Taking Houston to Net-Zero

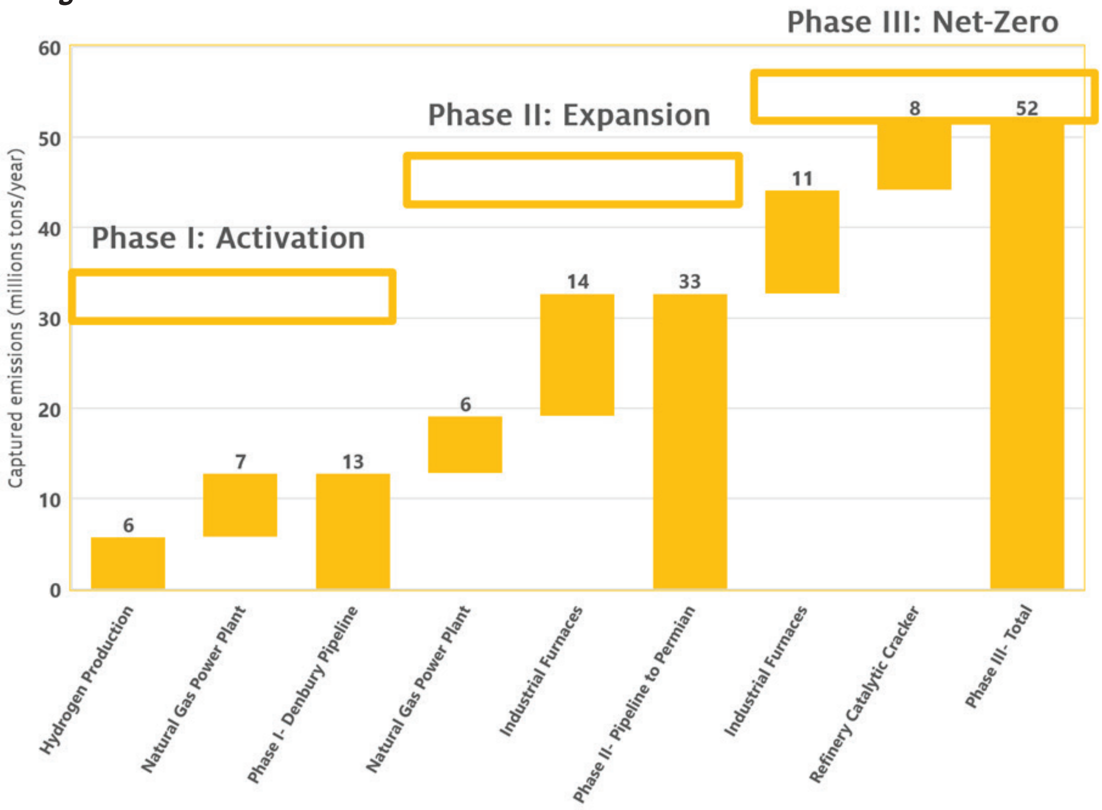

Figure 4. The 3 Phases of Carbon Capture – Identification of Emissions Sources and Capture Investments

Federal and state government policy support will be critical to address other technology and infrastructure challenges. That goes beyond investment incentives but includes market support to de-risk investments and provide long-term clarity and assurance of permits, operability and governmental support of CCUS as a key part of the energy system. The concept of common carrier CO_2 pipelines has been adopted in Europe as infrastructure for the "common good" and clearly will command attention in the U.S. for broad deployment.

Critical infrastructure isn't limited to CO_2 pipelines but also includes hydrogen pipelines, right of way and construction of electrical power line transmission to further enhance the grid. The infrastructure in and around Houston is a significant component of the region's competitive advantage, and a successful energy transition will demand strategic development and support. Investor confidence in a rule-based permitting process and permitting agencies that are aligned with the societal good of CCUS will also be necessary.

THE GEOLOGIC STORAGE AND UTILIZATION CHALLENGE

In addition to existing midstream infrastructure and a large volume of industrial emissions, Houston has the essential third component required for successful CCUS implementation – it is home to a vast amount of proximal geologic storage that is unmatched globally. The geologic storage exists in several forms with varying degrees of economic feasibility. We focus on two types: those suitable for EOR as the main form of utilization and combined storage today, and saline aquifers for pure storage.

There are significant risks – both real and perceived – that differ with EOR vs. pure storage. Generalizing is difficult, but several observations can be made regarding these two options.

EOR has been practiced for over 70 years in Texas and is currently used to produce over 10% of total U.S. crude oil output. In the Activation Phase, we can quickly target accessible EOR fields near Houston and begin utilizing and storing CO_2 emissions. This can be accomplished using current technology and incentives and by addressing markets where incremental CO_2 can be added to existing systems for greater oil yield. The Denbury pipeline system accesses a number of EOR fields that can make immediate use of incremental CO_2 for increased crude oil production, and these formations will then permanently and safely store the CO_2. These EOR geologic regions are also proximate to a significant amount of suitable saline aquifer storage. As the economics of EOR and/or pure storage play out over a 20-year investment and beyond, the optionality of either play is critical to investment de-risking. These geologic formations are often referred to as "stacked storage," in that the EOR and saline formations are at different depths in the same location. It is critical to recognize that using either approach will provide the absolute assurance of long-term safe and permanent emission storage. It should be noted that while EOR continues to be practiced in the United States in several geographic regions across the country, more than 80% of the CO_2 currently used comes from naturally occurring sources. CO_2 from man-made sources (anthropogenic) is of the same quality but is more costly to deliver to the fields for EOR. It is the use of anthropogenic CO_2 that makes this EOR an emissions reduction process.

EOR is a method of tertiary oil recovery, meaning it is typically performed after primary, conventional production and secondary enhanced gas or water flood stimulation. The geologic formations respond uniquely to primary and secondary oil recovery and resulting efficiencies vary widely, producing as much as 30% to 50% production of commercially recoverable oil in place by using such advanced enhancement techniques. In CO_2 flooding, CO_2 is injected and can sweep the depleted reservoir and produce another 5%-20% of the remaining hydrocarbon. This approach creates two streams of revenue. First, the oil produced can be sold at market price. Second, the CO_2 is permanently and safely stored in the reservoir, allowing the operator to claim a 45Q federal tax credit (currently $35/ton for EOR utilized CO_2) for each ton stored. These revenue streams offset project costs and over time can generate positive project economics with an appropriate incentive structure. The downside risk for EOR (or potential upside) is that investment economics hinge on the price of oil over a 20-year period. Sensitivity to oil price is significant in the 100% EOR strategy.

"Houston has the essential third component required for successful CCUS implementation – it is home to a vast amount of proximal geologic storage that is unmatched globally."

EOR targets for oil and for CO_2 storage are abundant onshore along the Gulf Coast, including Louisiana, Mississippi and Alabama, where there are 204 oil reservoirs that could be exploited using near-miscible CO_2 EOR. These reservoirs contain 6 billion barrels of technically recoverable oil that can be produced with 2 billion tons of CO_2. Also, in future scenarios of the Expansion (2030-2040) and Broad Deployment (2040-2050) phases, the vast east, central and west Texas geology provides over 400 additional oil reservoirs that contain 33.5 billion barrels of technically recoverable oil. That oil can be produced using EOR with approximately 11 billion tons of CO_2. Finally, there are over 600 identified oil reservoirs offshore in the U.S. Gulf of Mexico containing 6 billion barrels of technically recoverable oil that can be produced with 1.8 billion tons of CO_2. These volumes are taken from the carbon storage atlas produced by DOE and NETL.

In total, nearly 14.7 billion tons of EOR storage exists adjacent to Houston, in Texas, along the Gulf Coast and in the Gulf of Mexico. This is not to say EOR always will be the preferred method, as the costs – both in capital and operations and maintenance and resulting revenue trade-offs vs. pure storage – would be assessed by individual investors. But it illustrates the large geologic capacity for CO_2 storage.

The regulatory framework requires that wells be permitted for the application and use and the commonly accepted permitting is defined as a Class 2 well permit for EOR applications. The permitting describes the requirements necessary for development and use and also directly prescribes the necessary closure procedures once the well and formation have served its useful life. This is a long-standing Classification for EOR in the O&G community of operators and regulators.From a legal and regulatory perspective, Class 2 well permitting provides a long-standing structured, rule-based approach with very little ambiguity and thus the investor risk is well understood and acknowledged. This is in contrast to the Class 6 permits applied to pure storage CO_2 wells and sites. The Class 6 permitting was specifically designed to address the injection of CO_2 into geologic formations for the practice of storage of the CO_2. It was developed over the most recent 15-20 years as part of the regional partnerships demonstrations for the research and validation of the safe and permanent storage of CO_2 as a technically proven storage method. Because Class 6 CO_2 storages was originally designed for R&D and studies the Class 6 permitting process for broader commercial applications is far more uncertain than Class 2, open for interpretation, and carries much longer term liabilities for the site well beyond the site operations and closure. This contrast is not to be minimized as a distinct advantage to EOR operations and risk assessment. Class 6 permitting remains a marketplace uncertainty that will continue to receive attention – and thus add to short-term risk barriers to investment.

The Gulf Coast also is home to vast quantities of saline aquifer geologic storage. These saline aquifers are located deep beneath the surface and allow for the injection of CO_2 directly into the reservoir via injection wells. This is a demonstrated methodology for the safe and permanent storage of CO_2, broadly demonstrated through support from DOE and regional carbon sequestration partnerships over the past 20 years. However, without the potential for additional oil production, the current economics are challenging. As with EOR, the operator receives a 45Q tax incentive for pure storage (in this case $50/ton) and although the "certainty" of the $50/ton storage credit is less speculative than EOR revenues, there is no hydrocarbon produced and therefore no secondary revenue stream. There are also regulatory issues, discussed in subsequent sections. The 45Q credit is assessed as a critical sensitivity in our economic analysis section.

Region	Available Saline Storage (trillions of tons)
Onshore Gulf Coast (Louisiana, Mississippi and Alabama)	1.5
Texas	1.5
Offshore Gulf of Mexico	2.3

Despite those challenges, the sheer capacity of saline storage suggests it cannot be ignored. Total saline storage in the Houston area exceeds EOR storage by a staggering 350 times, enough capacity to store not only Houston's captured emissions but also those captured from other parts of the United States. This geologic storage is an asset to be maximized for economic development. The future value of global CO_2 emissions reductions will evolve over time. See the following table for a breakdown of saline storage capacity in Texas and along the Gulf Coast.

PROJECT ECONOMICS, OUR MODEL AND CHALLENGES

Beyond emissions, infrastructure and geologic storage, the key consideration for Houston is economics, that is, can investors count on a "reasonable" return? The answer is yes, with caveats.

We constructed a full-cycle, discounted cash flow model of a hypothetical, current-day CCUS project located in the Houston region. Economic assumptions for cost of capital and return criteria, all equity or debt financing, critical inputs for government tax credits and the price of oil were all considered and can be modeled in a myriad of scenarios.

We began with base investment assumptions in terms of "all equity" and cost of capital at 12%. This was a NPC economic modeling assumption using an open book common methodology. The model is designed to input the assumptions model the effects and create not only all possible assumptions and inputs but determine which assumptions and inputs are most consequential.

We did not model discrete components of the value chain where individual investors might participate, such as "the capture" or "the pipeline" or the "geologic operator." We assumed 45Q credits would flow to the project and that the disposition of those credits would be spread throughout the value chain of participants. The analysis shows striking advantages for the Houston region when compared nationally or globally, including:

- Constructability for individual sites, infrastructure and costs along the Gulf Coast
- Sheer scale of world-class investments
- Right-of-way for infrastructure expansion and access to new sites
- Offshore geologic resources to complement onshore, affording not just additional options but geology that has been characterized and demonstrated during years of oil and gas experience in EOR and pure storage
- Available workforce for both construction and ongoing operations
- Local states that recognize the economic value of additional, EOR-boosted production, as well as the economic value of pore space for storage and offshore rights to pore space for state economic benefit

The level of acceptable investor risk in various parts of the value chain will be individually determined. Additional credits, revenues, governmental support, etc. are considered only as one large investment to the overall project. We believe this approach to be the most beneficial, as individual investors in major energy projects must see "project viability" as a first-order determinate. It is also clear that risk and strategic value to discrete investors will not be universally

> "Beyond emissions, infrastructure and geologic storage, the key consideration for Houston is economics, that is, can investors count on a "reasonable" return? The answer is yes, with caveats."

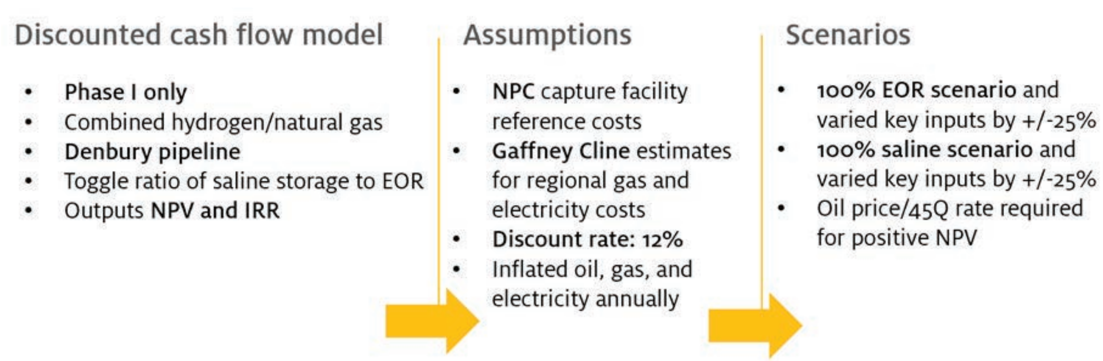

Figure 5. Description of the Economic Model employed in Phase I.

consistent, nor will the strategic weight of the investment be borne equally. The impact in terms of CO_2 footprint and emissions reduction – as well as to those holding a tax appetite for 45Q credits – will be determining factors for project interest and viability. That said, our model can accommodate multiple investors together or delinked.
The model makes clear that, at present in Greater Houston, EOR for storage is clearly the most attractive option due to lower capital investment thresholds and the ability to use existing infrastructure.

The model is based on Phase 1 of our proposed roadmap, where more than 12 million tons of CO_2 from hydrogen and natural gas power plant emissions are captured and transported via the existing Denbury system of pipelines to geologic storage along the Gulf Coast. The model includes 44 inputs and assumptions, based on the NPC Capture Facility Reference Sheet and updated to be Houston-specific. We used estimates for specific regional gas and electricity costs. The model allows the user to allocate captured emissions to EOR storage, saline storage or a mixture, calculating the 45Q tax credit for each use.

A series of analyses were run to provide insights about which parameters most heavily influence project return. It also provided breakeven prices for 45Q incentives and oil price. The sensitivity analyses, which varied certain parameters up and down by 25 percent, were performed on three scenarios:

- 100% EOR storage
- 100% saline storage
- Any number of EOR and saline storage combinations

For scenario 1 (100% EOR) and a 12% cost of capital, the base case provides positive returns. That is to say, project returns in the high single digits is possible with all equity financing. Five of the key 15 parameters considered in the sensitivity analysis had an overwhelming impact on project economics. These parameters, in order of decreasing importance, include WTI oil price, oil recovery, natural gas power plant CO_2 capture capital expenditures, 45Q rate and SMR hydrogen facility CO_2 capture capital expenditures. Capture costs currently make up 75% of project costs and influence the economics substantially. These costs will likely come down in coming decades with additional research and development and

Combined hydrogen and natural gas power plant model – 100% EOR

Sensitivity 1		
Base Case Assumptions (100% EOR)		
Online %	100	
bbls produced per metric ton of CO2	2	barrels
45Q rate (EOR)	$35	$/metric ton
45Q rate (saline)	$50	$/metric ton
WTI oil price	$40	$/bbl
Avg Hydrogen capex	$78,545,000.00	$/unit
Avg Nat Gas Power Plant capex	$527,505,000.00	$/unit
Tie-in pipeline cost per mile	$2,000,000.00	$/mile
Length of tie-in line	151	miles
Electricity usage (Hydrogen)	0.18	MWh/ton
Electricity usage (Nat gas)	0.16	MWh/ton
Electricity price	$10	$/MWhr
Gas usage (Hydrogen)	$2.55	MMBtu/ton
Gas usage (Nat Gas)	$2.80	MMBtu/ton
Gas price	$2	$/MMBtu
Opex, non-energy, annual	0.02	% of capex
Midstream tariff	$10.00	$/ton
Storage cost	$10.00	$/ton
NPV	$ 113,543,909.91	
IRR	12%	

- **Project can be NPV positive with 12% IRR today**.....however
- **US40/bbl price required for 20 years** for project with high-risk potential
- Most influential parameters include **oil price, recovery factor, nat gas capex, and 45Q rate**

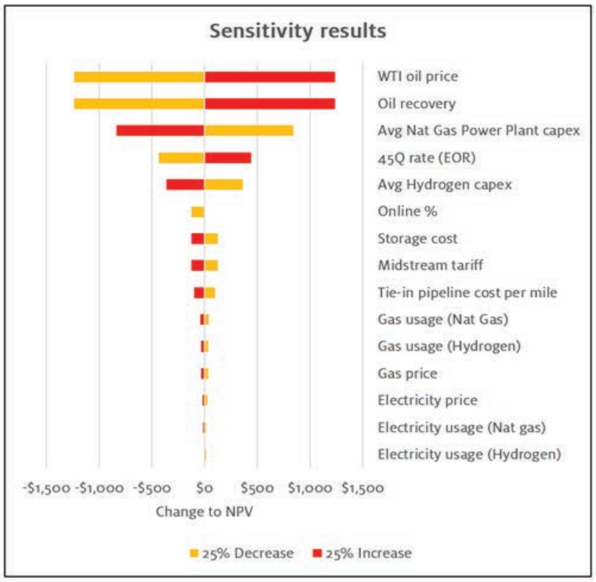

Figure 6. The results of the application of the economic model applied to Phase I under scenario 1 (100 % EOR) of the study described in this report.

as the industry achieves scale. The downside of the analysis highlights that project returns are vulnerable to commodity price and the amount of crude oil produced. An oil price of $40-$60 per barrel for the 20-year period is required for positive returns.

The scenario 2 base case, 100% saline storage, is not attractive for investment but economic inputs could change this perspective. Four parameters heavily impact a 100% saline storage project's viability, including natural gas power plant CO_2 capture capital expenditures, the amount of time a CO_2 capture unit is on stream and operational throughout a year, the 45Q rate and hydrogen plant CO_2 capture capital expenditures. The upfront cost of installing capture equipment to hydrogen and natural gas power plants far outweighs the revenue received from the 45Q subsidies. To make this scenario economically viable, project costs must come down and/or 45Q subsidies must increase. We calculate that the 100% saline storage 45Q rate needs to be at or above $122 per ton. It should be noted that the cost of capital is arbitrarily set at 12% for all modeling in our study, (as it was also used in the aforementioned NPC study) but our model is set up to enable a series of scenarios with multiple cost of capital assumptions, enabling all equity or levels of debt financing, and many other financial mechanisms. Our conclusions are direct results of the assumptions we used and are not positioned as "accurate" for anything other than the assumption scenario chosen. Scenarios combining EOR and saline storage will fall in between these extremes and are likely to be the investor's choice due to optionality and de-risking of the investment.

Although a tremendous amount of detail exists for the economic analysis in the Activation Phase, the subsequent phases – Expansion and At-Scale – make assessments about the necessary capital and construction required to enable these phases. The accompanying charts and maps suggest the enormity of the challenge but also provide a view of the opportunity.

The model was constructed to provide a mechanism to not only analyze scenarios and outcomes but to educate the general marketplace on the impact of real business investment choices and such impacts. Everything matters – but some things matter more. Real challenges in terms of these impacts clarify why investment is more or less "risky" and how such risks can be overcome or mitigated. Business returns and the commensurate returns are what is in question here, and we hope to provide that transparency at a high level for CCUS projects, including showing how the perception of risk is ultimately translated to expected returns. Commercialization is not simply "getting more subsidies" for CCUS, but an honest view of the early stage support from government that can lead to long-term commercial investment and operations. Anticipating policy and governmental change is impossible, but our effort here is to model it and provide real comparative analysis of CCUS projects, which can then be compared to the real analysis of competing lower-carbon energy technologies. This is a key in the effective planning of policies and investment determinations to solve for the "best choice" in terms of reliability, environmental performance and, of course, cost. An example of this is the Integrated Resource Planning process for new electricity generation and/or retirements of existing facilities. CCUS demonstrated technology should be deployed and modeled comprehensively and compared to alternative technologies with the same appropriate rigor.

HOW DO WE GET THERE?

The original project scope defined our research but also uncovered a far more impactful pathway for the U.S. Our methodology and project-based investment analysis – coupled with the geologic capacity in the region – suggest a much greater opportunity: allowing the Houston region to serve as a major hub for decarbonizing much of the nation and to supply international markets with low-carbon products.

Before summarizing regional deployment options for each of the three 10-year phases, we need to highlight the underpinning role of continuing to advance CCUS technologies to reduce costs, improve performance and increase the breath and scale of application for CCUS. As the NPC study highlighted, a commitment to CCUS must include a commitment to research, development and demonstration. While there have been tremendous efforts made to improve CCUS technologies over the past two decades, driven by public/private partnerships, relatively modest transformation has been realized in commercialization. Today, CCUS technologies across the supply chain vary in maturity. More mature technologies, like post-com-

bustion amine-based absorption capture, are well understood and have been used for decades but offer limited further potential for significant improvements. Making Houston a hub for deployment and technology research and development involving emerging CCUS technologies has the potential to spark a much greater impact. This could decrease costs and lower the investment needed to unlock the benefits of at-scale deployment.

Phase 1: Activation

Phase 1 starts now and would capture and permanently store more than 12 million tons of CO_2 emissions per year by 2030. The economic model discussed in the Project Economics section lays the foundation, focused on industries with low capture costs and with the motivation to decarbonize, uses existing infrastructure and EOR storage to reduce capital and operating costs, and maximizes incentives to bolster the project economics.

Capture

The initial 12 million tons per year of captured emissions would come from hydrogen production facilities (SMRs) and natural gas power plants. Seven world-scale SMR facilities emit nearly 6 million tons of CO_2 annually in the three-county region. These facilities represent the most attractive targets, with CO_2 capture costs that are the lowest of all industries at $65-$85/ton. An additional 7 million tons of CO_2 per year can be captured from four natural gas power plants. The capture cost for natural gas power plants is much higher, at $100-$130/ton, but companies operating these facilities are under increased pressure to decarbonize operations.

Marketplace competitive alternatives for zero-carbon footprint electricity generation from wind and solar make the challenge imminent and accelerate the need for CCUS. Wind and solar are providing a growing amount of zero-carbon footprint electricity, but that alone doesn't negate the need for CCUS, particularly in light of ongoing challenges with the needed energy storage capacity required for renewables to provide 24/7 power on demand. Carbon-free electricity that can support the baseload and on demand needs is critical to grid stability. It is worth noting that coupling natural gas generation with CCUS can produce carbon-free electricity available on demand, 24/7, something that currently exists only with nuclear power. System optimization will require the full cost of that available supply to be factored into the analysis of best supply options. In total, the installation of capture technology facilities will result in $3.6 billion of investment into the Houston economy and the creation of high-paying jobs through construc-

Capture

Facility type	Captured emissions (MM tons/yr)	Total investment (bil US$)
Hydrogen	5.7	$1.1
Natural gas power plants	7	$2.5

Transport

Pipeline	Available capacity (MM tons/yr)	Total investment (bil US$/yr)
Denbury	12.9	$0.12

- **Hydrogen emissions prioritized** due to cheaper capture cost.
- **Natural gas power plants second** due to increasing pressure from investors.
- **Denbury currently utilized at 1/3 capacity.**

Figure 7. Phase 1 – Point Source Emissions Facilities and Pipeline Transportation

tion and ongoing operational requirements.

Transport

Phase 1 uses the existing Denbury pipeline, extending 830 miles from Houston east across Louisiana and Mississippi to transport CO_2 captured in the Houston area to a series of EOR fields along the Gulf Coast adjacent to the pipeline. The pipeline has a total capacity of approximately 20 million tons per year but currently operates at one-third of capacity. That remaining nearly 13 million tons of available capacity could be used to transport captured Phase 1 emissions.

The dozen facilities that could contribute captured emissions to the Denbury pipeline are spread across Pasadena, Baytown, La Porte and Texas City. These facilities average 14 miles from the main pipeline; therefore tie-in lines will have to be constructed at an estimated cost $2 million per mile. However, 10 of the facilities are near one another, north of the Denbury pipeline. That could reduce the cost by constructing a single line to feed CO_2 to the main line. Shared infrastructure could also reduce costs for two facilities to the south in Texas City.

The EOR fields are also near pure storage geologic options both onshore and offshore. The opportunity to use this infrastructure immediately is significant.

Phase 1 transport from Houston will require $120 million per year in operating expenses (inclusive of pipeline compression and operations and maintenance charges) and an additional $300 million in capital expenditures to build the tie-in pipelines, assuming each facility builds its own tie-in line. In addition to jobs created for the installation of capture equipment, pipeline construction will create jobs and stimulate the local economy.

Storage

Location	Available storage (bil tons)	Total investment (bil US$/yr)
Gulf Coast EOR	1.4	$0.12
Gulf Coast saline	1,500	

- **Significant EOR storage** is available along Gulf Coast in the form of disparate oil fields.
- Denbury has identified **multiple EOR fields along the pipeline's path.**
- **Saline storage is sufficient** to handle Denbury capacity **for 75 years.**

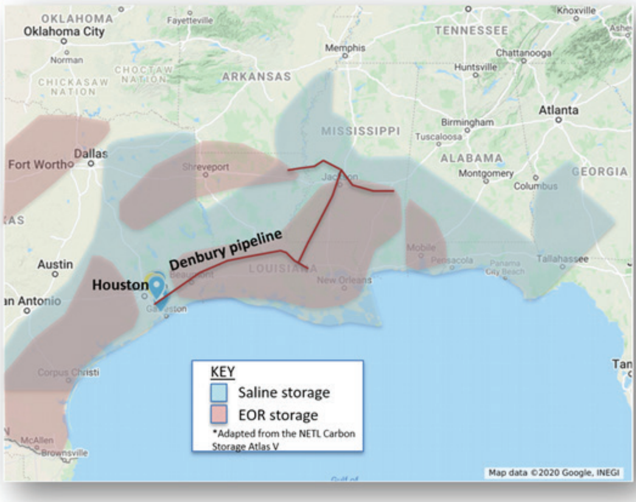

Figure 8. Phase 1 Geologic Storage Target Formations

Storage

While CO_2 captured in Phase 1 would be stored primarily using EOR, there is also the potential to sequester it in saline aquifers. Denbury Inc. has 20 current and potential EOR fields immediately adjacent to the pipeline in Texas, Louisiana and Mississippi. Seventy percent of the CO_2 used by Denbury's EOR operators is naturally occurring CO_2 from the Jackson Dome, Mississippi. This is not man-made (anthropogenic) CO_2 from industrial operations but is naturally available in existing formations. This CO_2 can be replaced by captured anthropogenic CO_2 from the Houston region over time as costs for anthropogenic CO_2 capture are lowered. The Denbury EOR fields will be used to permanently store a majority if not all of the CO_2 transported from Houston, but it's important to note that the Denbury fields represent only a fraction of the 204 total EOR fields that exist across the Gulf Coast states, which can be easily accessed by tie-in lines. Saline storage is also abundant throughout the Gulf Coast states both on and offshore, although it would require a significant increase to the 45Q credit to be economically viable.

Critical Objectives and Next Steps

1) Capture technologies and projects at identified sites would be evaluated.

2) Project investment economics and participants identified, and the business development community must convene the potential participation teams to effectively invest.

3) Pipeline construction for the short trunk lines to connect to the Denbury system identified and completed.

4) Contracts and ownership of the investment, and ownership pieces of the value chain, must be convened and executed.

5) Critical success would require the convening of capture facilities and site owners, the pipeline owner and field operations owners to create a working investment marketplace.

6) Identify state and intrastate support organizations for authorization and necessary permitting for construction and long-term operations.

7) Continued external marketing of the project and an ongoing business development effort to cultivate workforce and GDP advancements at the local, state and federal level.

8) Establish a region-wide baseline and index for carbon intensity, allowing the impact of investments and supporting policy on decarbonization to be quantified.

9) Evaluation of alternative geologic options would occur in this phase. Offshore demonstrations and validation of this storage approach would be achieved. Onshore abandoned gas wells could also be inventoried for storage.

10) State owned land and geology could be transformed into a revenue-generating opportunity by marketing it to store emissions from the rest of the country.

11) The establishment of a CCUS commercialization consortium would create the business leadership for deployment investment.

Phase 2: Expansion

Phase 2 spans 2030 to 2040 and would lead to the capture of 20 million tons per year of additional emissions from the remaining natural gas power plants not addressed in Phase 1, along with most of the industrial furnace facilities. It will also use a new pipeline to access East/Central Texas locations for geological storage purposes. This phase would use the model from Phase 1 to guide decision-making analysis, with business development beginning during Phase 1.

Capture

Capturing 6 million tons of emissions from the remaining natural gas plants will require a capital investment of approximately $2.2 billion, while capturing 14 million tons/year from industrial furnaces will require an investment of $6.4 billion. Total relative capital costs with an 85% utilization rate for industrial furnaces can be approximated at $140/ton, more expensive than required capital capturing emissions at a refinery fluidized catalytic cracker, about $130/ton. These cracker units are larger, easier to aggregate emissions and a more attractive source than the many industrial furnaces within the complexes. Costs for ongoing operations and maintenance would be in addition to these costs. It should be noted that furnaces provide attractive targets for other decarbonizing strategies such as electrification or hydrogen fuel. We want to acknowledge that the targets for point source emissions reductions used in our study should not necessarily be the boundary conditions for the expanded region. Many more point sources – with lower cost of capture investment – are additional targets. Hydrogen SMRs are prevalent throughout the Gulf Coast region, and we identified 45 units that would be proximal to geologic storage and transport infrastructure.

Transport

Phase 1 will fill the Denbury pipeline, necessitating construction of a new pipeline in Phase 2. Transportation plays a critical role in Phase 2, with challenges related to policy, permits and pipeline regulations. The new 250-mile pipeline cited in the study would be built from Houston to Dallas/Fort Worth with an available capacity of 20 million tons per year.

We chose this option to provide choices in terms of access to CO_2 storage from both EOR and pure storage. The implementation of land-based CO_2

Capture

Facility Type	Captured emissions (MM tons/yr)	Total Investment (bil US$)
Natural Gas Power Plant	6.4	2.2
Industrial Furnaces	13.5	6.4

Transport

Pipeline	Available capacity (MM tons/yr)	Total Investment (bil US$)
East/Central Texas	20	$0.5

- **Build 250-Mile** Houston -to- East/Central Texas **Pipeline**
- **Industrial Furnaces** are included to expand annual capture of CO_2
- Additional **Natural Gas Power Plants** are involved in the expansion of capacity transportation

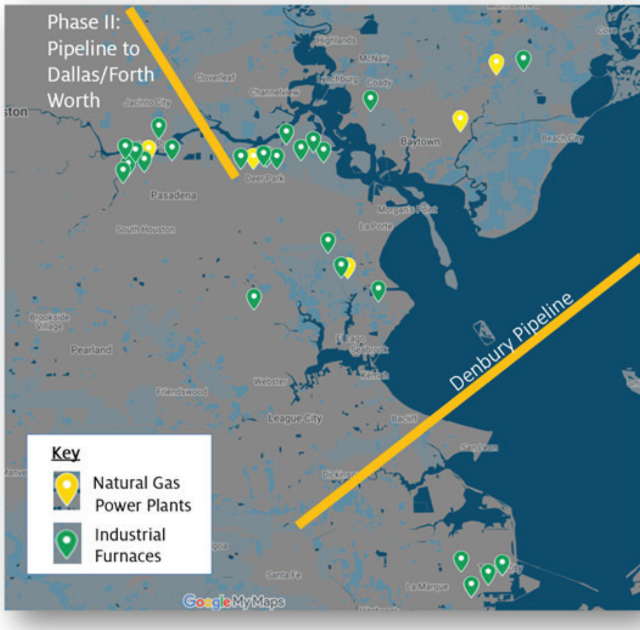

Figure 9. Phase 2 – Point Source Emissions Facilities and Pipeline Transportation

injection is known in terms of costs and operation al know-how, but it is clearly not the only option. Offshore geologic storage would provide optionality with significant advantage in terms of long-term rights and ownership issues. While the costs and operation are not yet fully known, associated site security and the ability to distinctly separate the injection site ownership and liability is a critical issue. The state of Texas has a market construct in place to effectively implement an offshore program both operationally and commercially in order to avoid the land and surface rights ownership issues and as such, the necessary pipeline access will be critical.

The Expansion phase will be predicated on the discovery and securing of additional geologic sites during the Activation phase.

Storage

During the Expansion phase, geologic reservoir storage in East and Central Texas would provide EOR or saline storage, enabled by the new pipeline from Houston to the Dallas/Fort Worth area. A second pipeline network will not only provide additional capacity but also open new geologic options. This creates a step out from the Greater Houston region. It is just one of several options, all of which will require competitive alternative analysis.

Critical Objectives and Aspirations

1) Strategic planning for the Expansion phase will begin during the next 10 years in order to prepare for right-of-way access for pipelines, etc.

2) Advanced capture technologies from current pilot facilities will be readied for deployment and scaled up for commercial use.

3) 45Q support must be increased to enable economic returns.

4) Tools and processes that will be significantly advanced in terms of industrial application for storage measurement, monitoring and verification - and the accounting for geologic storage - would be deployed for long-term operations. Digitizing the process and operations will advance the market and enable a broader group of operators and investors to speed deployment of CCUS and the effectiveness in the operations costs and reliability.

5) The market will evolve into commercial storage of CO_2-driven commerce. Geologic capacity will become a valuable commodity for owners and the state of Texas in terms of providing a commercial storage opportunity for CO_2 emissions.

Storage

Location	Available storage (bil tons)	Total Investment (bil US$/yr)
East/Central Texas EOR	3.6	TBD
East/Central Texas saline	501	

- **EOR and Saline storage** is available in East/Central Texas
- **Leveraging the demand for CO_2 EOR**, offering a relatively larger **economic benefit**

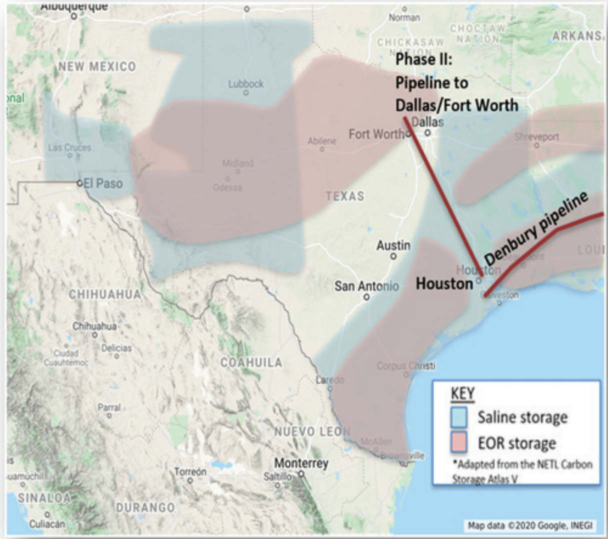

Figure 10. Phase 2 – Geologic Storage Target Formations

6) Ultimately, the ownership and operations and maintenance responsibility for the storage site will be determined by investors, service companies, offtake agreements and commercial terms.

Phase 3: At-Scale

At-Scale spans 2040 to 2050 and was defined by our original scope to create a net-zero emissions profile for Greater Houston. It focuses on capturing 19 million tons per year of CO_2 from the remaining industrial furnaces and refinery catalytic cracker facilities. It would require a new pipeline to the Permian, along with use of the Permian's geologic storage and EOR capacity.

Capture

Completing capture at industrial furnace facilities will require $2.8 billion in capital expenditures, while capture at catalytic cracker facilities will require $1.4 billion.

This effectively completes all the point-source emissions in today's Greater Houston operational database.

Transport

A 500-mile pipeline from Houston to the Permian will be required to take Houston to net-zero, allowing the transport of CO_2 from 13 industrial facilities. Projected cost of the pipeline is $1.5-$2 billion but will both provide more job and economic development opportunities and ultimately will contribute to the economic feasibility of CCUS projects nationally.

We recognize the construction of this infrastructure will be a multi-year task potentially undertaken in phases. Clearly the Permian is recognized as the ultimate prize in terms of connectivity and effectiveness of a broad, At-Scale approach

Storage

The Permian has 4.8 billion tons of capacity for EOR storage and 1 trillion tons of available storage in saline aquifers.

Permian expansion will require a thorough examination of offshore options and costs, both direct and indirect, as well as the risk of onshore versus offshore injection. But it offers a large target for EOR with both conventional and unconventional Residual Oil Zone geologies. Operational integration advantages will compare to the lower cost of transport pipeline investment and risk profile of offshore development.

Expansion to the Permian may be much more important to the long-term impact for the entire United States than for just the Houston region. Connecting the Permian provides access west and north to Wyoming and would enable emissions sources from the Gulf Coast and east to be integrated into the long-term business development planning.

Capture

Facility Type	Captured emissions (MM tons/yr)	Total Investment (bil US$)
Industrial Furnaces	11.4	2.8
Refinery Catalytic Cracker	7.8	1.4

Transport

Pipeline	Available capacity (MM tons/yr)	Total Investment (bil US$)
Permian	20	$1

- **Build 500-Mile** Houston -to- Permian **Pipeline**
- **Refinery Catalytic Cracker** are included to expand annual capture of CO_2
- Projected pipeline from Houston to the Permian Basin will **help with the economic feasibility of both carbon capture and pipeline projects**

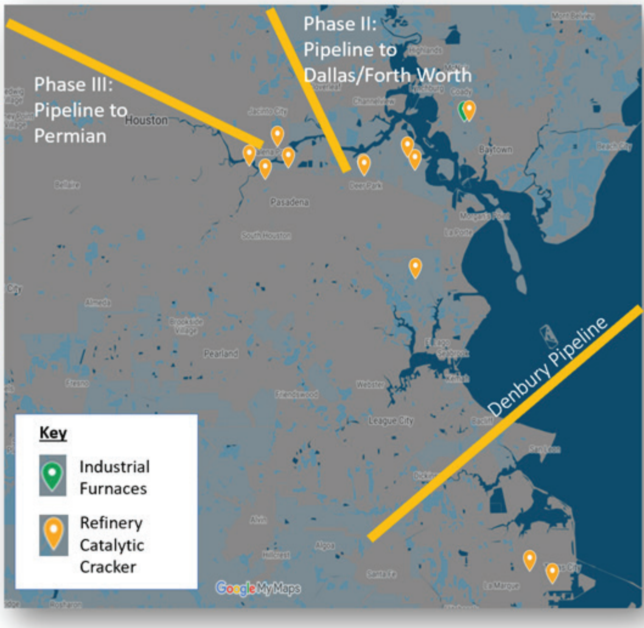

Figure 11. Phase 3 – Point Source Emissions Facilities and Pipeline Transportation

Storage

Location	Available storage (bil tons)	Total Investment (bil US$/yr)
Permian EOR	4.8	TBD
Permian saline	1000	

- **Large-scale of EOR and saline storage** available in the Permian Basin
- Storage capacity in the Permian will permit to **achieve net-zero in carbon goal**

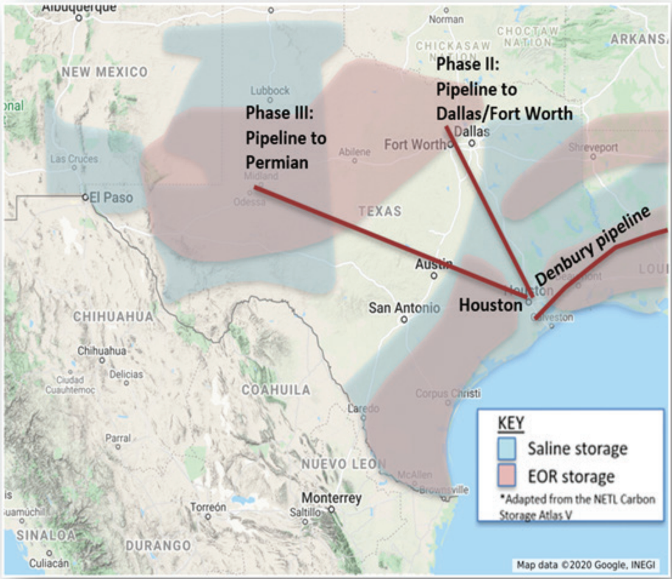

Figure 12. Phase 3 – Geologic Storage Target Formations

Summary Conclusions

The NPC study states that "the most critical needs for success reside in effective stakeholder engagement and public-private policies to encourage open and transparent CCUS discussions. Impacts to communities and building confidence in the technology and operational footprints are essential for broad acceptance. The (oil and gas) community and industrial community will be called to lead with thought and action to realize CCUS investments to achieve the emissions reduction goals for the energy transition and to support the industry transition."

The study also identified a number of recommendations in each of the phases that are critical to overall success. Policy, legal, business, technology and engineering are all critical, and we will not repeat those recommendations here.

Key conclusions:

1) The Houston region's geologic resources and concentration of point source industrial emissions are unmatched globally.

2) The region's infrastructure and pathways for its expansion will be critical to the success of CCUS, as will the regional knowledge base and experience.

3) The workforce's ability to transform itself is strongly supported by experiential and higher education learning opportunities.

4) The business community has a desire for Houston to continue as the energy capital of the world, as well as to achieve decarbonization and the long-term sustainability of the oil and gas, petrochemical and electric power industries. This must be cemented with public-private partnerships in industry, government and academia to achieve broad commercial deployment.

5) The concept of creating a Carbon Utilization Hub to drive utilization of CO_2 is a natural fit for Houston to complement the CCUS efforts discussed here. It is critical to recognize that opportunities for broad pathways hinge on the cost of capture and CO_2 made ready for use.

While the largest use of CO_2 today is EOR, there are many other potential uses, with CO_2 positioned as a source of carbon to make desirable products; product revenues can offset the costs of capture and transport.

There are four main pathways for utilizing CO_2 – thermochemical, electrochemical and photochemical, biological and carbonation – each of which has large potential and a range of technology readiness. While we have focused on the use and combined storage of CO_2 for EOR, existing multi-billion dollar markets such as fuels/chemicals and building materials offer great potential, despite the fact that the additional energy and feedstock required currently make these CO_2-based products uncompetitive.

One example: to produce fuels and chemicals from CO_2, splitting carbon from other stream components requires energy, and the carbon then must be combined with a source of hydrogen, requiring more energy to produce it. Another example is that to produce building materials, the CO_2 needs to be combined with a source of magnesium or calcium.

However, as markets for low-carbon products and technologies evolve, so too will the potential for expanded CO_2 utilization. Houston is well positioned to become a global Carbon Utilization Hub by leveraging its energy supplies, port infrastructure and workforce and academic capabilities to supply the world with those products.

CCUS and the geological aspects are strongly linked to the broader set of complementary opportunities for utilization and require concurrent efforts to successfully address the emissions and climate challenge.

FOOTNOTES

1 – National Petroleum Council. (2019). Meeting the Dual Challenge: A Roadmap to At-scale Deployment of Carbon Capture, Use and Storage in the United States. Retrieved from https://dualchallenge.npc.org/

2 – Deployment of Deep Decarbonization Technologies: Proceeding of a Workshop. (2019). Retrieved from http://www.nap.edu/read/25656

3 – BP. (2019). BP Energy Outlook - 2019, 68th Edition. Retrieved from https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf.

4 – ExxonMobil. (2019). 2019 Outlook for Energy: A Perspective to 2040. Retrieved from https://corporate.exxonmobil.com/-/media/Global/Files/outlook-for-energy/2019-Outlook-for-Energy_v4.pdf

5 – IEA. (2019). World Energy Outlook 2019, IEA, Paris. Retrieved from https://www.iea.org/reports/world-energy-outlook-2019

6 – NETL. (2016). Carbon SAFE – 2016. Retrieved from https://netl.doe.gov/coal/carbon-storage/storage-infrastructure/carbonsafe

7 – US DOE. (2015). Technology Readiness Guide – 2015. Retrieved from https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04-admchg1/@@images/file

8 – US EPA. (2019). Underground Injection Control (UIC) - 2019. Retrieved from https://www.epa.gov/uic/uic-injection-well-inventory

About UH Energy

UH Energy is an umbrella for efforts across the University of Houston to position the university as a strategic partner to the energy industry by producing trained workforce, strategic and technical leadership, research and development for needed innovations and new technologies.

That's why UH is the Energy University.