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Carbon Capture, Hydrogen and Collaborative Action to Reduce Industrial Emissions in Texas

CARBON CAPTURE IN TEXAS: COMPARATIVE ADVANTAGE IN A LOW CARBON PORTFOLIO

Kenneth B. Medlock III, Ph.D.
James A. Baker, III, and Susan G. Baker Fellow in Energy and Resource Economics and Senior Director, Center for Energy Studies

Keily Miller
Research Manager, Center for Energy Studies

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Introduction

World economic growth will drive future demands for energy. The International Monetary Fund's World Economic Outlook (April 2020) predicts that emerging and developing economies will account for the majority of global economic growth through the 2020s, with China and India leading the way. In general, as human and industrial activity expands, the concomitant growth in energy consumption introduces a complex paradigm. Achieving the dual goals of economic and environmental sustainability will be among the world's most pressing challenges, and the burden will not be evenly distributed. By 2050, it is expected that:

a. The world's population will increase by more than 2 billion people, with the increase primarily occurring in less developed regions.[1]

b. Global gross domestic product (GDP) will double in tandem with the rise in population, with developing economies taking a larger share of global economic activity.[2]

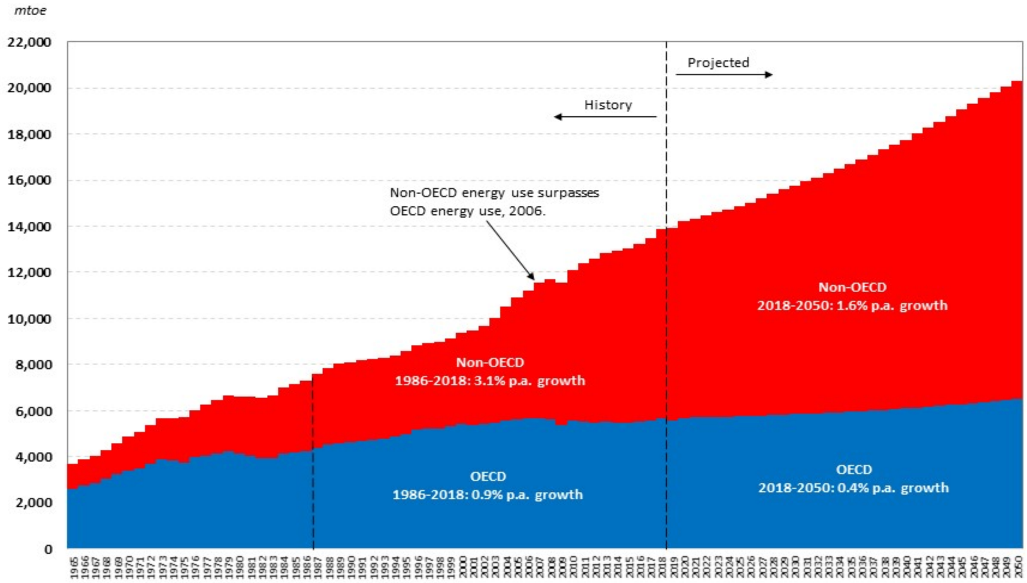
c. Global population and economic growth will drive energy consumption to new heights through 2050, albeit at a slower rate of growth.

We are already seeing this play out in the world's energy system (see Figure 1). Energy demand in the world's wealthiest, most developed nations—those that are a part of the Organization of Economic Cooperation and Development (OECD)—was surpassed by energy demand from emerging and developing nations (non-OECD countries) in 2006. This will not reverse.

The scale of the energy system is, in a word, massive. Moreover, much of the infrastructure that is in place has been developed with a focus on the world's advanced economies, so it was designed to serve only a fraction of the global population. While existing energy value chains are flexible and can shift to meet changing market conditions, they are insufficient to deal with the energy requirements of the future, both in scale and scope. Significant new investment in infrastructure will be needed in developing, non-OECD countries, while existing infrastructure must be maintained, upgraded and/or replaced in both OECD and non-OECD nations.

The scale of the global energy challenge will most effectively be tackled through a portfolio approach, which includes new energy sources, renewable energy technologies, energy efficiency, and existing energy sources. As much the case now as throughout the history of civilization, investments must leverage regional comparative advantages to maximize economic progress (see Appendix A1 for a brief discussion of the principle of comparative advantage). In regional economies with significant economic interest in fossil fuels and fossil fuel-using industries, one approach in the portfolio of options available to address CO_2 emissions is the umbrella of technologies collectively referred to as carbon capture, utilization and storage (CCUS). CCUS involves capturing CO_2 where it is produced and then compressing and transporting it to a location where it can either be converted into a useable product, utilized in enhanced hydrocarbon recovery, or permanently sequestered (see Appendix A2 for a brief discussion of CCUS).

Figure 1. Global Energy Consumption, OECD and Non-OECD (1965-2050)



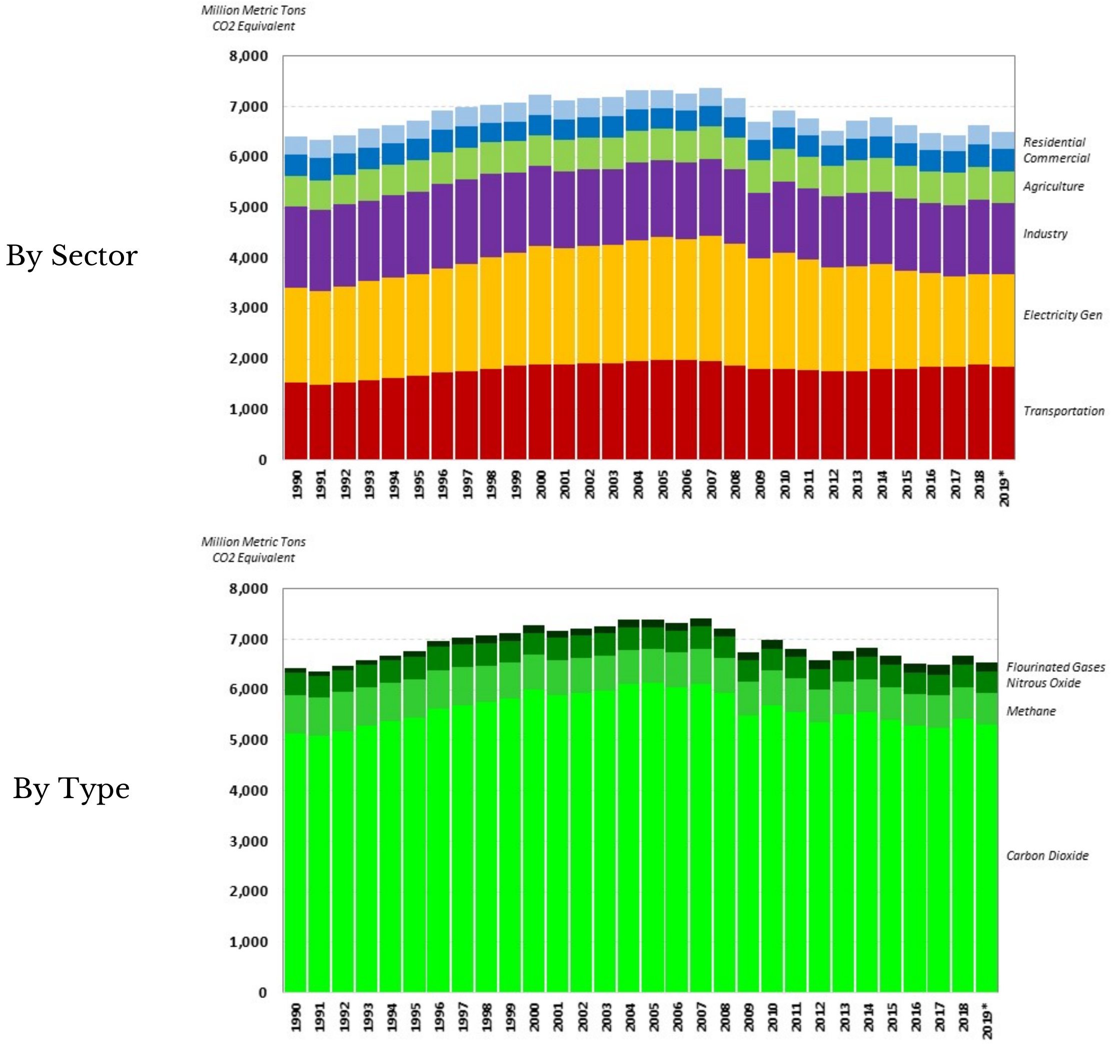
Sources: BP, “BP Statistical Review of World Energy,” 2019, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf; EIA (U.S. Energy Information Administration), “International Energy Outlook 2019,” September 2019, https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf.

Several efforts have highlighted the important role of CCUS in broad global assessments of CO_2 emission reductions pathways. The International Energy Agency (IEA), in its Clean Technologies Scenario, showed CCUS technologies contribute to 13% of global cumulative CO_2 emissions reductions through 2060, making CCUS the third-largest contributor to global decarbonization efforts after energy efficiency (39%) and renewables (36%).[3] In the Sustainable Development Scenarios, also developed by the IEA, CCUS was found to reduce global CO_2 emissions by 9% cumulatively through 2050. The Intergovernmental Panel on Climate Change concluded in its Fifth Assessment Report that the costs of achieving a global temperature increase of no more than 2°C would more than double without CCUS.[4]

CCUS in the Sustainability Portfolio

The portfolio of options available in the US to address greenhouse gas (GHG) emissions spans across virtually every sector of the economy and extends beyond CO_2 abatement. As indicated in Figure 2, over 75% of GHG emissions come from transportation (~28%), electricity generation (~27%), and industry (~22%), with agriculture (~10%), commercial (~7%), and residential (~6%) accounting for the remainder. CO_2 accounts for a large majority (~80%) of the GHG emissions portfolio, with methane (~10%), nitrous oxide (~7%), and fluorinated gases (~3%) rounding out the inventory of emissions.

Figure 2. US GHG Emissions by Sector and Type, 1990-2019



Note: * indicates estimate

Source: EPA (United States Environmental Protection Agency), Greenhouse Gas Inventory Data Explorer: Inventory of Greenhouse Gas Emissions and Sinks: 1900 – 2018, https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

Here, we must distinguish between *energy-related* emissions and *total* emissions. The former is the result of the combustion of fossil fuels. The latter includes the former, along with emissions related to forestry and land-use practices, agricultural activities and fertilizer application, waste management and biomass incineration, and more. Therefore, efforts to reduce GHG emissions can address combustion of fossil fuels as well as a variety of other activities. Moreover, the distribution of emissions varies across sectors,[5] providing a robust assortment of different GHG abatement opportunities. Complete abatement of non-CO_2 GHGs would reduce emissions by just over 19% in the US (and over 22% globally).[6] Nevertheless, since electricity generation, industry, and transportation account for more than three-quarters of GHGs, and CO_2 is over four-fifths of the GHG inventory, a major focus of policy and commercial interest has been centered on reducing CO_2 emissions ("decarbonization") in the electricity, industry, and transportation sectors.

Across the globe, decarbonization efforts (or, more generally, efforts to achieve "net carbon neutrality") have rallied behind a range of sustainability solutions that fall primarily into a handful of categories: renewable energy, energy efficiency, fuel switching, nuclear power, CCUS, and nature-based solutions such as reforestation. This categorical optionality underscores the multitude of pathways that exist, each varying in its regional and sectoral applicability. Regarding CCUS in particular, in 2017 the IEA described it as "a critical part of a complete clean energy technology portfolio."[7]

The most salient aspect of the IEA's description of CCUS is in characterizing it as "part" of a portfolio, thereby supporting the notion that there is no "one-size-fits-all" solution that cuts across the operational, financial, and geographic heterogeneity characterizing the world's regional economies and their main emissions sources. Aside from the complexities derived from regional economic variation, different energy-using sectors—including power generation, transportation, industry, agriculture, commercial, and residential—each present their own disparate characteristics. As such, achieving global decarbonization targets requires a mix of technologies and approaches that have applicability across a variety of sectors.

A Focus on Industrial Emissions

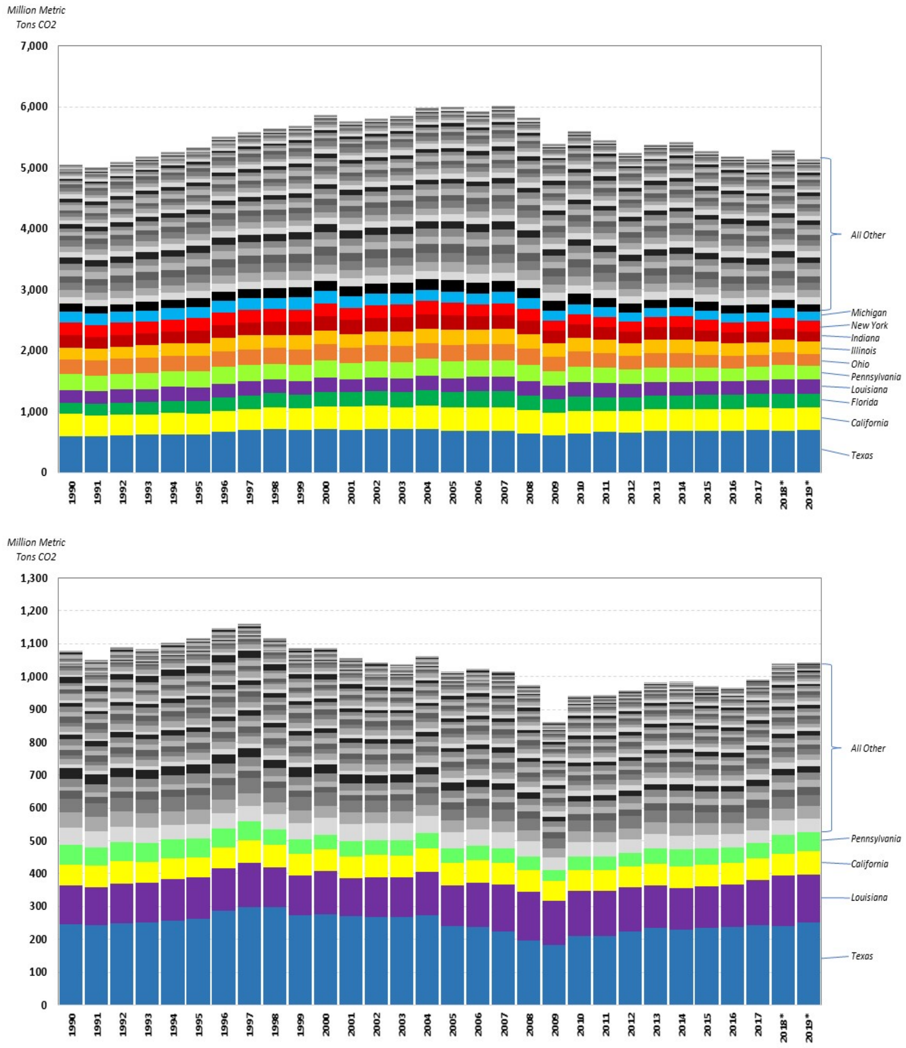
On a global scale, as estimated by the IEA in 2019,[8] industrial sector emissions account for nearly one-quarter of global CO_2 emissions, and they are among the most difficult to abate in the energy system. More than half of total CO_2 emissions in the industrial sector came from just three sub-sectors: chemical production, petroleum refining, and mining. Ethanol production, ammonia production, and natural gas processing represent ideal targets for CCUS, with production processes yielding high-purity streams of CO_2 that are comparatively inexpensive to capture. The IEA also identified CCUS as the most significant strategy for decarbonizing the chemicals sector, having the potential to contribute up to 38% of CO_2 emissions reduction in the chemicals sector by 2060.[9]

The US has a large industrial base that, while vital to its economic health, represents a significant source of CO_2 emissions. In 2019, the US industrial sector directly accounted for about 20% of total GDP.[10] It also accounted for about 20% of energy-related CO_2 emissions. As a significant contributor to both the national economy and the CO_2 volumes the country emits, the US industrial sector appears to hold tremendous potential as a candidate for carbon capture technologies.

Figure 3. State Energy-related CO_2 Emissions, All Sectors and Industry

All Sectors (Industry, Electricity, Transport, etc.)

Industry



Note: * indicates estimate

Source: EIA, "2017 State energy-related carbon dioxide emissions by sector," May 2020, https://www.eia.gov/environment/emissions/state/.

Since US CO_2 emissions are distributed unevenly across sectors and regions, emissions reduction efforts will likely vary across different areas of the country. As indicated in Figure 3, if we focus on energy-related emissions (or those from the combustion of fossil fuels) half of US CO_2 emissions originate in just 10 states. Geographic concentration of energy-related CO_2 emissions is even higher in the industrial sector, where half of emissions originate from just four states—Texas (~24%), Louisiana (~14%), California (~7%), and Pennsylvania (~5%)—and these statistics do not even take into account process emissions, such as those associated with chemical reactions and other processes that are part of various industrial activities. To the extent that technologies such as CCUS exhibit economies of scale, implementation could yield relatively low-cost CO_2 emissions reduction solutions in regions with large industrial sectors where scale can be achieved.

With applications spanning a multitude of industries, CCUS represents an important step toward achieving global sustainability targets. Indeed, there is already movement to expand carbon capture, with the oil and gas industry playing a central role (see Appendix A3). This raises a very salient point; CCUS has tremendous potential where there is an intersection of industrial activity, oil and gas production, geologic storage potential, and subsurface expertise (see Appendix A1). There are few places around the world with a greater coalescence of these factors than the state of Texas. Hence, carbon capture and storage in the state could present an ideal opportunity to capture comparative advantage while developing a low carbon portfolio.

Policy Pathways: CCUS in Texas

In Texas, the oil and gas industry and related activities—petrochemicals and refining—represent the largest pillar of the state economy. These activities directly account for over 13% of gross state product, with indirect multiplier effects estimated to be much higher.[11] In 2019, Texas also accounted for 41% of US crude oil production and 25% of US marketed natural gas production. For perspective, crude oil and petroleum products and natural gas accounted for 37% and 32% respectively of the more than 100 quadrillion British thermal units (BTUs) of total US energy consumption in 2019. Thus, oil and gas and related industries in Texas are critical for the economic prosperity of Texans and essential to the US energy portfolio. This derives from geologic, geographic, and human capital comparative advantages that seed a robust energy sector in the Texas economy.

At the same time, industrial activities in Texas are responsible for nearly one-quarter of all industrial CO_2 emissions in the US. The state therefore possesses a unique opportunity to transform the industrial CO_2 footprint on a national scale through CCUS deployment. Many commercial actors in Texas are already exploring ways to reduce their carbon footprints, and a concerted statewide policy effort could allow Texas industries to build expertise and advance critical technologies. Indeed, many regions around the world are developing policies to catalyze CO_2 reduction technologies in order to capture economic advantage (e.g., port of Rotterdam). In the US, other energy producing states (e.g., Louisiana and North Dakota) are already working to advance CCUS deployment.

In June 2019, Rice University's Center for Energy Studies (CES) at the Baker Institute for Public Policy and the Kinder Institute for Urban Research convened a stakeholder working group (SWG) comprised of seven special interest groups and NGOs, two academic institutions, and 19 corporations across the energy value chain (from production and transportation to conversion and end-use) with an active interest in CCUS. The SWG has periodically reconvened to discuss the issues stakeholders see as critical to the deployment of CCUS at scale in Texas. The goal of the SWG is explicitly *not* to draft specific legislation or regulations. Instead, the goals are to ascertain where common ground exists with regard to policy and regulation related to CCUS deployment and to provide guidance on policies that could advance CCUS with the least possible resistance.

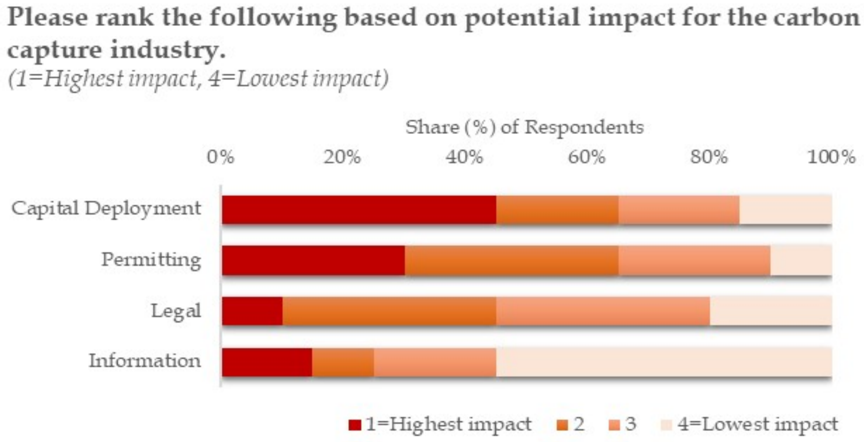
In March 2020, the CES surveyed members of the SWG on a list of issues related to CCUS in Texas. The stakeholders were asked to express their opinions about the political will to address each issue and the potential impact that the resolution of each issue would have on CCUS advancement. Respondents were asked to rank the following four areas based on (i) their potential impact on the CO_2 capture industry in Texas, and (ii) the feasibility of policy action in Texas:

1) Permitting (with the intention to reduce regulatory uncertainty and resulting impediments for investments across the CO_2 value chain):
    a. Enact legislation that directs the state to request primacy from the Environmental Protection Agency (EPA) and clarifies regulatory agency jurisdiction for permitting CO_2 sequestration sites (TCEQ, RRC, etc.) so that a unifying authority exists to streamline the approval process.
    b. Outline the permitting pathways in Texas to address any permitting bottlenecks that impede the development of CO_2 capture, transportation, and sequestration infrastructure.
2) Capital Deployment:
    a. Explore fiscal and regulatory measures aimed at promoting capital investment in carbon capture, use, and sequestration (e.g. different tax/regulatory treatments to incentivize infrastructure deployment and research and development). Such measures could leverage existing federal policies.
    b. Explore precedent policy mechanisms used in other states to support investment in and deployment of carbon capture, use, and sequestration technologies.
3) Legal:
    a. Clarify rules of ownership of subsurface pore space for CO_2 storage.
    b. Address long-term liability of sequestration sites.
4) Information:
    a. Create an information hub for carbon capture by compiling and disseminating research on (i) legislation that could advance the viability of creating a commercial CO_2 value chain in Texas, and (ii) CO_2 sources and potential sinks in Texas.

Results from the survey are shown in Figures 4 and 5. As indicated in Figure 4, "capital deployment" was rated the most *impactful* policy area to address by almost half of all respondents. Moreover, about two-thirds of respondents indicated "capital deployment" to be the first or second most impactful area to address. Interestingly, about two-thirds of respondents indicated the same to be true for "permitting" although the relative ranking—

first versus second—was reversed. Altogether, this indicates that tax and regulatory measures aimed specifically at promoting capital investment are thought to have the greatest impact, with addressment of various permitting issues a close second.

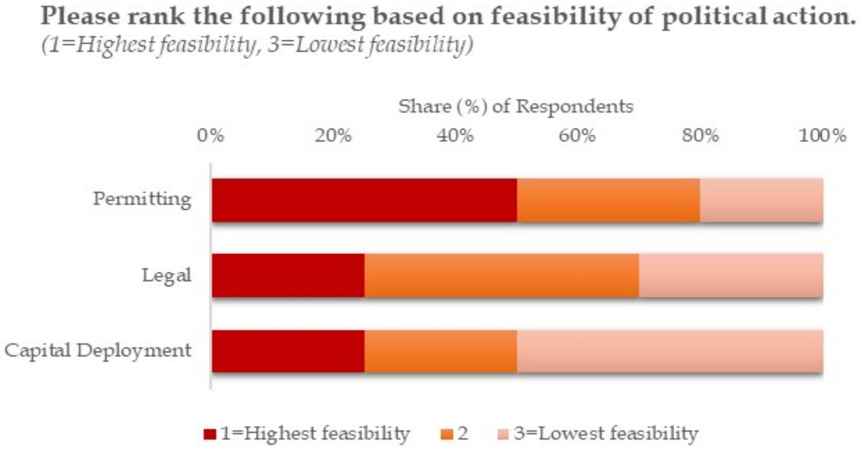
Figure 4. Impact-Based Issue Ranking



Source: Baker Institute Center for Energy Studies, SWG Survey, March 2020.

As indicated in Figure 5, 80% of respondents indicated that "permitting" is either the first or second most *feasible* policy action for advancing the CO_2 capture industry in Texas. In stark contrast to the *impact* ratings, policies aimed at promoting "capital deployment" were ranked the least *feasible* by the majority of respondents, with "legal" issues coming in second. It is also worth noting that the survey was completed by all respondents by the first week of March, which was just before the macroeconomic and energy sector downturn associated with Covid-19.

Figure 5: Feasibility-Based Issue Ranking



Source: Baker Institute Center for Energy Studies, SWG Survey, March 2020.

When the results on impact and feasibility are combined, there appears to be agreement that achieving CCUS deployment at scale in Texas will require a regulatory and legal framework that offers clarity throughout the permitting process. While it is largely agreed that policies promoting capital investment would have an impact, any uncertainty around existing laws and regulations could impede CCUS deployment, regardless of the economic value proposition.

The results of the survey very much reflect the conversations at the various SWG meetings that have been convened since mid-2019. It has also been noted in various SWG meetings that public support of CCUS from the governor, state agencies, and elected officials will prove a determining factor in whether existing barriers—such as uncertainties in the permitting process, legal ambiguity related to CO_2 storage, and high capital costs—will be removed or overcome. A recent study by the National Petroleum Council (NPC) estimated that by clarifying existing regulations and tax policy, the US has the potential to double its current CCUS capacity within seven years, even without any congressional action.[12] At a minimum, addressing existing hurdles is a necessary precursor to wider, accelerated deployment of a broader suite of CCUS technologies.

Conclusion

CO_2 emissions come from a variety of sources including electricity generation, oil refining, paper and pulp industries, chemical plants, cement and concrete production, and others. A wide variety of energy projections (including those from the IEA, the US Energy Information Administration, and scenarios from corporate entities such as BP, Shell, and Equinor, to name a few) consistently demonstrate that CO_2 emissions will continue—albeit perhaps in shrinking volumes—for decades to come. The principle of comparative advantage bears significance in determining which technologies and approaches will work in specific regions around the world. Given the volume of CO_2 emissions from industrial activity, the amount of oil and gas production, the scale of geologic storage potential, and the breadth of subsurface expertise in the state of Texas, CCUS can be a significant part of a low carbon portfolio in the region.

In general, a sustainability “portfolio” encompassing a broad range of approaches is important to mitigate CO_2 emissions. CCUS is a critical technology for reducing emissions in hard to decarbonize sectors such as industry. Moreover, CCUS leverages the engineering and technical capabilities abundant in the oil and gas industry, it can effectively decarbonize fossil fuel use, and it has a diverse set of potential applications.

The development pathways in the renewables sector can offer important parallels for CCUS. Over the past decade, strong policy frameworks and incentives have played an essential role in the advancement and market successes of renewable energy technologies. Equally, the commercial and technological advancement of CCUS hinges on appropriate regulatory clarity and policy guidance.

Ongoing research at the CES includes the development of a policy “roadmap” for CCUS technology deployment in the state of Texas. There are many examples of roadmaps at national and regional levels from different places around the world.[13] They tend to comingle timelines for technology and policy, and each one looks different from the next. Our work will not be focused on technology; rather, we will be focused on policy in the state of Texas. The CCUS policy roadmap for the state of Texas is forthcoming in the third quarter of 2020.

The Covid-19 crisis has created uncertainties in the policy landscape, placing a sizeable fiscal burden on government budgets and diminishing near-term appetites for large-scale investment by energy and industrial sector firms. Yet even amidst this climate of uncertainty, there is a growing resoluteness towards reducing the net carbon footprint of economic activity. Consequently, near-term policy pathways that focus on removing regulatory uncertainties will prove a vital step in the deployment of carbon capture technologies. Indeed, against a backdrop of bearish macroeconomic sentiment, the need for clarification and stabilization of existing rules and regulations is more important now than ever before.

Appendix

The appendix is structured to provide additional information on issues raised in the main text. Section A1 provides a definition of the principle of comparative advantage and why it matters when considering carbon mitigation options. Section A2 is a brief exposition of what CCUS is, from capture, to transport, to storage. Section A3 provides a short outline of the role that CCUS technology could play in reducing the net carbon footprint, with a discussion of existing and prospective projects and their costs. As such, while the focus of the main text is the discussion of the survey results of the stakeholder working group convened by the Baker Institute, the materials in the appendix provide some grounding for the discussions around potential policy pathways for broader CCUS deployment in the state of Texas.

A1. The Principle of Comparative Advantage and Its Relevance to a Portfolio Approach to Emissions Mitigation and Varied Regional Pathways

A comparative advantage exists when a region can produce a good or service at a lower price than exists elsewhere. This, in turn, pushes that region to specialize in the production of that good or service for sale into the global market, thereby driving local economic activity. Comparative advantages can exist for various regions in heavy industry, manufacturing, fossil fuel production and processing, financial services, and more. To the extent a regional comparative advantage results in CO_2 emissions, mitigation presents risks and opportunities for maintaining regional economic prowess. This may not be so simple an issue as switching energy sources, because regional economic engines are not easily deconstructed. So, as the world seeks lower carbon intensity, approaches that leverage existing comparative advantages, as opposed to approaches that ignore or deconstruct them, can address economic sustainability while also addressing environmental goals. Regional economies that are heavily invested in energy-intensive industries and/or fossil fuel production with massive existing infrastructures will present unique challenges as well as opportunities. All this suggests that mitigating CO_2 emissions will look different everywhere, especially if the principle of comparative advantage is leveraged, as regional economies will seek to maximize their natural resources, human capital, and geographic comparative advantages.

A2. What Is CCUS?

CCUS involves capturing CO_2 where it is produced, then compressing and transporting it to a location where it can be either converted into a useable product, utilized in enhanced hydrocarbon recovery, or permanently sequestered. Several recent reports have outlined the technologies and processes involved in detail. Most notably, those include a recent report by the National Petroleum Council (NPC) ("Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use and Storage")[14] published in December 2019, as well as a report by the Congressional Research Service ("Carbon Capture and Sequestration (CCS) in the United States")[15] published in August 2018. In this paper, we therefore do not delve into details of specific technologies, but instead refer the interested reader to the relevant reports. Here, we provide a very brief summary of what is involved in order to orient the discussion that follows.

Capture

In general, the most capital-intensive part of the CCUS supply chain is CO_2 separation and capture. Moreover, there is a parasitic load associated with equipment operation that also adds cost. As such, the choice of technology and scale of operation is heavily determined by CO_2 volume, purity, and concentration. In general, CO_2 capture technologies can be sorted by type into absorption, adsorption, membranes, and cryogenic distillation, with each at varying stages of maturity.[16]

Amine absorption—a technique that is the predominant choice of separation technologies—has been used extensively for more than 40 years and continues to evolve today. In fact, as stated by G.T. Rochelle,

> The history of conventional amine scrubbing includes more than 30 applications on flue gas from gas combustion and six on flue gas from coal. Improvements in the process design and solvent selection have resulted in continuous reduction of energy use and capital cost. By analogy to the development of limestone slurry scrubbing for flue gas desulfurization, amine scrubbing has been and will continue to be the technology of choice for CO_2 capture.[17]

Once CO_2 is captured, it is then refrigerated or compressed into a supercritical state so that it is ready for transport.

Transport

There are four common transport methods: pipeline, truck/rail, ship, and barge. As with transport of other commodities, economies of scale tend to favor pipelines over other methods, so pipelines are the primary method for transporting large volumes of CO_2. Even so, pipeline transport costs can vary in ways that are typical for any pipeline system regardless of the commodity being shipped, with the costs of construction, operation, maintenance, access and right-of-way, regulatory burdens, etc. all playing a role. Due to an inability to capture economies of scale, CO_2 transport by truck and rail, although less capital-intensive than pipelines, can cost significantly more than pipeline transport for long distance, large-scale transportation of CO_2. Maritime shipping can also be an effective method of waterborne CO_2 transport over long distances where pipelines are not an option, such as from the US to Europe or Asia, but demand is currently minimal.

Storage and Use

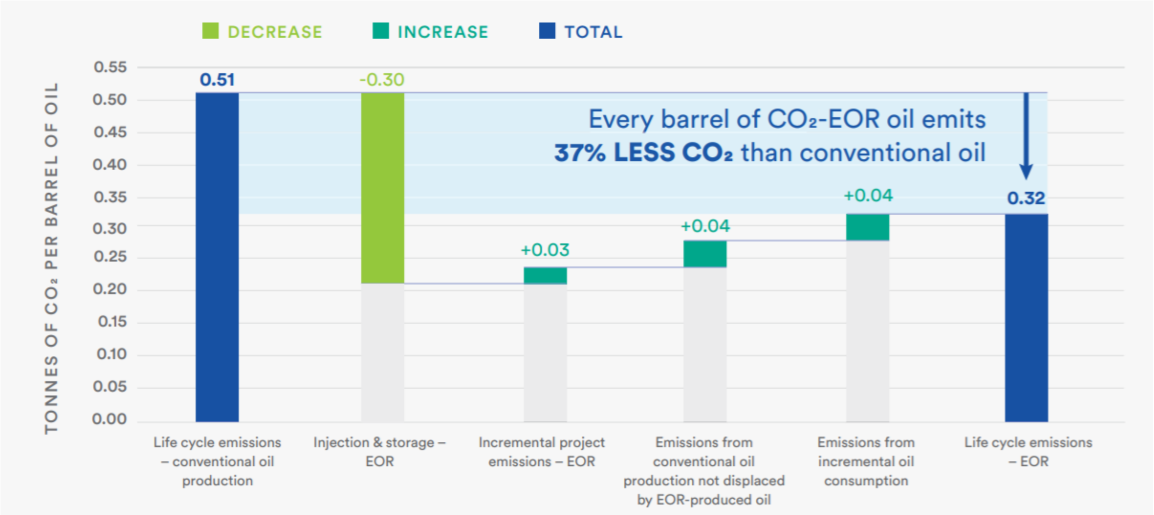
Multiple options exist for storing CO_2. Typical for consideration is the injection of compressed, supercritical CO_2 into any number of potential subsurface geological formation candidate sites, such as deep saline formations, depleted oil and natural gas reservoirs, and unmineable coal seams. In general, the process of CO_2 injection for geologic storage is well understood, and large-scale geologic storage of CO_2 has been done for more than 20 years in locations such as the Sleipner gas field in the Norwegian North Sea.

Another common practice that is currently used by the petroleum industry is to inject CO_2 into oil and gas reservoirs to enable greater production, i.e., enhanced oil recovery (EOR). This practice, which falls under the umbrella of CCUS, is most widely used in the state of Texas. During the EOR process, an estimated 99% of the CO_2 used for that purpose is ultimately trapped in the subsurface reservoir formation from which the oil is produced.[18] In a comprehensive assessment performed in 2015, the IEA estimated that the utilization of industrial CO_2 in EOR resulted in a net reduction in well-to-wheel emissions.[19] Based on estimates from the IEA and further analysis by the Clean Air Task Force (CATF), the CATF reported estimates of a 37% net reduction in lifecycle CO_2 emissions per barrel of oil produced through CCUS-EOR compared with conventional oil production (see Figure A1).[20]

Thus, CCUS for EOR has the potential to significantly reduce the net CO_2 footprint of the oil and gas industry, and industrial activity more generally, as it is a known technology that is already in use.

Although most captured CO_2 ends up in geologic storage, there is enormous potential to use CO_2 to create other products, such as building materials and carbon fiber materials. There is growing interest from governments and the private sector in nascent technologies and applications for the use of CO_2-derived products and services in a few distinct categories—such as fuels and organic chemicals, building materials from minerals, and building materials from waste and CO_2 use to promote plant growth.[21] Today, a relatively small amount of captured CO_2 is put towards productive use, as current CO_2-based products are still in the early stages of technology development.

Figure A1. Net CO_2 Emissions per Barrel of Oil Recovered through CO_2-EOR



Source: CATF (Clean Air Task Force), "CO_2 EOR Yields a 37% Reduction in CO_2 Emitted Per Barrel of Oil Produced," 2019, https://www.catf.us/wp-content/uploads/2019/06/CATF_EOR_LCA_Factsheet_2019.pdf.

In Europe, several projects involving the production of hydrogen from natural gas were underway in 2019.[22] A critical aspect of the value proposition associated with hydrogen from natural gas coupled with CO_2 capture is the potential monetization of CO_2, perhaps as a feedstock in other products. As the technical and economic feasibility of using CO_2 in various products improves, the economic viability of CO_2 capture will increase because the CO_2 will have positive value. In turn, this could accelerate the development of a CO_2 value chain in which hydrocarbon fuels play the traditional role of energy carrier while also serving as a "feedstock" for CO_2 product development.

A3. CCUS Projects and Costs

Climate change is a problem of the global commons, and it requires collective action across multiple regions, the impact of which will be felt at local levels. CCUS could play an important role in decarbonizing the global economy, and it stands to play a very important role in regions with significant industrial activity. In a September 2019 report, German environmental organization Urgewald reported that China and India accounted for more than 50% of new planned coal-fired power plants globally. The expanding energy needs of these economies will require new technologies and new solutions—some to replace older fossil fuel infrastructure and others to make newer infrastructure less CO_2 intensive.

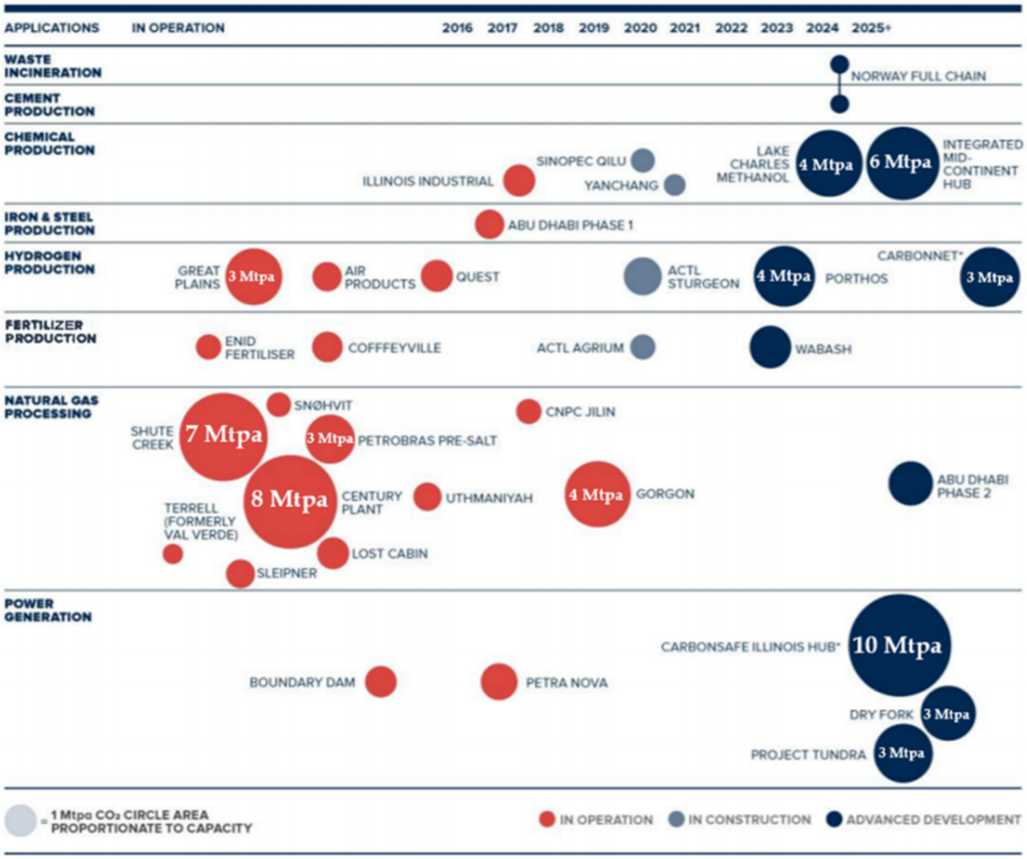
Indeed, given that coal plants have typical lifespans of up to 50 years, achieving the goals of the IEA's Sustainable Development Scenarios will require wide-scale adoption of CCUS either at those sites or in other areas (or both), lest they be prematurely retired, which can carry significant direct economic costs.

A variety of industrial activities—like the production of power, steel, hydrogen, fertilizer, etc.—use CCUS technologies in their facilities today, and the US holds tremendous potential to scale the use of CCUS. With one of the largest assessed CO_2 geologic storage capacities in the world and adequate onshore geologic capacity to store hundreds of years of CO_2 emissions from large stationary sources (such as power plants and industrial facilities), the US possesses a geologic advantage.[23] Offshore storage resources in the US are also estimated to be similarly large in scale.[24]

CO_2 has been naturally trapped and stored in subsurface geologic formations for millions of years. From these deposits, a great deal has been learned about the geologic conditions necessary for secure CO_2 storage. As noted above, CCUS has been occurring in the US for some time, driven largely by EOR activities, so firms have accumulated substantial experience in practice. Agencies such as the EPA, the Department of the Interior, the Pipeline and Hazardous Materials Safety Administration, and others regulate the performance, safety, and compliance of CO_2 capture and storage activities through established frameworks, including the Safe Drinking Water Act and the EPA's Greenhouse Gas Reporting Program required under the Clean Air Act for the injection of CO_2 into geologic storage.

With investment of \$4.5 billion in public-private partnership funding over the last 20 years, the US Department of Energy has implemented 26 different CO_2 injection pilots and test projects across the US and Canada. Out of the 19 CO_2 sequestration projects operating globally in 2019 (see Figure A2), 10 are located in the US. With a combined sequestration capacity of 25 million tonnes per annum (mtpa), those 10 projects accounted for nearly 80% of the worldwide total, which amounts to 32 mtpa.[25] Of the 10 US-based CCUS projects, six were economically viable without any significant policy support, while the remaining four hinged on policy support, including federal, state, and regional tax incentives and the provision of \$3.4 billion in funding to the Department of Energy under the 2009 Recovery Act.[26]

Figure A2. Large-Scale CCUS Facilities by Sector

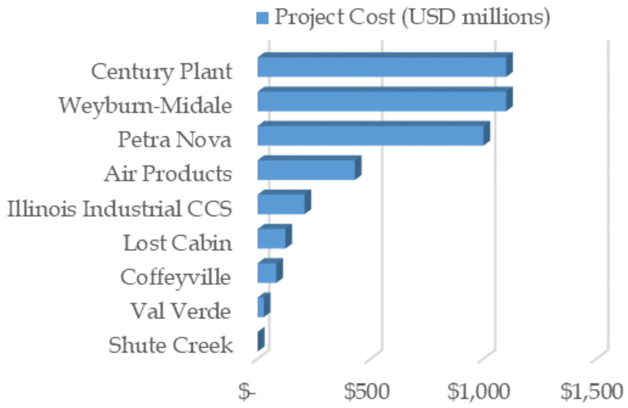


Source: "The Global Status of CCS: 2019," Global CCS Institute, 2019, https://www.globalccsinstitute.com/resources/global-status-report/.

According to the data available from the National Energy Technology Laboratory (NETL) Carbon Capture and Storage (CCS) Database, project costs ranged from \$1.1 million USD for the capture project at ExxonMobil's Shute Creek Plant to as much as \$1.1 billion USD for the Century Plant Gas Processing capture and storage project (which includes development of related pipeline infrastructure).[27] The costs for each of the projects currently operational in the US (excluding the Enid Fertilizer Plant project) are shown in Figure A3.

The investment cost can be substantial, but so too is the economic and environmental payoff. According to the recent NPC study, deployment of CCUS at scale has the potential to generate around $20 billion in GDP annually and support more than 200,000 jobs each year.[28] In addition, the investment in CCUS yields an estimated $1.25 billion annually in state and local tax revenue, plus an estimated $2.25 billion annually in federal tax revenue.

Figure A3. Project Costs for CCUS Projects Operating in the United States



Source: NETL (National Energy Technology Laboratory), Carbon Capture and Storage (CCS) Database, accessed May 6, 2020, https://netl.doe.gov/coal/carbon-storage/worldwide-ccs-database.

Endnotes

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[28] NPC, "Meeting the Dual Challenge."