INVESTING IN TEXAS

21st Century Energy Capital of the World

by John Diamond and Jorge Barro

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The development of oil production in Texas throughout the 20th century led to the State's accelerated economic growth and the establishment of industries that dubbed Texas the Energy Capital of the World. As the world expands toward renewable and low-carbon technologies, Texas energy production has adapted in several ways and continues to display leadership in the exploration and expansion of alternative energy markets. Still faced with significant uncertainty over the future of emergent energy technology, however, policymakers must find ways to capitalize on its existing resources and foster a hospitable environment to maintain Texas' position as the energy capital of the world throughout the 21st century.

Although oil production originally led to its accelerated economic growth, the Texas energy portfolio eventually expanded into alternative clean energy production, including wind, solar, and hydroelectric power. Other technologies, such as geothermal energy and hydrogen production, still present unique opportunities to expand a clean energy industry with significant upside potential. Federal-level incentives have allowed these new industries to grow while allowing improvements in cleaner energy production from the existing fossil fuel industry. With growing demand for power in an evolving energy market, evaluating allocation of state-level resources and incentives will be critical to striking the right balance between promoting growth in the energy industry and maintaining a competitive economy.

Carbon Capture, Use, and Sequestration

A shift from fossil fuel to low-carbon and renewable energy sources has been underway in the United States for the last 20 years.[1] Accounting and preparing for this shift is important in Texas because fossil fuel energy is a significant share of the Texas economy. In 2020, Texas—the top producer of fossil fuel energy in the United States—accounted for 43% of the nation's crude oil production and 26% of its marketed natural gas production.[2] Texas also leads the nation in carbon emissions with twice as much than the next largest emitter (California), and two-thirds of emissions in Texas come from industry.[3] It is important to note, however, that Texas also leads the nation in wind-powered electricity generation, producing about 28% of all U.S. wind-powered electricity in 2020.[4]

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[1] The share of final energy consumption from renewable resources was 4.68% in 2001 and steadily rose to 8.72% in 2015 (see Our World in Data, 2021).

[2] Our World in Data, 2021. "Share of final energy consumption from renewable sources, 1990 to 2015," Our World in Data.

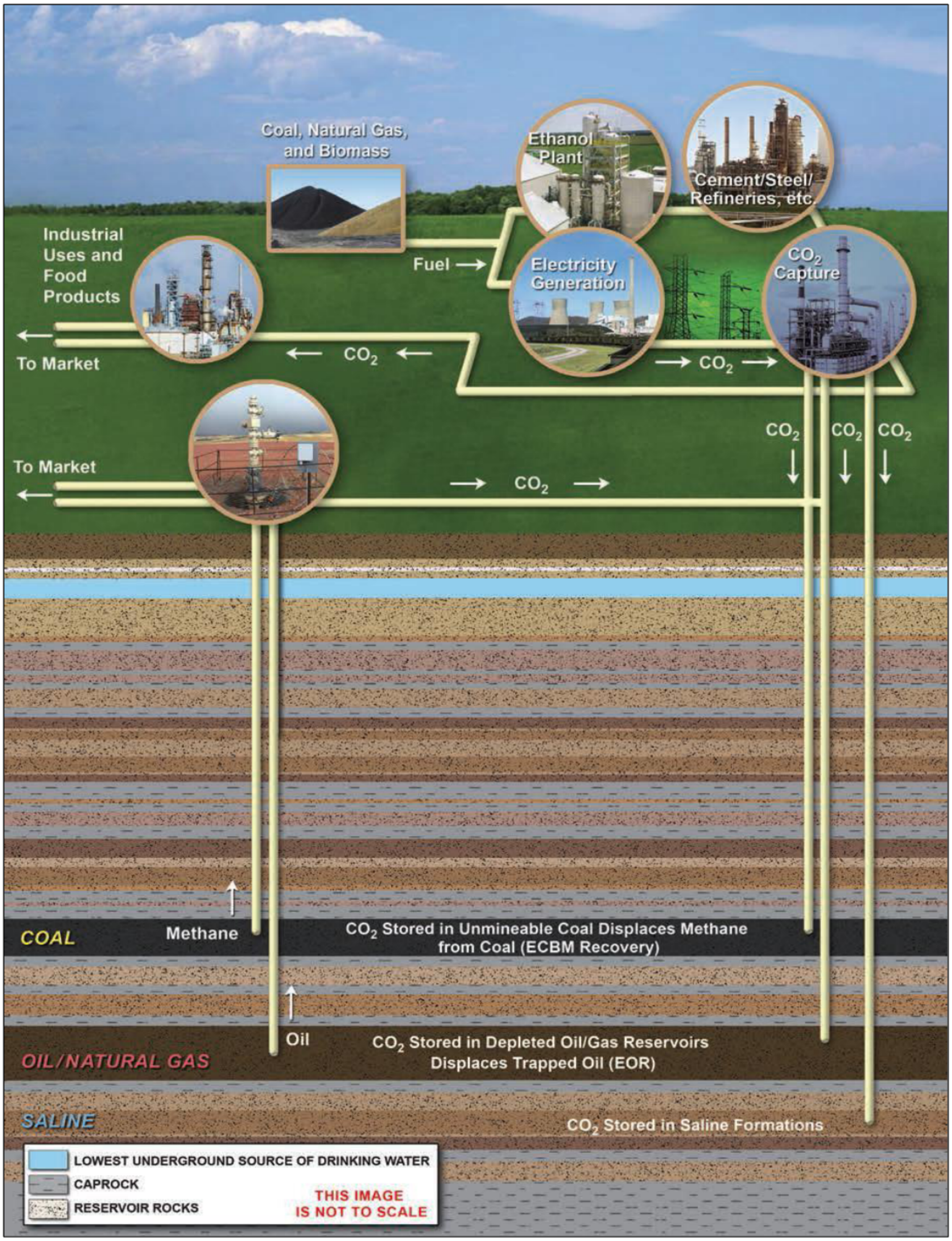
[3] https://www.dallasfed.org/~/media/documents/research/swe/2019/swe1903c.pdf

[4] U.S. EIA, "Texas State Profile and Energy Estimates," Texas Profile Overview and Quick Facts, U.S. Energy Information Administration.

The sectoral shift away from fossil fuels to low-carbon energy will affect the number of jobs in the oil and gas industry, suppliers of intermediate inputs to the oil and gas industry, and tax revenues generated from economic activity in oil and gas industry. The shift to low-carbon and renewable energy will create new jobs that offset a share of the lost jobs in the Texas oil and gas industry, but the job losses will likely dominate in the first few decades. Enacting economic policies that encourage and support the creation of new industries is necessary for Texas to remain the energy capital of the world in the 21st century. These policies need to support research and development of new technologies, regulatory changes to allow for coordination and development of market supply chains, and infrastructure investment. Some of the most promising technologies include carbon capture and storage, battery storage, hydrogen and ammonia-based energy, and related technologies.

Carbon capture, use, and sequestration (CCUS) is the process of capturing CO2 at the source of emission, such as at power plants and other large industrial plants, and then sequestering (and permanently storing) the CO2 underground. The main difference between carbon capture and direct air capture (DAC) is location of capture; however, the costs of direct air capture are considerably higher and currently not economically feasible at significant scale. Carbon utilization is the process of using the captured CO2 to produce goods such as chemicals, cements, fuels, and plastics. CO2 is also useful in enhanced oil recovery (EOR), which is the process of injecting CO2 into an old well to enhance the recovery of oil. However, there is a major difference between utilization and storage. Storage of CO2 underground does not have any additional benefits other than the environmental benefit of reducing the amount of greenhouse gases in the atmosphere, while utilization (either EOR or to make goods from CO2) involves the production of a valuable output that can be sold.

Figure 1: Carbon Capture, Use, and Storage Process



Source: U.S. Department of Energy, Office of Fossil Energy, "Carbon Utilization and Storage Atlas," Fourth Edition, 2012, p. 4.

Notes: *EOR* is enhanced oil recovery; *ECBM* is enhanced coal bed methane recovery. *Caprock* refers to a relatively impermeable formation. Terms are explained in "CO2 Injection and Sequestration."

Regardless of the final use of captured CO_2, this process requires a supply chain that consists of capture and separation of CO_2 from other chemicals, compression and transportation of CO_2, and use or sequestration into a geological reservoir. Figure 1 shows a schematic of the process. Developing this technology and the supply chain is costly and involves significant financial risks to the parties involved. The costliest part of the process is capturing and compressing the CO_2, which can consume 20 percent of the electricity output at a power plant.[5] Coordinating the development of the supply chain is a critical step in the formation of a market for CCUS. If any part of the CCUS supply chain is undeveloped, then development of the other components will not materialize. Solving this coordination problem requires overcoming private, legal, and regulatory risks. Government policy initiatives can help create an environment that supports the creation of a market for CCUS. To date, the U.S. federal government has appropriated roughly $10 billion in research and development funds to CCUS.[6] While continued fiscal support is necessary, addressing regulatory and legal issues will also be fundamentally important. At the state level, the state has applied for underground injection control permits for level IV wells. Other issues that the state clarifies include legal liability of well sites and ownership and location of pipelines.

There is a debate about the use of CCUS to reduce greenhouse gases in atmosphere. Proponents argue it is essential to reaching net zero emissions targets and that growing energy demand will require the use of all energy sources to satisfy demand. For example, the IEA states that "achieving net-zero goals will be virtually impossible without CCUS."[7] Thus, abandoning CCUS is not an option if we are committed to achieving net-zero energy goals. Opponents argue that CCUS will encourage the continued use of fossil fuels, is too expensive, will be unable to operate at a scale to contribute to reducing greenhouse gases enough to be useful, and that leaks from underground storage could have detrimental effects on the environment (such as ocean acidification).[8] [9]

A common concern is that CCUS may be too expensive, and additionally that the high cost of implementing CCUS may be to blame for the slow development of the market. King et al. (2013) estimate the net present value of CCUS on the gulf coast including the cost of capturing CO_2 at coal fired power plants, transporting CO_2 to nearby oil wells or storage locations, and using the

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[5] Congressional Research Service, Carbon Capture and Sequestration (CCS) in the United States, p. 2, located at https://sgp.fas.org/crs/misc/R44902.pdf
[6] Congressional Research Service, Carbon Capture and Sequestration (CCS) in the United States, located at https://sgp.fas.org/crs/misc/R44902.pdf
[7] https://www.iea.org/reports/ccus-in-clean-energy-transitions
[8] https://www.globalwitness.org/en/campaigns/fossil-gas/world-cannot-meet-climate-targets-relying-carbon-capture-and-storage/
[9] https://www.ciel.org/reports/carbon-capture-is-not-a-climate-solution/

CO2 for EOR. They present a number of different scenarios but find that all the scenarios produce net present values ranging from negative $1 billion to negative $25 billion.[10] The negative valuations reflect the additional costs of capturing and sequestering CO2 after using all of the derived oil revenues to cover a large fraction of the costs. It is worth noting that these estimates used oil prices around $100 per barrel. The conclusion is that CCUS is not a profitable market activity and will require a subsidy to be viable.

Chris Nichols (2019) also examines the impact of section 45Q sequestration tax credits using the National Energy Technology Laboratory's (NETL) enhanced National Energy Modeling System (NEMS).[11] Nichols enhanced the NEMS model "to represent CO2 capture opportunities at industrial sources, focusing on Ethanol, Hydrogen and Natural Gas Processing facilities." He uses the model to examine the impact of extending the 45Q tax credit to any facility started by 2050 from a sunset date that allows facilities to take the deduction if construction is started by January 1, 2024. He finds that there is economic justification for CCUS given the extended model, which is at odds with King et. al (2013). The NEMS model is a macroeconomic model that includes a well-defined energy sector extended to include a carbon capture, transportation, use and storage (CTUS) module. He draws the following conclusions from his simulations about the effects of extending the 45Q tax credit:

- industrial sources of CO2 capture increase but top out relatively soon;
- the largest impacts occur in the power generation sector with substantial deployment of CCUS (much of this is so that clean coal can replace natural gas and renewable energy sources);
- CO2 used in EOR increases but reaches a saturation level;
- that storage in geological reservoirs is economically viable; and
- deploying CCUS leads to learning by doing which will lead to lower energy costs eventually.

[10] Carey W King *et al* 2013. "The system-wide economics of a carbon dioxide capture, utilization, and storage network: Texas Gulf Coast with pure CO2-EOR flood." *Environ. Res. Lett.* **8** 034030 (accessed online at https://iopscience.iop.org/article/10.1088/1748-9326/8/3/034030 on 11/22/2021).
[11] https://netl.doe.gov/sites/default/files/netl-file/C-Nichols-NETL-Modeling-CCUS-Deployment.pdf

Table 1: Qualifying Facilities and Emissions, Great Plains Institute, 2019

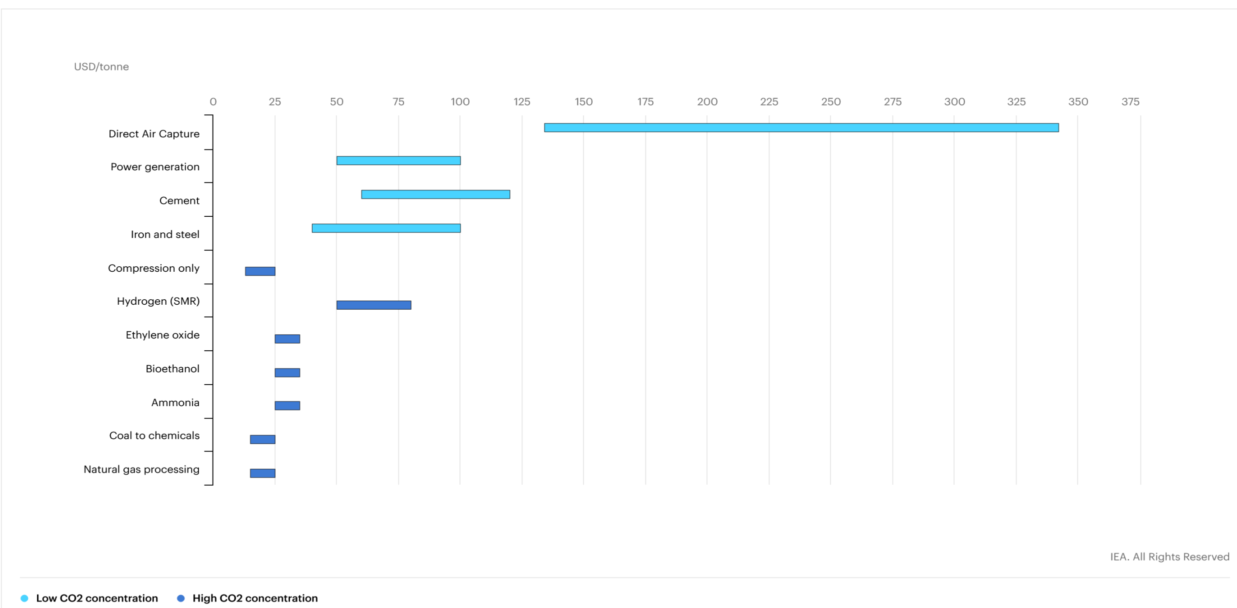
Industry	# of 45Q Qualifying Facilities	Qualifying Emissions MMT CO2	Total # of TX Facilities	Share of TX Industry Emissions
Coal Power Plants	20	127.4	20	99%
Gas Power Plants	51	81.4	106	91%
Refineries	24	60.2	31	98%
Petrochemicals	16	16	32	52%
Gas Processing	12	4.9	259	21%
Hydrogen	16	12.5	16	100%
Cement	16	10.4	26	96%
Chemicals	-	-	65	-
Metals & Minerals	3	0.5	84	8%
Pulp & Paper	-	-	5	-
Ammonia	1	0.7	1	100%
Ethanol	4	1.2	4	100%
Grand Total	**190**	**314**	**651**	**84%**

A third study by Great Plains Institute (GPI, 2019) that looked at opportunities for carbon capture in the Texas power and industrial sectors found similar results. For example, GPI found that 84 percent of Texas emissions would qualify for the section 45Q credit as shown in Table 1. However, as shown in Table 2, out of the 314 million tons of CO2 that they identify as qualifying emissions it is only economically feasible to capture, transport and store roughly 9 million tons of CO2. If the cost of CCUS falls by $9 it would be economically feasible to capture, transport and store an additional 11 million tons of CO2. If the cost of CCUS falls by $10-$20 it would be economically feasible to capture, transport and store an additional 58 million tons of CO2. In this last case, total capture would be roughly 78 million tons of CO2. The takeaway is similar to studies discussed above; lower costs and increased sequestration credits will lead to large expansions in the scale of CCUS.

Table 2: Average Capture Cost and Economic Feasibility by Industry, Great Plains Institute, 2019

			Required cost reduction	
Industry	Average Capture Cost	Currently Feasible	$9 Reduction	$10 - $20 Reduction
Natural Gas Processing	$14.46	1.13		
Ethanol	$16.54	1.02		
Hydrogen	$42.03	4.36	0.67	
Cement	$51.88		6.47	0.80
Refineries	$56.07	2.71	3.37	3.43
Coal Power Plant	$57.28			24.0
Gas Power Plant	$59.85			26.37
Petrochemicals	$61.73			3.43

Figure 2: Cost of CO2 Capture by Sector and Initial CO2 Concentration, 2019



IEA, Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019, IEA, Paris https://www.iea.org/data-and-statistics/charts/levelised-cost-of-co2-capture-by-sector-and-initial-co2-concentration-2019

The optimal size of the subsidy is complex and depends on a number of factors. First, there is no single cost of CCUS. As shown in Figure 2 (and in Table 2), the cost of CO2 capture depends on the industry and CO2 concentration. There are also costs of transporting carbon and either using it in EOR (in which case the cost may be negative) or sequestering onshore or offshore.

However, abandoning CCUS as a feasible option could be a mistake, as technological advancements will continue improving its efficiency. Historically, these advancements have reduced CCUS costs in the power sector by as much as 35%, with significant potential future gains remaining in the industry.[12]

Given the need for CCUS, policymakers should focus on supporting the development of the market segments, noting again that all three components of the supply chain must develop simultaneously. This problem of coordinating market creation is a classic economic issue that calls for government policy aimed at reducing market and coordination risks. Medlock and Miller (2021) provide a list of such possible policy actions.[13] They argue that the following issues are important to the development of CCUS: streamlined jurisdictional control and regulations, legal liability, access to pore space, regulation of underground storage of CO2, research and development, and fiscal subsidies.

The Energy Improvement and Extension Act of 2008 created a sequestration tax credit (often called 45Q tax credit after the IRC section). The Bipartisan Budget Act of 2018 increased and expanded the credit as shown in Figure 3, which is from a CRS report on the 45Q credit.[14] H.R. 5376, the Build Back Better Act, would increase the credit amount to $85 ($60) from $50 ($35) for geologically sequestered (injected and used for enhanced oil or gas recovery), extend the period for claiming the credit for any facility that is started by January 1, 2032, and reduce capture requirements to be eligible for the credit. The Joint Committee on Taxation estimates that these changes will reduce revenues by $2.1 billion over the period 2022-2031.[15]

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[12] https://www.iea.org/commentaries/is-carbon-capture-too-expensive

[13] Medlock, III, Kenneth B. and Keily Miller, 2021. "Executive Summary: Expanding Carbon Capture in Texas." Baker Institute Center for Energy Studies, January. https://www.bakerinstitute.org/media/files/files/1f114745/expanding-ccus-in-texas-executive-summary.pdf

[14] https://crsreports.congress.gov/product/pdf/IF/IF11455

[15] https://www.jct.gov/publications/2021/jcx-45-21/

Figure 3: Key Elements of the Section 45Q Credit

Equipment Placed in Service Before 2/9/2018	Equipment Placed in Service on 2/9/2018 or Later
Credit Amount (per Metric Ton of CO_2)*	
Geologically Sequestered CO_2	
\$23.82 in 2020. Inflation-adjusted annually.	\$31.77 in 2020. Increasing to \$50 by 2026, then inflation-adjusted.
Geologically Sequestered CO_2 with EOR	
\$11.91 in 2020. Inflation-adjusted annually.	\$20.22 in 2020. Increasing to \$35 by 2026, then inflation-adjusted.
Other Qualified Use of CO_2	
None.	\$20.22 in 2020. Increasing to \$35 by 2026, then inflation-adjusted.
Claim Period	
Available until 75 million tons of CO_2 have been captured and sequestered.	12-year period once facility is placed in service.
Qualifying Facilities	
Capture carbon after 10/3/2008.	Begin construction before 1/1/2026.
Annual Capture Requirements	
Capture at least 500,000 metric tons.	*Power plants:* capture at least 500,000 metric tons. *Facilities that emit no more than 500,000 metric tons per year:* capture at least 25,000 metric tons. *DAC and other capture facilities:* capture at least 100,000 metric tons.
Eligibility to Claim Credit	
Person who captures and physically or contractually ensures the disposal, utilization, or use as a tertiary injectant of the CO_2.	Person who owns the capture equipment and physically or contractually ensures the disposal, utilization, or use as a tertiary injectant of the CO_2.

Source: CRS analysis of IRC Section 45Q.

At the federal level, the expansion of the 45Q tax credit to \$85/ton from \$50/ton is a powerful incentive to support the development of the CCUS market. However, as mentioned above the coordination of development of the full supply chain is necessary to reduce the risks that currently hinder market creation. Figure 2 shows the costs of carbon capture by sector and carbon concentration of emissions. Note that power generation, cement production, iron and steel production all have costs for carbon capture that fall between \$50/ton and \$100/ton. These sectors are responsible for nearly 40 percent of global CO2 emissions, and the steel, cement, and chemicals industries are the largest industrial emitters. Thus, increasing the credit to \$85/ton from \$50/ton would increase incentives for carbon capture in the industrial sectors that are producing a significantly large share of emissions. Thus, an increase of the 45Q credit in this range will significantly increase the economies of scale throughout the supply chain. It is also important that H.R. 5376 would extend the sunset to facilities started by January 1, 2032 as this reduces the economic risk associated with building such a facility.

Figure 4: The Carbon Capture Landscape in Texas by Great Plains Institute, 2019

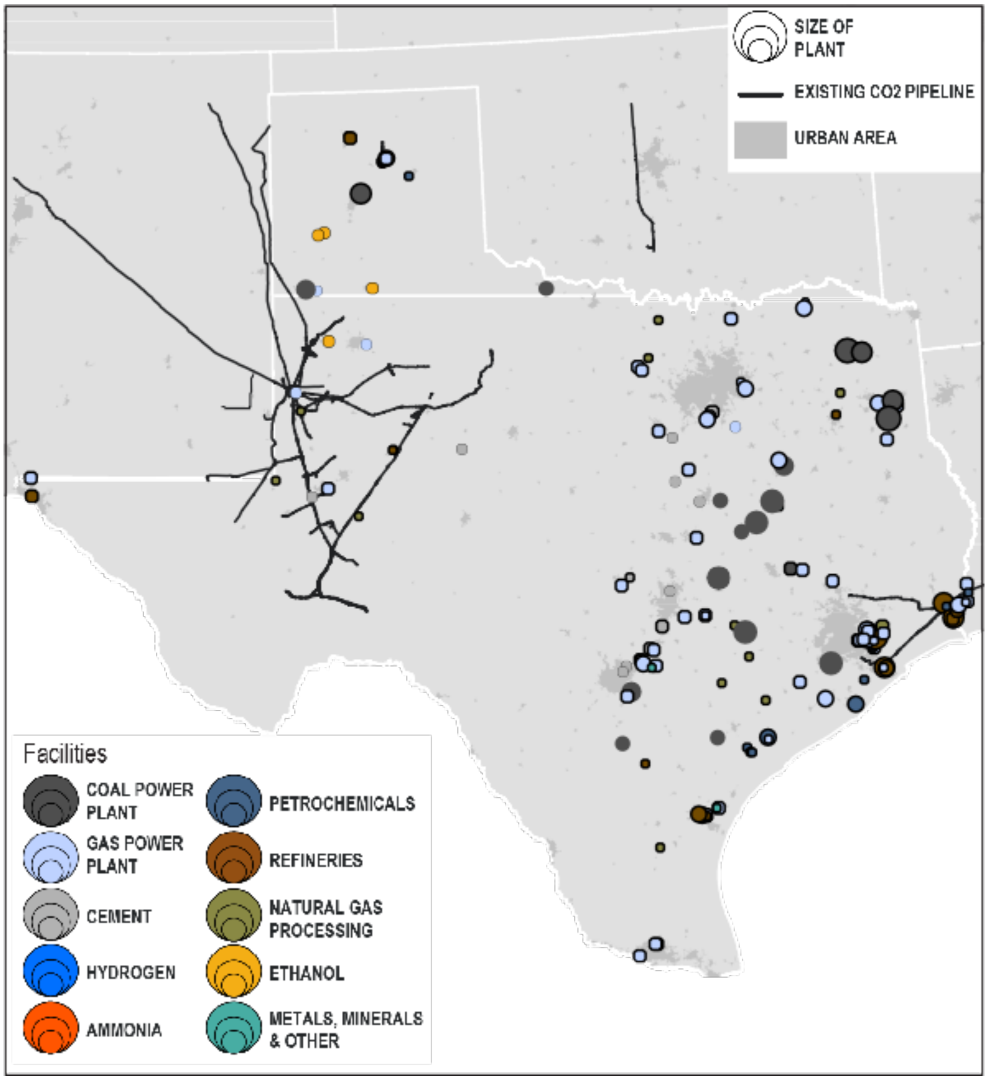
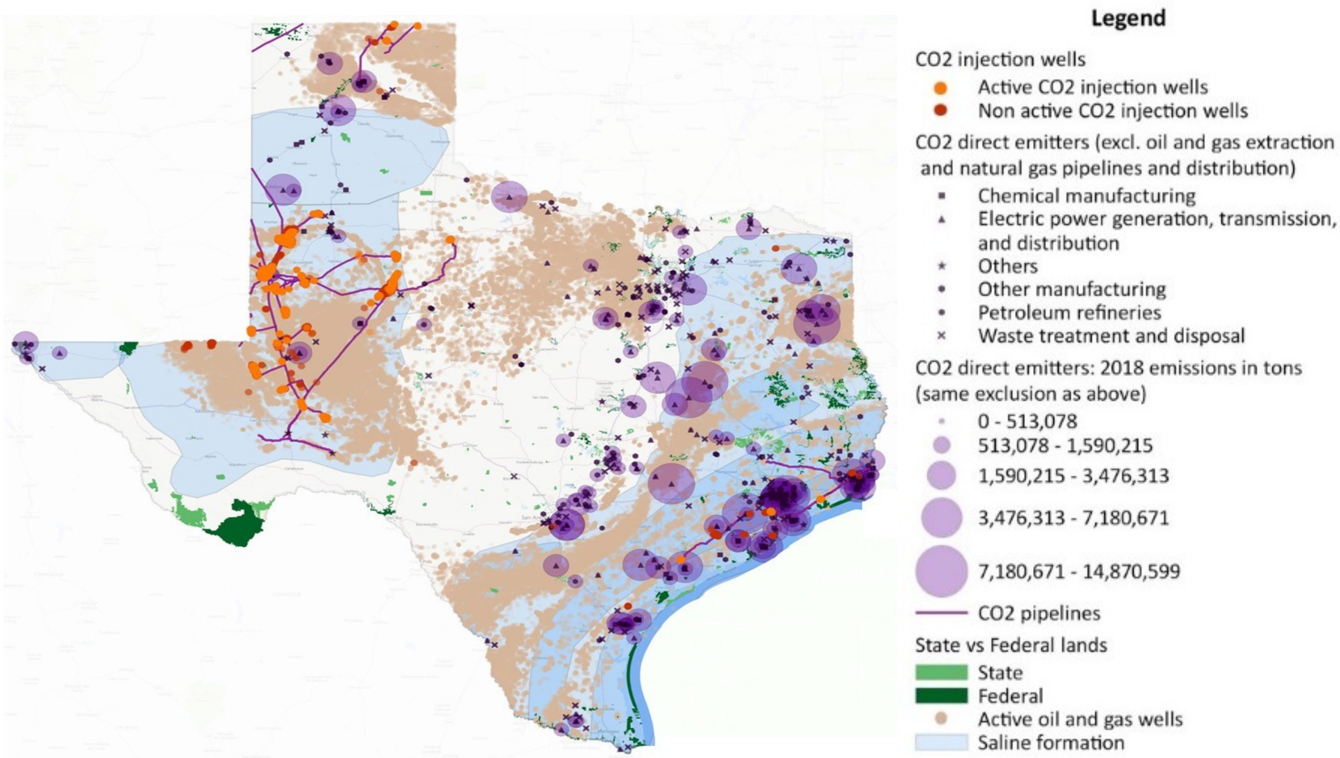


Figure 5: The Carbon Capture Landscape in Texas



Source: Medlock, III, Kenneth B. and Keily Miller, 2021. “Carbon Capture in Texas.” Baker Institute Center for Energy Studies, January. https://www.bakerinstitute.org/research/carbon-capture-texas/

Texas has many comparative advantages and existing synergies that make it an ideal environment for a CCUS industry to grow and flourish. Figure 4 and Figure 5 show current industrial emitters by size and existing pipeline infrastructure in Texas. The Texas gulf coast exhibits ideal characteristics for becoming a hub for the carbon capture industry. Specifically, the concentration of industry and the nearby geological formations in the Gulf that are ideal storage sites make Texas a prime candidate to be a major hub for CCUS. In addition, existing oil and gas wells and existing pipeline infrastructure also are competitive advantages for the state in becoming a carbon capture hub. Shared hubs can reduce costs by as much as 20%, enhancing both the local competitive advantage and the returns to local CCUS infrastructure.[16] Moreover, the supply of human capital in engineering, geology, chemistry, and supply chain management is unmatched anywhere in the world. These advantages can help the industry accelerate and achieve economies of scale, adding to the private sector incentives to establish a local CCUS market.

[16] https://www.woodmac.com/news/opinion/cop26-carbon-capture--storage-and-low-carbon-hydrogen/

Finally, there are potentially large benefits to Texas from the creation of a market for CCUS. The revenues from carbon capture would offset the lost revenues from other oil and gas severance taxes as the US expands low-carbon production and renewables. For example, a functioning carbon capture market would allow the continued use of oil and gas products with significantly reduced negative environmental impacts. Thus, the decline in oil and gas jobs are likely to be much smaller in a world with CCUS as opposed to a world without it. Another additional source of revenue would come from lease payments on the storage facilities that are used to permanently store the captured carbon. This would reduce the extent of labor market transitions given the smaller reduction in oil and gas production. Given the importance of these jobs in Texas and the relative high wages of these jobs (relative to other jobs with similar education levels), in all likelihood it would significantly reduce transition costs in the labor market of moving to more environmentally sustainable energy production.

Geothermal Energy and Natural Climate Solutions

Carbon capture technology is an important method in expanding energy production and reducing environmental damage. However, no single method will suffice in meeting energy demand. Instead, we must implement multiple energy expanding methods to provide stable and affordable energy. A particularly interesting method and one that is especially interesting for the state of Texas is geothermal energy. The production of geothermal energy uses heat from the earth's core to heat water and then uses the steam to generate power. Note that geothermal energy production uses a common set of skills with the existing oil and gas industry, including directional drilling, chemical and structural engineering, geology, and more. It has a number of advantages and disadvantages. Its advantages include[17]:

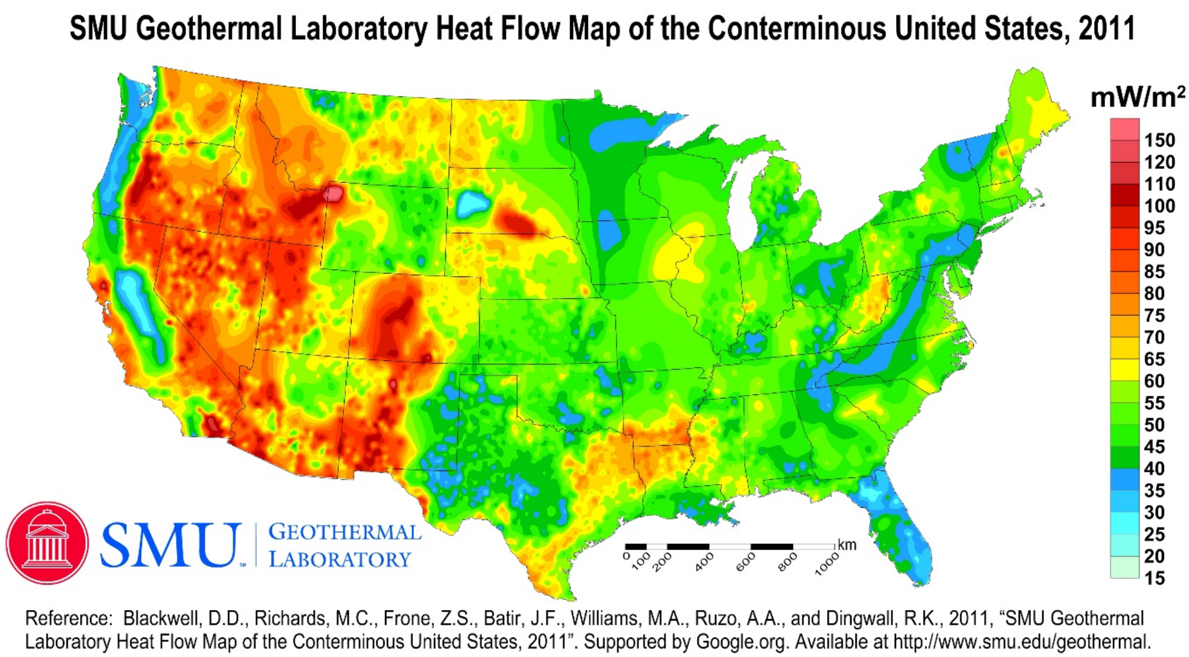
- It is a relative clean source of energy.
- It can provide enough energy to power the earth indefinitely ("Worldwide energy consumption, which is around 15 terawatts, can be harnessed by the energy stored in the earth's core for ages without depletion."[18])
- It is a baseload source of power. Because geothermal power plants produce uninterrupted power supplies, it would increase the reliability of the power system.
- It boosts GDP and creates more jobs relative to wind and solar. In addition, it uses many of the processes and human capital used in the oil industry.[19] It would reduce the transition costs of scaling down oil and gas production (to the extent this occurs) as those resources would be directly employable in the geothermal sector.

[17] https://greencoast.org/pros-and-cons-of-geothermal-energy/
[18] https://greencoast.org/pros-and-cons-of-geothermal-energy/
[19] https://www.energy.gov/eere/geothermal/geothermal-development-job-types-and-impacts

Its disadvantages include:

- It does release pollutants into the air such as silica, sulfur dioxide, and others.
- It can lead to seismicity issues. This is similar to the issues of seismicity related to shale oil and gas production. However, we already have substantial information on how to prevent these issues.
- It requires large up-front investments, but then produces power for a long time.
- Must manage geothermal reservoirs or sustainability issues can occur as heat levels are dissipated.
- Locally specific as transporting the power is not efficient. This implies that geothermal plants must be located in places where heat sources are accessible through drilling. Figure 6 shows a map of heat sources in the continental United States.

Figure 6: Continental United States Heat Flow Map



This is a particularly interesting source of energy production for Texas because of the crossover in skills between the oil and gas industry and geothermal energy production. For example, the ability to find relatively shallow hot spots and drill down a mile or more to reach reservoirs of hot water and steam requires knowledge and skills that already exist in the Texas oil and gas sector. Thus, existing oil and gas resources can shift to geothermal energy production with relatively low transition costs if changes in the production of oil and gas lead to lower demand for labor in the oil and gas sector. Otherwise, the knowledge and resources that are necessary to expand energy by using geothermal energy production already exist in Texas. Finally, geothermal is not a new technology. It has been widely used for decades in places well suited to its use. For example, Iceland has used geothermal energy production since 1907, and 25 percent of their power comes from geothermal.

Natural climate solutions (NCS) include reforestation, avoided forest conversion, and the maintenance of wetlands.[20] While there is a large potential for climate mitigation through NCS strategies, there is also significant uncertainty about the political, economic, and social risks associated with NCS. Much of the gains depends on changes in food production, diets, and use of natural resources that will be hard to implement. While NCS is an important component in reaching climate protection goals, it is not a strategy that Texas has a particularly strong comparative advantage. In addition, the economic benefits would not accrue directly to Texas. Given this, it is best to leave NCS as a national and international strategy in reducing climate change.

Other advanced technologies will also help to transform the energy sector in Texas and the United States, including hydrogen, nuclear, biofuels, new storage innovations, and many more. Funding research and development across a wide range of potential new energy sources will continue to be critical for many years to come. As the market for energy expands to low-carbon and renewable alternatives Texas must capitalize and take a lead on developing these new industries.

Hydrogen

One of the most promising yet complicated prospects for clean energy production involves hydrogen creation, storage, transportation, and power generation. Most hydrogen is currently produced for use in oil refining and in ammonia, methanol, and steel production.[21] In the future, however, hydrogen could play an increasingly important role as a power source in applications where electric power is less feasible and in temporal energy grid stabilization (or *load balancing*), enhancing grid reliability as the energy industry expands towards renewable energy.

Production of hydrogen currently takes several forms with varying environmental impacts. In the United States, 95 percent of commercial hydrogen is produced by reforming natural gas.[22] Although the process releases carbons as a byproduct, a smaller share of greenhouse gasses are

[20] https://www.pnas.org/content/114/44/11645
[21] https://cockrell.utexas.edu/news/archive/9160-texas-poised-to-become-leader-in-hydrogen-production-energy-and-policy-leaders-say
[22] https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

produced (relative to other fossil fuels), and the environmental impact could be reduced through the use of carbon capture. Alternatively, hydrogen could be produced through electrolysis, which uses electric currents through water to separate hydrogen from oxygen. If the electricity used to produce hydrogen is generated from renewable power (so-called *green hydrogen*), then the process yields the highest environmental benefits, leaving only hydrogen and oxygen as byproducts.[23] While this may seem ideal, two issues limit its widespread adoption. First, hydrogen's round-trip efficiency, which measures the share of power maintained after electricity is converted into hydrogen and back to electricity, falls well below the efficiency of alternative storage technologies.[24] Second, hydrogen production from renewable energy results in prohibitively high prices for widespread adoption in industries where electricity lacks feasibility and efficacy as a power source.

Despite its shortcomings, hydrogen power appears to be at the early stages of its development as a component of a low-carbon energy ecosystem, and cost reductions from efficiency improvements could make the industry increasingly viable over time. According to estimates from the IEA, hydrogen produced from low-carbon electricity was between $3.2/kg and $7.7/kg in 2019, and the cost is expected to fall to a range between $1.3/kg to $3.3/kg by 2060, reflecting a potential improvement of roughly 80%.[25] The US Department of Energy, however, recently introduced a hydrogen initiative aimed at reducing hydrogen costs from around $5/kg to within $1/kg over the next decade, also reflecting approximately an 80% cost improvement but 30 years sooner.[26] With price reductions of this magnitude, hydrogen could become a viable alternative for fossil fuels in industries where batteries are impractical at current standards.

[23] https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php
[24] https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/hydrogen-technology-faces-efficiency-disadvantage-in-power-storage-race-65162028
[25] https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050
[26] https://ieefa.org/us-department-of-energy-announces-green-hydrogen-cost-cutting-goal/

Table 3: Miles of hydrogen pipeline by state (Source: h2tools.org)

State	Miles	%
Alabama	31.1	2.0%
California	16.2	1.0%
Indiana	13.9	0.9%
Kansas	0.4	0.0%
Louisiana	507.9	32.4%
Michigan	5.5	0.4%
New York	2.9	0.2%
Ohio	9.2	0.6%
Oklahoma	1.5	0.1%
Texas	968.1	61.8%
Utah	6.5	0.4%
Washington	2.9	0.2%
Total	1566.1	

Understanding the value of policy initiatives aimed at expanding the hydrogen industry in Texas involves measuring the local comparative advantage, as well as the long-term market outlook. Based on 2016 data, Texas has 61.8% of U.S. hydrogen pipeline and 34.3% of the world's hydrogen pipeline (see Table 3).[27,28] This concentration of pipeline in Texas is largely due to the substantial hydrogen demand at petroleum refineries.[29] Consequently, the value of the current infrastructure to green hydrogen expansion could depend on the long-term sustainment of the fossil fuel industry, as well as the fungibility of the existing infrastructure for alternative hydrogen uses.[30] Regardless of the eventual outcome, with a large concentration of the world's hydrogen pipeline along the Gulf Coast, the resources to expand transportation and distribution infrastructure are localized, indicating higher advantages to agglomerate the hydrogen industry in Texas.

In addition to its existing infrastructure, Texas has two natural features that contribute to its comparative advantage as a hub for hydrogen production. First, Texas has access to ports, making it ideal in the production of hydrogen for future exporting to the rest of the world.[31] Second, Texas has natural geological hydrogen storage capacity that has been used by industry for several years.[32] Natural underground repositories, such as depleted gas and oil reservoirs,

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[27] https://h2tools.org/hyarc/hydrogen-data/hydrogen-pipelines
[28] This measure refers to length but not necessarily potential volume.
[29] https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf
[30] https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/021821-texas-has-resources-infrastructure-to-become-global-hydrogen-hub-speakers
[31] https://news.utexas.edu/2020/07/27/hydrogen-should-be-the-next-big-energy-business-for-texas/
[32] https://technicalreports.ornl.gov/cppr/y2001/rpt/125102.pdf

aquifers, and salt caverns, provide ideal conditions for long-term, high-volume hydrogen storage.[33] The abundance of these storage facilities in Texas further enhances the value of hydrogen production agglomeration, distribution, and storage within the state. Hydrogen storage capacity could also play a role in load balancing if round trip efficiency improves or if clean hydrogen costs fall significantly.

The long-term economic outlook for commercial hydrogen production in Texas could depend extensively on several factors, including the temporal variability in energy production associated with the expansion of renewable energy sources and the success of initiatives aimed at enhancing hydrogen production and demand. Variability in electricity production is expected to increase with the expansion of renewable energy, leading to corresponding electricity price fluctuations that could affect the prospect of green hydrogen production. Since electricity is an input into green hydrogen production, the value of hydrogen production through electrolysis rises as the price of electricity falls.

Whether temporal variability in renewable energy production results in a high frequency of low-price electricity periods determines the potential economic value of electrolytic hydrogen production. Capacity expansion models can be used to simulate the impact of variable renewable energy on electricity prices in the presence of electrolytic hydrogen production. A recent study modeled and projected energy prices in Texas in 2050 with significantly decarbonized energy production, designed to simulate the local energy market under a variety of different scenarios.[34] The results indicated a high frequency of low-price hours throughout the year, creating higher value to electrolytic hydrogen production for non-electric use. The frequency of the low-price hours also increased with tighter constraints on carbon emissions. Under the scenarios studied, green hydrogen production in Texas could become increasingly valuable as energy production expands into renewable resources.

Viability of the hydrogen production industry also relies on projected demand for hydrogen. Both domestically, through dedicated federal funding, and abroad, through similar incentives and regulations, the international community is supporting the expansion of hydrogen markets. Domestically, the recent infrastructure bill dedicated $8 billion to the development of at least four clean hydrogen hubs, $1 billion towards the costs of clean hydrogen production from electrolyzer systems, and $500 million towards a clean hydrogen supply chain, including research and development projects.[35] Across the globe, investments through 2030 total an estimated $500 billion, with projects spanning the entire value chain.[36] This concerted effort to grow the hydrogen industry is expected to increase global hydrogen demand by 137% between

[33] https://www.sciencedirect.com/science/article/pii/S0360319912017417
[34] https://www.nber.org/papers/w29510
[35] https://www.natlawreview.com/article/infrastructure-investment-and-jobs-act-accelerating-deployment-hydrogen
[36] https://hydrogencouncil.com/en/hydrogen-insights-updates-july2021/

2020 and 2030.[37] Hydrogen demand is expected to accelerate thereafter, rising orders of magnitude between 2035 and 2050.[38] Clear commitments by the international community to establishing a global hydrogen market and growing exploration of its use indicate sustained long-term demand for hydrogen.

Although current hydrogen use in Texas is highly concentrated in the fossil fuel industry, other local industries could see significant growth in hydrogen demand, further enhancing the agglomeration value of local hydrogen production. Because of its higher energy density relative to batteries, hydrogen maintains significant potential as a fuel in several transportation industries, including trucking and aviation.[39] Battery-powered trucks are making great strides in the transportation industry, exemplified by a Tesla Gigafactory in Austin expected to produce such vehicles, but hydrogen-powered trucks also hold significant potential, pending cost-reducing technological advancements.[40] In particular, fast refueling time and long driving range make the prospect of hydrogen power attractive for long-haul trucking, relative to battery-powered trucks.[41] Initial estimates suggest that enhanced fuel range of hydrogen-powered trucks would be sufficient to meet the needs of at least 95% of the daily routes throughout the nation.[42] Several of the largest truck manufacturers, including Daimler, Volvo, and Toyota have already been dedicating significant resources towards the development of hydrogen-powered trucks.[43,44]

Innovations in hydrogen-powered long-haul trucking could be particularly influential in Texas, which employs more truck drivers than any other state.[45] Texas maintains several inherent advantages in the industry, including its access to deep-water ports, extensive interstate system, shared border with Mexico—a major trading partner, and broad integration with freight transportation networks.[46,47] If hydrogen becomes a viable alternative to fossil fuels—whether through technological improvements or increased constraints on carbon emissions—access to low-cost hydrogen in Texas could provide a significant advantage to the local trucking industry and expand trade within the state. As supply chain integrity and low-carbon energy production become increasingly prioritized across the globe, Texas would remain well-positioned and insured within the transportation industry over time by facilitating access to hydrogen.

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37 https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-by-sector-in-the-net-zero-scenario-2020-2030
38 https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html
39 https://rmi.org/run-on-less-with-hydrogen-fuel-cells/
40 https://electrek.co/2021/09/07/tesla-gigafactory-texas-attracts-suppliers-as-production-nears/
41 https://newscenter.lbl.gov/2021/04/08/hydrogen-offers-promising-future-for-long-haul-trucking-industry/
42 https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf
43 https://www.wsj.com/articles/the-electric-truck-battle-to-come-batteries-versus-hydrogen-fuel-cells-11636466414
44 https://www.nytimes.com/2021/05/23/business/hydrogen-trucks-semis.html
45 https://www.bls.gov/oes/current/oes533032.htm
46 https://www.thetrucker.com/truck-driving-jobs/resources/states/texas
47 https://ftp.txdot.gov/pub/txdot/move-texas-freight/studies/freight-mobility/2018/summary.pdf

Advancements in low-carbon aviation might also introduce significant potential for Texas hydrogen agglomeration. Several companies in the aviation industry, such as Airbus, are exploring several different models of hydrogen-powered aircrafts.[48] United Airlines recently indicated plans to purchase up to 100 hydrogen-electric engines.[49] With one of their major hubs at Houston's George Bush Intercontinental Airport, United Airlines' introduction of hydrogen-powered planes could generate a significant complementarity in local hydrogen demand and increase local air travel as the aviation industry expands its low-carbon fleet.[50]

One unique prospect for demand in the Texas hydrogen industry is the growing aerospace industry. Liquefied hydrogen is one of the primary sources of rocket fuel, having a long history of use as rocket propellant in NASA spacecrafts.[51] The hydrogen used at NASA's Kennedy Space Center (KSC) in Cape Canaveral, Florida, for example, is produced from reformed natural gas in either New Orleans, Louisiana or Mobile, Alabama and transported in 13,000-gallon mobile tankers.[52,53] Although NASA has historically launched rockets from Florida, the private aerospace industry has experienced considerable growth in Texas, attracting several companies to operate locally.[54] Most notably, SpaceX and Blue Origin both chose launch facilities in Texas (SpaceX in Brownsville and Blue Origin in Van Horn) and have launched rockets within the state.[55] Although SpaceX plans to continue relying on fossil fuels to propel its rockets, Blue Origin's rockets are fueled by liquid hydrogen.[56,57] The growing commercial aerospace industry could generate significant future demand for hydrogen in Texas, mutually benefitting the respective industries and contributing to the value of proximity in hydrogen production.

Coordination and infrastructure investment would play a key role in developing a clean hydrogen hub in Texas. Currently, renewable energy—particularly wind energy—is mainly produced in west Texas and, to a lesser extent, in the southernmost parts of Texas.[58] Hydrogen demand, however, is currently highly concentrated in Southeast Texas, where it is used as feedstock in the

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48 https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe
49 https://www.cnbc.com/2021/12/14/investment-from-united-to-purchase-hydrogen-electric-engines-.html
50 https://www.united.com/ual/en/us/fly/travel/airport/maps.html
51 https://www.nasa.gov/content/space-applications-of-hydrogen-and-fuel-cells
52 https://www.nasa.gov/centers/kennedy/pdf/167433main_Propellants08.pdf
53 https://www.energy.gov/eere/fuelcells/h2iq-hour-cold-and-cryo-compressed-hydrogen-storage-rd-and-applications-text-0 (slides: https://www.energy.gov/sites/default/files/2020/08/f77/hfto-webinar-cryogenic-h2-july2020.pdf)
54 https://gov.texas.gov/uploads/files/business/aerospace_report.pdf
55 https://www.houstonchronicle.com/news/houston-texas/space/article/Bezos-vs-Musk-is-a-space-race-like-no-other-16313585.php
56 https://www.bloomberg.com/news/articles/2021-01-30/elon-musk-plans-to-use-texas-natural-gas-for-his-starships
57 https://www.marketwatch.com/story/as-bezos-completes-blue-origin-mission-many-ask-whats-the-climate-change-impact-11626795950
58 https://windexchange.energy.gov/states/tx

refining process. The area could also play a significant role in future hydrogen exporting through the Port of Houston.[59] Remoteness of renewable energy production from hydrogen demand in Texas introduces a logistical issue that could be resolved through the government's efforts to coordinate outcomes and invest in infrastructure development.

With hundreds of miles separating renewable energy production and hydrogen demand, the industry would be left with two choices—produce hydrogen near the energy source and transport it through pipeline or transport electricity through transmission lines and produce hydrogen at the point of use. A recent study produced by the University of Texas indicates that producing hydrogen in west Texas and transporting it through hydrogen pipelines to southeast Texas would cost roughly one-third of the costs associated with requisite expansion and upgrades to transmission lines necessary to transport the energy in the form of electricity.[60] Moreover, by allowing pressure in the hydrogen pipeline to rise above the minimum pressure (but remain below the maximum pressure), the pipeline infrastructure itself could serve as a form of hydrogen storage, possibly playing a role in future grid reliability. The study also indicates that local brackish water in west Texas aquifers could be desalinated to affordably produce enough water for electrolysis to generate the Houston area's entire hydrogen demand for 4,000 years. Finally, the study highlights the role that hydrogen demand and transportation could play in determining future wind power generation locations. The Texas Gulf Coast has been identified as an area that could generate significant offshore wind power.[61] With proximity to the state's existing hydrogen pipeline infrastructure and boundless water supply, wind-powered renewable energy generation along the Texas Gulf Coast could provide complementarity to the existing energy infrastructure and play a key role in determining the success of green hydrogen production.

With a specialized workforce, existing infrastructure, and established demand, Texas maintains a clear comparative advantage in developing a clean hydrogen hub. Expanding the hydrogen production industry into generation from renewable energy and using other clean technology, like carbon capture in the case of natural gas reforming, will generate new jobs and contribute to state-level economic growth. According to one set of projections, hydrogen could generate an estimated $140 billion in revenue and 700,000 jobs at the national level by 2030 and generate $750 billion in revenue and 3.4 million jobs by 2050.[62] If Texas' economic gains from hydrogen proliferation were proportional to its share of the US population (likely understating its share of

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[59] Countries that import hydrogen could require that the hydrogen be produced through renewable energy, possibly requiring separate pipelines.
[60] https://sites.utexas.edu/h2/files/2021/08/H2-White-Paper_Hydrogen-Pipelines-versus-Power-Lines.pdf
[61] https://www.nrel.gov/news/program/2020/studies-find-gulf-of-mexico-well-positioned-for-offshore-wind-development.html
[62] https://www.fchea.org/us-hydrogen-study

future hydrogen production), it would imply roughly $12 billion in revenue and 61,000 jobs by 2030 and $66 billion in revenue and 300,000 jobs by 2050.[63]

Hydrogen expansion would diversify the state's energy production and could play an increasingly important role as the energy grid expands its reliance on renewables. The state should have a clear plan to coordinate outcomes with private industries and provide guidance in the expansion of infrastructure—particularly other complementarities, like wind power. Finally, policymakers should continue encouraging research and development to ensure Texas supplements private sector ventures with the resources that enhance the likelihood of success and contribute to the local intellectual environment.

The Texas Deep Freeze and the Case for Weatherization

Disruptions in electricity and natural gas service in Texas during Winter Storm Uri were the result of widespread outages and failures across all types of generation technologies (coal, natural gas, nuclear, solar, and wind). Winter Storm Uri resulted in the largest outage of electricity to Texas customers on record. Leading up to the outages, weather forecasts failed to predict the severity and timing of the winter weather event, estimated demand for electricity during the winter weather event fell short of actual demand, power generation was curtailed, and power grid failures rapidly deteriorated due to widespread transmission failures.

Investment in technology and processes to fix the underlying problems with the electric grid, including weatherization, transmission, and reliability would yield significant economic benefits to consumers and producers. Garrett Golding, Anil Kumar and Karel Mertens of the Federal Reserve Bank of Dallas published an assessment of the costs of the winter storm and power outages to the Texas economy.[64] Golding, Kumar, and Mertens (2021) stated that:
"Early estimates indicate that the freeze and outage may cost the Texas economy $80 billion–$130 billion in direct and indirect economic loss. These initial calculations come with significant uncertainty. Estimates of insured losses, which are easier to quantify, range from $10 billion to $20 billion."

However, total or insured losses do not indicate the amount of additional investment that is required to provide the optimal supply of power or optimal amount of reliability. To determine optimal expenditures, energy experts calculate the value of lost load (VOLL) – which represents

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[63] These results are derived from input-output economic modeling, which is a controversial method in academic economic research.

[64] Golding, Garrett, Anil Kumar and Karel Mertens, 2021. "Cost of Texas' 2021 Deep Freeze Justifies Weatherization." https://www.dallasfed.org/research/economics/2021/0415

the willingness of consumers to pay for reliable power supply. Note that this implies there are some prices at which consumers would be unwilling to pay for uninterrupted service depending on the nature of interruption (length, time of day, time of year, etc.) and other factors.

Golding, Kumar, and Mertens (2021) report a VOLL for winter storm Uri of $4.3 billion. This calculation was based on an average VOLL of $6,733 per megawatt hour (MWh) for firms and $117.60 per MWh for households, a total duration of load shed of 70.5 hours, and an average load shed of about 14,000 MW. Assuming that this type of event happens approximately once every 10 years, they estimate that consumers are willing to pay $430 million per year to avoid this type of power outage. Given this, Golding, Kumar, and Mertens (2021) argue that the economically justifiable investment (such as on winterization and de-icing measures) to avoid an outage similar to the February 2021 event is roughly $430 million per year (which is about 0.8 percent of 2020-2021 biennial revenue estimate). Note there is considerable uncertainty in estimating VOLL.

One major source of uncertainty is that the demand for reliable energy is dependent on the nature of the market. Thus, an economy in transition will face a more uncertainty regarding the efficient level of investment in energy reliability. Texas is in the midst of such a transition on several fronts. Growth in renewable energy and low-carbon options will impact the optimal level of investment. Also, a number of new industries are locating in Texas because of its low tax, low regulation and business friendly environment. Several recent examples of this include Telsa moving its headquarters to Austin[65], Samsung building a chip manufacturing plant in Taylor[66] (a huge investment that will create almost 2,000 jobs), and crypto miners flocking to Texas.[67] The projected influx of crypto miners—up to 20% of the world's Bitcoin network in the next two years—is expected to cause power demand to surge, potentially exacerbating grid reliability issues. According to one staggering estimate, crypto miners will demand twice as much power as the city of Austin.[68] The important point is that backward looking measures such as VOLL are useful but do not provide sufficient information. VOLL tells us how much we should invest if the status quo remains. However, Texas will undergo massive changes in energy production and demand in the next several decades. We need to think strategically about where we are heading, as opposed to solving the problem of what we need now.

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[65] https://www.wsj.com/articles/tesla-to-move-headquarters-to-austin-texas-musk-says-11633646229

[66] https://www.foxbusiness.com/technology/samsung-build-17-billion-chip-making-plant-taylor-texas

[67] https://www.ibtimes.com/crypto-miners-flocking-texas-can-stress-states-power-grid-analysts-warn-3343607

[68] https://www.bloomberg.com/news/articles/2021-11-19/texas-plans-to-become-the-u-s-bitcoin-capital-can-its-grid-ercot-handle-it

Conclusion

Texas energy markets face two major issues. The first major issue is the ongoing growth of low-carbon and renewable sources of energy. For Texas to remain as the energy capital of the world in the 21st century, a key determinant will be research and development, coordination of market supply chains, and policy changes to support the creation of new industries in Texas. Policy changes that would have significant impacts in this regard include expanding section 45Q tax credits from $50/ton to $85/ton, streamlined jurisdictional control and regulations, legal liability reforms, regulating access to pore space, regulation of underground storage of CO2, and increased research and development. Some of the most promising technologies to develop include carbon capture and storage, battery storage, hydrogen and ammonia-based energy, and related technologies. The second major issue is the appropriate level of investment in reliable production and distribution of electricity during extreme weather events. Golding, Kumar, and Mertens (2021) find that investments to winterize production and distribution of electric power in Texas is justifiable up to about $430 million annually (or 0.8 percent of 2020-2021 biennial revenue estimate). Projected growth in energy demand, however, could justify even larger investments.

As the world pivots towards clean energy production, significant uncertainty remains over the long-term prospects of both existing and emergent technologies. To remain the energy capital of the world, Texas must continue working with the energy industry to explore alternative paths and coordinate a broad set of development efforts. By providing a competitive fiscal environment, facilitating the development of infrastructure, and maintaining a high-skilled workforce, policymakers would sustain into the future the factors that accelerated Texas' historical growth in the energy industry.