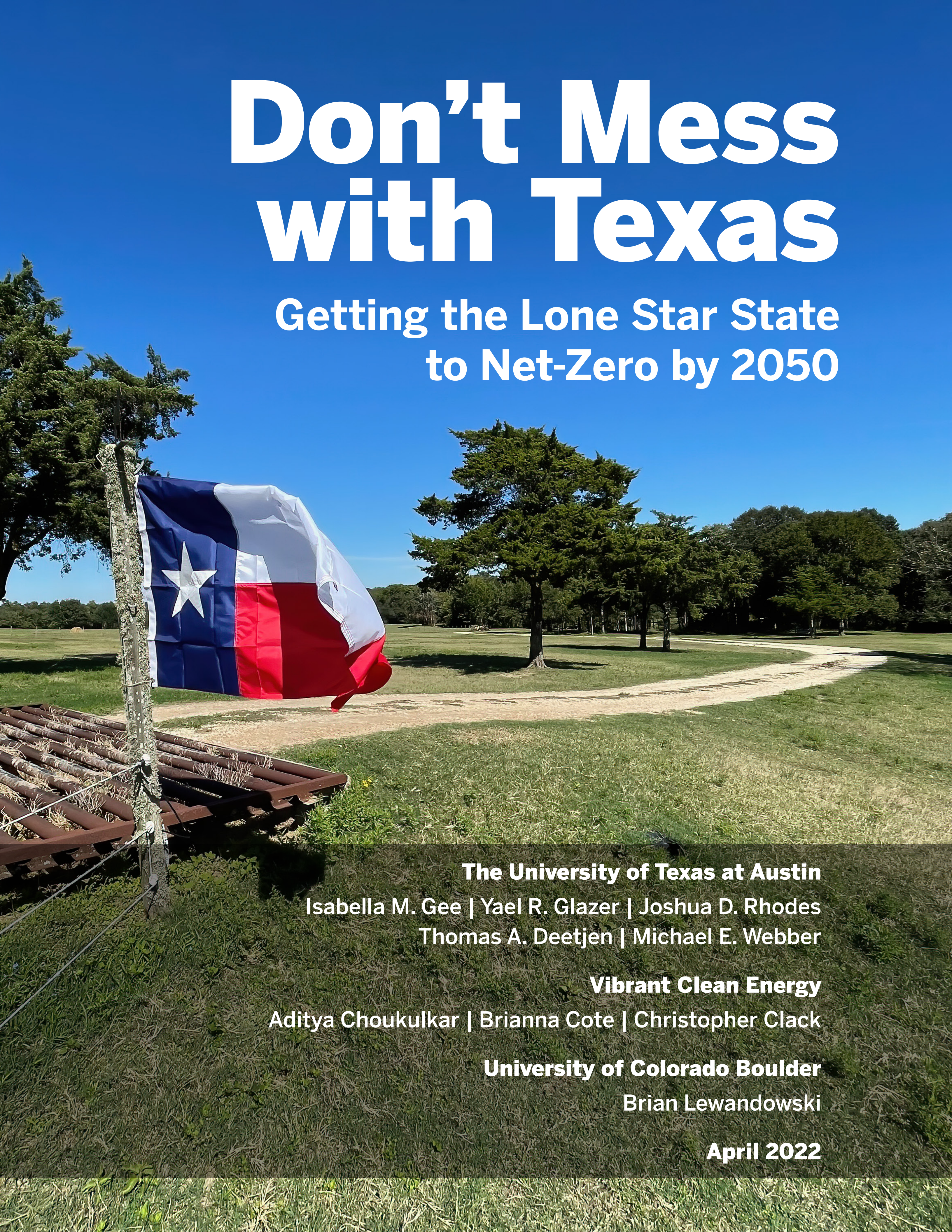
Don't Mess with Texas

Getting the Lone Star State to Net-Zero by 2050



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Contents

Glossary

ACP	Accelerated Clean Power
AIM	American Innovation and Manufacturing
BAU	Business as Usual
BECCS	Bioenergy with Carbon Capture and Sequestration
CCS	Carbon Capture and Sequestration
CCUS	Carbon Capture, Utilization, and Storage
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
CREZ	Competitive Renewable Energy Zone
CSS	Community shared solar
DAC	Direct Air Capture
DACS	Direct Air Capture and Sequestration
DER	Distributed Energy Resources
DPV	Distributed Photovoltaic
DSM	Demand-Side Management
EASIUR	Estimating Air Pollution Social Impact Using Regression
EGS	Enhanced Geothermal Systems
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
EPS	Energy Policy Simulator
ERCOT	Electric Reliability Council of Texas
ESG	Environmental, Social, and Governance

EV	Electric Vehicle
F-gas	Fluorinated gas
FERC	Federal Energy Regulatory Committee
GDP	Gross Domestic Product
Geo/Bio	Combined Geothermal and Biomass *(separate but summed together under same category)*
GHG	Greenhouse Gas
GW	Gigawatt
GWh	Gigawatt hour
GWP	Global Warming Potential
H_2	Hydrogen
HDV	Heavy Duty Vehicle
IEA	International Energy Association
IPCC	Intergovernmental Panel on Climate Change
ISIC	International standard Industrial Classification of All Economic Activities
kWh	Kilowatt hour
LDV	Light Duty Vehicle
LMI	Low- and moderate-income
LULUCF	Land Use, Land Change, and Forestry
mmt	Million metric tons
MW	Megawatt
MWh	Megawatt hour
N_2O	Nitrous Oxide
NASEM	National Academies of Science, Engineering, and Medicine
NET	Negative Emission Technology
NGCC	Natural Gas Combined Cycle
NGCT	Natural Gas Combustion Turbine

NH_3	Ammonia
NO_x	Nitrogen oxides, including nitric oxide (NO) and nitrogen dioxide (NO_2)
PACE	Property assessed clean energy
PAYS	Pay as You Save
PI^+	Policy Insight
PM_{10}	Particulate matter with diameter less than 10 microns
$PM_{2.5}$	Particulate matter with diameter less than 2.5 microns
PUC	Public Utility Commission
PV	Photovoltaic
REMI	Regional Economic Modeling, Inc.
REMI-PI^+	Regional Economic Modeling, Inc. - Policy Insight
RPS	Renewable Portfolio Standard
SCC	Social Cost of Carbon
SMR	Steam Methane Reforming
SMR Nuclear	Small Modular Reactor Nuclear
SNG	Synthesized Natural Gas
SO_2	Sulfur Dioxide
TWh	Terawatt hour
TX-EPS	Texas Energy Policy Simulator
UPV	Utility Photovoltaic
VMT	Vehicle Miles Traveled
VOC	Volatile organic compound
WIS:dom-P model	Weather-Informed energy Systems: for design, operations, and markets - Planning model

Executive Summary

The world is decarbonizing. Many countries, companies, and financial institutions have committed to cutting their emissions. Decarbonization commitments have been issued by: 136 countries including Canada, China, and the UK, at least 16 U.S. states including New York, Louisiana, and Virginia, and a third of the largest 2,000 publicly traded companies in the world, including Apple, Amazon, and Walmart, and numerous Texas companies like ExxonMobil, American and Southwest Airlines, Baker Hughes, and AT&T.[1–9] These decarbonizing countries, states, cities, and companies are Texas's energy customers. If Texas ignores the challenge to decarbonize its economy, it may eventually face the more difficult challenge of selling carbon-intensive products to customers around the world who do not want them. We are already seeing this scenario beginning to play out with France canceling a liquified natural gas deal from Texas gas producers and both U.S. and international automakers announcing shifts to electric vehicles. Proactive net-zero emissions strategies might allow Texas to maintain energy leadership and grow the economy within a rapidly decarbonizing global marketplace.

Thankfully, Texas is uniquely positioned to lead the world in the transition to a carbon-neutral energy economy. With the second highest Gross State Product in the US, the Texas economy is on par with countries like Canada, Italy, or Brazil. Thus, Texas's decisions have global implications. Texas also has an abundant resource of low-carbon energy sources to harness and a world-class workforce with technical capabilities to implement solutions at a large-scale quickly and safely. Texas has a promising opportunity to lead the world towards a better energy system in a way that provides significant economic benefits to the state by leveraging our renewable resources, energy industry expertise, and strong manufacturing and export markets for clean electricity, fuels, and products. The world is moving, with or without Texas, but it is likely to move faster—and Texas will be more prosperous—if Texans lead the way.

There are many ways to fully decarbonize the Texas economy across all sectors by 2050. In this analysis, we present a Business as Usual (BAU) scenario and four possible pathways to Texas achieving state-wide net-zero emissions by 2050. Figure ES-1 provides a visual comparison of scenario conditions.

			Future Energy Scenarios				
			BAU	Electrification	Electrification ACP	Hydrogen and Carriers	Extensive Capture
Scenario Conditions	Transportation	Electric LDV Penetration	▨	■	■	■	▨
		Hydrogen LDV Penetration	□	□	□	▨	□
		Electric HDV Penetration	□	■	■	□	□
		Hydrogen HDV Penetration	□	□	□	■	□
		Electric Air Travel and Shipping	□	▨	▨	□	□
		Hydrogen Air Travel and Shipping	□	▨	▨	▨	□
	Buildings	Building Efficiency Improvements	□	■	■	■	□
		Building Component Electrification	□	■	■	▨	□
	Industry	Industrial Efficiency Improvements	□	■	■	■	□
		'Clean-up-your-act' Efforts	□	■	■	■	□
		Electricity for Industrial Fuel Use	□	■	■	■	□
		Hydrogen for Industrial Fuel Use	□	□	□	■	□
		Electrolysis for Hydrogen Production	□	□	□	■	□
		Carbon Management Technology Penetration	□	■	■	■	■
	Agriculture	Afforestation and Reforestation Efforts	□	■	■	■	□
		Livestock Measures for Methane Reduction	□	■	■	■	□

Figure ES-1: Comparison of future scenario conditions out to 2050. Tan indicates low growth rate, light blue a moderate growth rate, and dark blue a high growth rate. Note that this list represents the major differences between scenarios but does not include all policies. For a complete list of policy changes, please see Appendix C. Also note that this chart indicates the relative intensity of growth rates for the various categories, not absolute values. For example, both Electrification and Electrification: ACP (Accelerated Clean Power) see high growth in low-carbon electricity generation, but the grid in Electrification: ACP reaches zero emissions in 2035 compared to near-zero by 2050 in Electrification.

There are multiple ways Texas can reach net-zero, and the scenarios we developed are just four of those possibilities. They are not predictive, but rather meant to illustrate an envelope of possible pathways and necessary ingredients for Texas to reach net-zero emissions by 2050 and to show what might be needed to achieve it. Scenarios were designed to be ambitious but achievable and reflect a Texan desire to minimize political intervention and disruptions to the economy and labor market. Though we avoided explicit interventions like subsidies or mandates, we used policy levers in the TX-EPS to visualize what would happen if certain technologies won out in Texas in the future. Actual policy implementation might look different, but comparing between the scenarios can help inform future decision-making and identify particularly effective or advantageous policies and technologies to support.

We modeled changes to end-use sectors, demand management, electrification, and technology development and adoption to evaluate the systemic energy requirements for reaching net-zero emissions across multiple scenarios. We then used a detailed power sector model to identify the least-cost options for supplying electricity under these conditions. Existing technologies could be deployed more aggressively, or nascent technologies scaled to reach decarbonization goals. Because Texas has demonstrated an ability over the last century to deploy new technologies quickly at scale, we modeled decarbonization strategies using steep adoption curves and price drops from technological learning. For example, complete electrification of heavy-duty vehicle (HDV) sales in Texas would be difficult to achieve, but we include these conditions in both the Electrification scenarios to quantify the impact of a highly electrified transportation sector. We also include the option of building direct air capture (DAC) systems, which is a nascent but growing technology that removes carbon dioxide directly from the air. This process is different than carbon capture and sequestration (CCS), which cleans smokestacks that spew high concentrations of CO_2 to prevent emissions. Importantly, we assumed in all net-zero scenarios that a drop in fossil fuel consumption within Texas corresponded to an equal drop in production, but we also assumed exports would stay constant and not fall below BAU values. This very well might not be the case in the future if out-of-state customers continue to decarbonize. Scenario definitions are as follows, with complete details available in Appendix C.

Business As Usual (BAU)

This scenario serves as the baseline for comparison. In this scenario, we assume Texas continues the status quo: new policies are not enacted but existing policies such as tax breaks for gas producers, absence of fees for greenhouse gas emissions, corporate automotive fuel economy standards, and investment or production tax credits for certain types of renewables are retained subject to their expirations or sunsets. Emissions from some sectors decline out to 2050 due to existing market forces alone. For example, carbon dioxide emissions from the power sector fall as coal generation declines and more renewables come online due to existing market forces. Carbon emissions from transportation also fall as electric vehicles reach about 50% of new light-duty vehicle sales and 5% of heavy-duty vehicles in 2050. However, these declines are offset by growth in other sectors, primarily industry, and state-wide emissions increase overall. This scenario did not quantify the potential job losses or possible economic slow-down that could happen if global demand for fossil fuels stagnates and Texas does not decarbonize.

Electrification

This scenario, along with Electrification: Accelerated Clean Power (see below), adopts the highest level of economy-wide electrification relative to the other scenarios. There is no mandate for carbon-free electricity generation, but the grid decarbonizes by over 90% by 2050 and a significant portion of the economy electrifies, such as buildings, transportation, and portions of the industrial sector. Building energy use reaches 100% electrification by 2050, new sales of light- and heavy-duty vehicles are 100% electric by 2035 and 2050, respectively. Aircraft sales are 25% electric by 2050, and new ships are 50% electric and 50% hydrogen by 2050. Industrial fuel (non-feedstock) energy use is electrified as much as possible by 2050 based on industry-specific electrification potentials.[10] Building and industrial efficiency standards are tightened, and 'clean up your act' policies (e.g., preventing leaks, reducing flaring, and improving end-of-life practices for methane and fluorinated gases in industry and mining) are implemented. Afforestation and reforestation efforts are increased to promote carbon soil sequestration in land sinks, and methane emissions from livestock are reduced. Any remaining emissions in 2050 that are not reduced through decarbonization efforts are removed through carbon capture and removal technologies, including CCS or direct air capture and sequestration (DACS). The entire economy reaches net-zero emissions in 2050.

Electrification: Accelerated Clean Power

In this scenario, we model the same Electrification scenario again but with a fully ***zero-emission*** (not net-zero) electric grid by 2035. In the other three scenarios—Electrification, Hydrogen and Carriers, and Extensive capture—the power sector itself is not required to be zero-emission, but is instead constrained by the overall requirement that the full economy be ***net-zero*** in 2050. A decarbonized electric grid by 2035 aligns with current federal targets that are under consideration and with natural retirement timeline for many greenhouse gas emitting power plants. As in Electrification, building energy use reaches 100% electrification by 2050, new sales of light- and heavy-duty vehicles are 100% electric by 2035 and 2050, respectively. Industrial fuel (non-feedstock) energy use is electrified as much as possible by 2050. Building and industrial efficiency standards are tightened, and 'clean up your act' policies (e.g., preventing leaks, reducing flaring, and improving end-of-life practices for methane and fluorinated gases in industry and mining) are implemented. Afforestation and reforestation efforts are increased to promote carbon soil sequestration in land sinks, and methane emissions from livestock are reduced. Any remaining emissions in 2050 that are not reduced through decarbonization efforts are removed through carbon capture and removal technologies, including CCS and DACS. The entire economy reaches net-zero emissions in 2050.

Hydrogen and Carriers

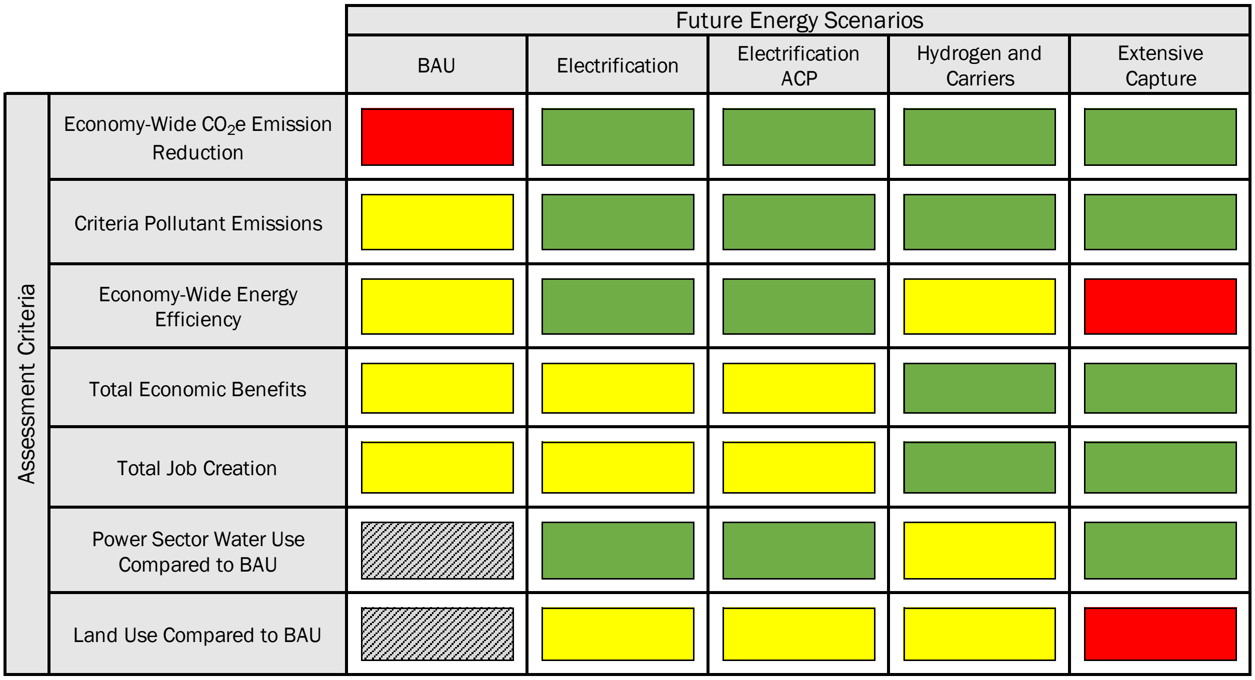
In this scenario, sectors throughout the economy shift a large portion of end-use energy consumption to a mixture of electricity and hydrogen produced from electrolysis. There is no mandate for carbon-free electricity generation, but the grid decarbonizes by more than 90% by 2050. We also model power-to-X systems where additional variable renewable energy supply can be used to produce hydrogen or other energy carriers like synthetic methane and ammonia. Building energy use is more than 90% electric in 2050, with the remaining gas demand met through synthetic natural gas made from hydrogen and carbon dioxide through the Sabatier process. New sales of light-duty vehicles max out at 90% electric by 2035 and 10% hydrogen by 2050, while new sales of heavy-duty vehicles reach 100% hydrogen by 2050. New aircraft sales are 25% hydrogen-based by 2050, and 50% of new passenger ships are electric. Ammonia made from low-carbon hydrogen replaces bunker fuel for cargo shipping by 2050. Industrial fuel (non-feedstock) energy use is electrified as much as possible by 2050, and the remaining fuel demand is met by hydrogen. Building and industrial efficiency standards are tightened, and 'clean up your act' policies (e.g., preventing leaks, reducing flaring, and improving end-of-life practices for methane and fluorinated gases in industry and mining) are implemented. Afforestation and reforestation efforts are increased to promote carbon soil sequestration in land sinks, and methane emissions from livestock are reduced. Any remaining emissions in 2050 that are not reduced through decarbonization efforts are removed through carbon capture and removal technologies, including CCS and DACS.

Extensive Capture

In this scenario, we assume Texas continues along Business as Usual (BAU) conditions and can only reach net-zero through power sector decarbonization and carbon capture and removal technologies. No new policies are enacted but existing policies such as tax breaks for gas producers, absence of fees for greenhouse gas emissions, corporate automotive fuel economy standards, and investment or production tax credits for certain types of renewables are retained subject to their expirations or sunsets. There is no mandate for carbon-free electricity generation, but the grid decarbonizes by more than 90% by 2050. All remaining emissions are abated through carbon capture and removal technologies. The entire economy reaches net-zero emissions in 2050.

We developed each net-zero scenario using the publicly available economy-wide Texas Energy Policy Simulator (TX-EPS [11–13]) model that generated estimates for future electricity demand and emission profiles. These profiles were then analyzed with a robust power-sector model, the Weather-Informed energy Systems: for design, operations, and market-planning model (WIS:dom-P [14–16]), which seeks to build the lowest-cost power system under the constraint of net-zero emissions by 2050. The TX-EPS sets assumptions on technology adoption, end-use electrification, hydrogen demand, efficiency improvements, and 'clean-up-your-act' policies. WIS:dom-P decides how to meet the generated electricity demand profiles, how to meet hydrogen demand (i.e., through steam methane reforming or electrolysis), and how to abate any emissions not reduced through the TX-EPS. The Regional Modeling Services, Inc. Planning Insights (REMI-PI± [17–19]) model was then used to provide a detailed economic impacts analysis.

Achieving net-zero is difficult, but it’s also potentially lucrative; our analysis estimates it could spur economic growth and create jobs. In each scenario, we consider the environmental, economic, and jobs impacts to Texas over the next thirty years in transitioning Texas to net-zero conditions. We compare and discuss each scenario, including BAU, to reveal key policies, technological developments, economic impacts, and environmental trade-offs across the various pathways. These scenarios are neither predictive nor prescriptive. Rather, they are illustrative. ***A key takeaway is that it is possible for the Lone Star State to achieve a net-zero future, and there are multiple ways of getting there.*** The actual path Texas takes will likely look different from any of these scenarios, but assessing the trade-offs of different pathways can provide valuable insight for the next steps to take. Scenario conditions that have an outsized influence on future emissions or are present across multiple pathways should be strongly considered in the near term as win-win decisions Texas can make now while future technology development and market conditions continue to unfold. Figure ES-2 summarizes the major impacts from each scenario.



		Future Energy Scenarios				
		BAU	Electrification	Electrification ACP	Hydrogen and Carriers	Extensive Capture
Assessment Criteria	Economy-Wide CO_2e Emission Reduction	🟥	🟩	🟩	🟩	🟩
	Criteria Pollutant Emissions	🟨	🟩	🟩	🟩	🟩
	Economy-Wide Energy Efficiency	🟨	🟩	🟩	🟨	🟥
	Total Economic Benefits	🟨	🟨	🟨	🟩	🟩
	Total Job Creation	🟨	🟨	🟨	🟩	🟩
	Power Sector Water Use Compared to BAU	▨	🟩	🟩	🟨	🟩
	Land Use Compared to BAU	▨	🟨	🟨	🟨	🟥

Figure ES-2: Comparison of impacts from each scenario using various criteria. Category rankings are individual and not comparative. All rankings are relative to the 2020 baseline except water use and land use, which are relative to the BAU. Note that the BAU scenario does not take into account possible falling global demand for fossil fuel products in the future. Color coding is as follows:

> **Economy-wide CO_2e emissions:** red: high growth in emissions, yellow: no or mild growth, green: large reduction in emissions to net-zero conditions
>
> **Criteria pollutant emissions:** red: high growth in emissions, yellow: mild decrease in emissions, green: large reduction in emissions
>
> **Economy-wide energy efficiency:** red: significant growth in total energy consumption, yellow: mild growth in total energy consumption, green: large reduction in energy consumption
>
> **Total economic benefits:** red: economic losses, yellow: mild economic benefits, green: substantial economic benefits
>
> **Total job creation:** red: substantial job loss, yellow: mild job growth, green: substantial job growth
>
> **Power sector water use compared to BAU:** red: increase in water use, yellow: mild reduction in water use, green: large reduction in water use use, grey: not applicable
>
> **Land use compared to BAU:** red: substantial increase in land use, yellow: moderate increase in land use, green: reduction in land use use, grey: not applicable

All scenarios reach net-zero emissions by 2050 except for BAU, which rises from about 930 million metric tons CO_2 equivalent (CO_2e includes CO_2, CH_4, N_2O, and fluorinated gases) in 2020 to about 950 million metric tons CO_2e in 2050. Though economy-wide emissions grow in the BAU scenario, power sector emissions actually fall. In the BAU scenario, the grid decarbonizes by 70% due to existing market forces, with coal completely retiring by 2035. A decarbonizing power sector reduces criteria pollutant emissions as well, which fall in all scenarios, but fall much more steeply in the net-zero scenarios. Reduced air pollution in these scenarios leads to greater public health, and thus economic, benefits across the state.

Our results indicate that there are multiple ways Texas can achieve economy-wide net-zero emissions by 2050 and spur economic growth. All net-zero scenarios see higher economy-wide GDP growth compared to BAU, and two see greater job creation. GDP also grows in BAU based on increasing demand for fossil fuels and industrial products, but is dragged down by high emission costs relative to the net-zero scenarios. All scenarios see benefits from investments in the power sector, and some net-zero scenarios see additional benefits from pivoting the fuel sector towards low-carbon options. Fossil fuel consumption, and thus production, decreases in all net-zero scenarios other than Extensive Capture. GDP growth is highest in the Hydrogen and Carriers scenario in large part because the negative impacts to the fuels sector from declining fossil production are offset by a thriving hydrogen industry. This new industry is also why the Hydrogen and Carriers scenario sees an increase in economy-wide energy consumption compared to the BAU, Electrification, and Electrification: ACP scenarios.

Though all scenarios have economic benefits, there are other trade-offs between them. The Hydrogen and Carriers scenario has the highest overall GDP growth, but economy-wide energy consumption slightly increases and both relative land and water use compared to BAU are higher than other scenarios due to large expansion of electrolyzer capacity for hydrogen production. The Extensive Capture scenario sees economic growth and job creation with minor impact to existing industrial activities, but economy-wide energy consumption grows substantially due to a significant build-out of DACS capacity, which also requires substantial land use. The Electrification and Electrification: ACP scenarios generally see economic benefits and improving economy-wide energy efficiency with job creation that is similar to the BAU scenario but lower than in the Extensive Capture and Hydrogen and Carriers scenarios. Carbon removal technologies also play a large role in the trade-offs between scenarios, particularly for the Extensive Capture scenario. Removal technologies can help abate emissions that are expensive or difficult to decarbonize in other sectors, like industrial process emissions, but many of the removal technologies require electricity and space. That said, Texas might be well suited to house substantial electrolysis and carbon removal capacity given our existing energy infrastructure, vast wind and solar resources, and available space. In that case, Texas and its oil and gas sector would transition from a 'hydrocarbon' identity to a 'hydrogen and carbon' identity.

Top Ten Takeaways

Decarbonizing by 2050 can spur economic growth and create jobs. Taking into account economy-wide impacts and the cost of emissions, all four net-zero scenarios see higher average annual GDP than the Business as Usual scenario. Trends in total employment are similar to trends in GDP; the Hydrogen and Carriers and Extensive Capture scenarios see higher annual average employment than BAU, while the Electrification and Electrification: Accelerated Clean Power scenarios have more minor employment impacts. Because we will have to build and operate more infrastructure, decarbonization will spur investment and add jobs while improving the competitiveness of Texas's industrial economy. Overall, the Hydrogen and Carriers scenario sees the highest economic and employment benefits primarily because of a large new electrolysis industry for hydrogen production that offsets losses from reduced fossil fuel production. The Extensive Capture scenario also sees benefits to GDP growth because it maintains the BAU status quo while also developing robust DACS infrastructure. It is important to consider that the BAU outlook for fossil fuel demand might itself be overestimated. In addition, doing nothing to decarbonize means Texas's economy faces the risk that its global customers will choose low-carbon or carbon-neutral fuels and goods manufactured in other locations. That possibility would have a large impact on the Texas economy, but Texas can prepare for a future decline by expanding the types and volumes of other energy resources we produce.

Zero-carbon hydrogen from electrolysis and renewable energy could help spur economic growth while decarbonizing hard-to-abate sectors and products/carriers. Both hydrogen and ammonia can be generated using renewable electricity. Hydrogen made through electrolysis and low-cost wind power can be used to power industrial processes and long-haul, on-ground freight transportation needs that are difficult to electrify. Ammonia produced from zero-carbon hydrogen could help reduce emissions from fertilizer applications and agriculture, could replace bunker fuel for cargo shipping, and is compatible with newer turbines available for power generation. Hydrogen and ammonia can also both be used themselves to generate electricity if needed. Texas can leverage its existing hydrogen infrastructure and industrial capacity to become a leader in hydrogen production, which can provide substantial economic benefits. The Hydrogen and Carriers scenario sees the highest GDP and employment growth over BAU of all net-zero scenarios, primarily due to a growing electrolysis industry that offsets declines in the fossil fuel industry.

The industrial sector presents a large opportunity for emission reductions, but is also the most difficult sector to fully decarbonize. Texas is the number one industrial emitter in the nation, driven by consumption of fossil fuels for both energy and feedstocks. Industrial emissions can be readily reduced through efficiency standards and 'clean-up-your-act' policies as well as using electricity and green hydrogen for fuel and heat, which have the added effect of reducing emissions from oil & gas refining by reducing on-site consumption of fossil fuels. Together, these measures could reduce projected 2050 annual greenhouse gas emissions by 40%. Still, industrial process emissions are the largest source of 'leftover' emissions in 2050, i.e., those that are abated through carbon management strategies (rather than reduced or prevented through other policies). Decarbonizing the industrial sector thus warrants further research and investment.

Clean electricity can flexibly power multiple sectors, drive state-wide energy efficiency, and significantly reduce greenhouse gas and criteria pollutant emissions, improving air quality and public health. Clean electricity has multiple benefits. Many end-use sectors are easily electrified, which centralizes emissions within a decarbonizing power sector. Even without policy intervention—i.e., the BAU scenario—the grid reduces carbon emissions by about 70% primarily because of market forces alone due to the relatively low cost of wind and solar generation. Net-zero scenarios achieve even steeper emission reductions and corresponding economic savings. Electricity can also be more efficient than other fuels, as with electric vehicles, reducing overall energy consumption as compared to internal combustion engines. The Electrification and Electrification: Accelerated Clean Power scenarios, those with the highest degree of electrification, yield the greatest reductions in total energy demand compared to BAU and thus represent increased society-wide efficiency. The Hydrogen and Carriers scenario also has less total energy demand in 2050 compared to BAU. Additionally, cleaning electricity generation and retiring old, high-emitting power plants will have a positive impact on local air quality for the surrounding communities, as will fewer emissions from oil & gas refining operations. The power sector alone reduces future criteria pollutant emissions (SO_2, NO_x, CO, VOCs, PM_{10}, and $PM_{2.5}$) by an average of 90% across all scenarios, including BAU, saving billions of dollars per year from reduced mortality and morbidity. Economy-wide, reductions in criteria pollutant emissions range from an average of 43% in the BAU scenario to 84% in the Hydrogen and Carriers scenario. Policies to incentivize end-use electrification and power sector decarbonization provide dual benefits of centralizing emissions into fewer point sources that are easier to decarbonize (e.g. one power plant versus thousands of cars) and helping prevent toxic air pollution.

Wind, solar, and storage dominate the Texas clean electricity narrative, but natural gas still has a role to play. In some scenarios, geothermal and nuclear are also important contributors, but about half of electricity will be generated by wind power in 2050 under BAU conditions. Up to 90% is generated by wind in other scenarios to help power substantial DACS capacity. Wind is more valuable than solar in the ERCOT system in later years in our analysis, particularly when coupled with DACS systems that can be more easily matched to the ramping profiles of wind generation than solar, and using a substantial portion of wind resources to power flexible electric DACS systems might ameliorate some of the difficulties associated with operating grid systems that have a high portion of intermittent renewables. Texas has excellent wind resources as well as many potential consumers, industries, and technologies that can use it. Removing roadblocks to the development of these resources would better support rural economic growth and decarbonization. Further, natural gas can be a complement to high levels of renewables on the grid. In all scenarios except Electrification: Accelerated Clean Power, Texas retains some natural gas resources to provide additional firm generation.

Efficiency standards, 'clean-up-your-act' policies, and electric transportation are effective, low-hanging fruit with low barriers to entry. Easily implemented efficiency standards foster resilient systems by lowering overall energy burden. Along with properly implemented retrofits, both can help address some of the energy inequities across Texas' regions and reduce the unequal energy burden on vulnerable populations. 'Clean-up-your-act' policies reduce emissions by preventing methane leaks in industrial equipment and pipelines (including upstream oil & gas operations), substituting high-GWP (Global Warming Potential) fluorinated gases (F-gases) with less-harmful alternatives, reducing nitrous oxide emissions from livestock and industry, and better capturing methane and F-gases at the end of their lives to be recycled or destroyed. These practices are more easily implemented than large industrial equipment overhauls and, because they target gases with high GWPs, can have an outsized effect-to-effort ratio. Electric vehicles help reduce both greenhouse gas emissions and criteria pollutants for improved air quality.

Carbon management technologies like Direct Air Capture and Sequestration (DACS) are important for getting all the way to zero and can foster new industries around capturing the hardest-to-abate emissions. Economy-wide emissions can be reduced by about 80% with a mix of carbon-free electrification, 'clean-up-your-act' eforts, efficiency standards, zero-carbon hydrogen, and other strategies. Carbon removal technologies can capture the remaining emissions from hard-to-abate sources like industrial process emissions or to offset emissions from the production of fossil-based fuels and products that lack sufficient low-carbon alternatives. DACS for economy-wide emissions can complement CCS in the power and industrial sectors and, in some cases, out-compete it. Texas has the resources to create a leading DACS industry, one that could be used to abate emissions from Texas and other states if so desired. However, there are risks in relying too heavily on a single, still developing technology. Similarly, a ton of carbon removed is not the same as a ton of carbon never emitted, and there are co-benefits of preventing emissions of the accompanying criteria pollutant emissions. Emission removal, while important, shouldn't overshadow emission prevention.

Going net-zero provides opportunities to improve energy-system resilience and mitigate the impacts of extreme weather events. When Winter Storm Uri hit Texas in February 2021, it highlighted the importance of increasing resilience in our energy systems. While much of this study's analysis was conducted prior to the winter storm, many of the key elements of resilience were already included in the model, such as winterization and demand response. While we did not model a specific resilience scenario and did not put a cost on resilience, these elements are considered throughout the report. For example, electrifying more sectors can add more controllable loads to the grid, like electric vehicles and DACS, making the energy system more flexible in the face of disruptions via demand response programs. A large build-out of DACS in particular might be able to provide ancillary services, ramping up when there is excess wind available or down when generating capacity needs to be directed elsewhere. Future work should investigate this potential in more detail. Additionally, increased production of hydrogen and ammonia provides stores of dense energy carriers that can be used for heat and electricity generation if necessary.

Decarbonization comes with multiple environmental co-benefits and trade-offs. Transitioning to a net-zero economy requires significant changes to infrastructure and operations across all sectors that lead to environmental trade-offs between land, air, and water. Decarbonizing the power sector and reducing the number of thermal power plants reduces the amount of water withdrawn for cooling purposes, though increased electrolysis for hydrogen production might offset a portion of these reductions. Increased use of wind, utility solar, and DACS has large land requirements, but these areas can be co-located with other services and neither release the same harmful pollutants into the air nor require as much cooling water as thermal power plants, easing the burden on nearby communities.

To ensure decarbonization is the most equitable solution for everyone, supporting policies should be designed to remedy rather than exacerbate distributional equity gaps. By helping ameliorate the worst effects of climate change, decarbonization overall benefits the vulnerable communities that will bear the brunt of those impacts. Further, infrastructure changes that support a net-zero transition often have direct benefits for vulnerable fence-line communities. For example, retiring coal plants or replacing industrial fuel sources with clean alternatives improves local air quality. However, other programs or incentives meant to promote decarbonization can leave vulnerable communities behind, such as rooftop solar or electric vehicle incentives that historically have primarily benefited wealthy consumers, or efficient appliance/building retrofit incentives targeting homeowners and bypassing renters. Special care needs to be taken to ensure these kinds of programs benefit all Texans but especially those who have been historically marginalized and have endured environmental injustice over generations.

1.0 Introduction

Commitments to Decarbonization will Change the Global Economy

Decarbonization—the intentional reduction of greenhouse gas emissions—is both a global imperative and a trend. The world is seeking to reduce its emissions, driven by a multitude of influences: technological innovation, economic opportunities, employee pressure, pursuit of efficiency at manufacturers, consumer preferences, investor requirements, international agreements, and a mix of policies at the municipal, state, and national levels. To avoid the worst impacts of climate change, many policymakers and corporations have targeted 2050 as a target year by which net-zero emissions should be achieved.

Many countries, companies, and financial institutions have committed to cutting their emissions. Decarbonization commitments have been issued by: 136 countries including Canada, China, and the UK, at least 16 U.S. states including New York, Louisiana, and Virginia, and a third of the largest 2,000 publicly traded companies in the world, including Apple, Amazon, and Walmart, and numerous Texas companies like ExxonMobil, American and Southwest Airlines, Baker Hughes, and AT&T.[1–9] Other major industrial players like DOW chemical, Ford Motor Company, General Motors, Nestlé, S&P Global, and more have also committed to achieving net zero emissions by 2050 by manufacturing new products (such as electric vehicles instead of those with internal combustion engines) that facilitate decarbonization by their customers.[20,21] Banks like Morgan Stanley, Barclays, and TD Bank Group are committed to being carbon neutral by mid-century.[22] Oil & gas companies are following suit, with similar commitments issued by companies including BP, Shell, Total, Repsol, and Equinor.[23] In this context where shareholders, investors, employees and customers are demanding it, large-scale decarbonization has become a necessity to remain economically competitive.

Authoritative scientific research continues to affirm that the current rate of global greenhouse gas emissions will likely lead to ecological damage, climate change, displacement of people, and economic loss unless mitigation steps are implemented.[24–28] Many communities are already experiencing these impacts via more frequent and intense weather events, extended drought, sea level rise, heightened risks to human health, and an exacerbation of economic inequalities.[24,29–33] The U.S. financial system is also at risk for both aggregate, high-level shocks that impact financial institutions and local shocks that primarily affect small businesses, farmers, and households.[25] The U.S. Department of Defense has formally recognized climate change as a national security issue for more than a decade.[34] Multiple countries have even declared climate emergencies, including the entire European Union.[35] To avoid the worst of these effects, researchers have concluded that net-zero greenhouse gas emissions should be achieved by 2050 or sooner.[24,30] The scope of this undertaking will be massive and represents a substantial and rare opportunity for new investment and economic growth. It also represents the possibility of social disruption if policymakers and industry are ill-prepared for or non-responsive to the transition that is underway.

Global decarbonization by 2050 can leverage existing industries (such as oil & gas, utilities, the tech sector, etc.) but will also require new industries, technologies, and innovations that will stave off costly environmental damage while advancing the global economy. Emerging sectors such as renewable electricity, electrified transportation, and high-efficiency buildings promise opportunities for technological innovation, entrepreneurship, and job growth while reducing costs and improving quality of life for consumers. Depending on what choices it makes, the oil & gas sector could be particularly well-poised to be a beneficiary of a low-carbon economy as many low-carbon solutions leverage the sector's technical products and capabilities. For example, drilling technology can be used for geothermal energy; flowback and production separations expertise and carbon management experience can be used for carbon dioxide capture and sequestration; chemical facilities can be used to produce hydrogen and synthetic fuels; offshore capabilities can be used for wind generation; and pipeline operations can be used for transporting low-carbon fuels (such as hydrogen or hydrogen carriers) and greenhouse gases such as carbon dioxide.

Recent analysis from PriceWaterhouseCoopers found that investment in climate tech grew five times faster than total venture capital investment from 2013 to 2019.[36] A record seventeen billion dollars of venture capital was invested in climate tech in 2020 alone, and, in 2021, the IEA projected global investment in clean energy and energy efficiency to total $750 billion for that year.[37,38] Moreover, market capitalizations for manufacturers of low-carbon products (such as electric vehicle makers) and renewable energy providers (such as electric utilities) have grown significantly while those of traditional energy companies have struggled. The U.S. green economy is estimated to be the largest in the world, with $1.3 trillion in revenue representing 16.5% of the global market and supporting almost 10 million jobs.[39,40] In addition to their cleaner profiles, these growing sectors often have higher performance. For example, electric cars have higher efficiency, lower energy and maintenance costs, faster acceleration, and quieter operation than vehicles operating with internal combustion engines. Though first-generation electric vehicles had limited range, the latest models have similar range per charge as petroleum-fueled vehicles per tank. In the built environment, energy efficient homes are not only cheaper to maintain at comfortable temperatures than older buildings with leaky envelopes or inefficient, outdated appliances, but they have better indoor air quality and can protect the inhabitants for longer durations during power outages and extreme weather events.

All told, decarbonization is an economic opportunity to deploy new technologies, launch new businesses, improve quality of life for individuals and communities, and reinvigorate entire sectors that will lead to a cleaner world. Importantly, Texas has a uniquely compelling mix of natural resources, technical capabilities, and pioneering spirit to be the global leader for this transition.

Texas Decarbonization: An Opportunity for Leadership

Texas has an unrivaled opportunity to lead the clean energy transition. The Lone Star State has long standing expertise in energy, manufacturing, and international trade. Texas can leverage these resources to decarbonize its own economy, and in the process become a global leader in the production of clean energy and export of low-carbon value-added goods such as products, chemicals, and fuels. In contrast, doing nothing and ignoring the global decarbonization transition presents a significant risk to Texas's economy as customers for low-carbon solutions will look to other providers with cleaner options. In a global, low-carbon marketplace, Texas could find that many of its high-energy, high-emissions industries lose their appeal, as well as the jobs they support, unless they transform to cleaner processes. According to current reporting from the Texas Workforce Commission, in 2021, the oil and gas industry supported nearly 300,000 jobs in upstream exploration and production, product manufacturing, and distribution and pipeline operations.[41] And according to the Texas Oil & Gas Association, it might be twice that.[42,43] Taking proactive steps to facilitate a smooth transition for the oil & gas workforce rather than endure an abrupt loss of jobs would be in everyone's interest. Furthermore, leveraging our resources and expertise to become a climate leader could position Texas for job growth and economic development.

A low-carbon global economy will demand energy and products made with fewer emissions—emissions associated with the fabrication, transportation, manufacturing and all other processes along the supply chain required to produce an item or service. Leading investment management firm BlackRock recently committed to push their portfolio companies to disclose plans for going net-zero by 2050.[44] Other investment groups have similar pledges. All told, as of late 2020, Environmental, Social, and Governance investing was responsible for about one third of total US assets under management and their requirements include mandates for lower emissions.[45] In other words, investment capital will become increasingly available for the low-carbon economy and increasingly scarce for a high-carbon economy. Greater demand for low-carbon energy and goods will impact the energy manufacturing and export sectors that drive a significant portion of the Texas economy. As such, it is in the interest of industry and state policymakers to prepare for and acknowledge this reality. If these sectors maintain their current energy and emissions status quo, they could struggle to compete in a global economy that prefers low-carbon alternatives. Consider the following examples of competitive threats to Texas or deals that were recently canceled with Texas firms due to environmental concerns:

> In January 2021, the Port of Cork, Ireland declined to renew a contract with a Texas Liquified Natural Gas exporter claiming political aversion of its citizens to hydraulic fracturing.[46]
>
> French oil company Total left the US oil lobby, the American Petroleum Institute, citing multiple differences in environmental priorities.[47]

> Low-carbon industrial clusters are being developed around the world in places like Norway, the UK, China, and the Netherlands that could take market share away from Texas products and existing industrial clusters like the Texas Gulf Coast.[48–53]
>
> In November 2020, France canceled negotiations on a $7 billion contract with a Texas natural gas exporter claiming environmental concerns over hydraulic fracturing.[54]
>
> Saudi Arabia, Norway, Canada, Nigeria some of Texas's leading competitors in the global oil & gas market, all have net-zero targets.[55,56]

Texas could lose more business in the future if its industries do not make the transition to provide lower-carbon products since about 90% of the global GDP comes from countries, industries, and companies with net-zero targets.[57] These nations and cities are expected to weave climate considerations into their future purchasing decisions. By maintaining the status quo, Texas invites an economic future where its emissions-intensive energy sources and manufacturing exports face shrinking global demand. Since the energy, manufacturing, and export sectors comprise a large portion of the total Texas economy, the risk—and cost—of doing nothing is potentially significant. At the same time, global decarbonization provides an economic opportunity that Texas is well-positioned to seize. In particular, Texas has four major strengths over other states and countries that give it a strong and sizeable competitive advantage:

Institutional Knowledge: Texas is home to some of the world's largest energy companies and an energy workforce highly skilled in engineering, project development, project management, and finance. The engineering capabilities, logistical knowledge, and financial capital that help these companies compete in the oil & gas industry are also applicable to build and maintain the clean energy infrastructure of the future. Particular opportunities that align are for carbon capture and management, midstream (pipelines and storage for gases and liquids), fuels synthesis, offshore energy, and drilling for geothermal energy or sequestration. Texas also has a high level of competency building large infrastructure projects from electric transmission lines like the competitive renewable energy zones (CREZ) to some of the world's largest petrochemical facilities.

Manufacturing Capability: More than 10% of U.S. manufacturing GDP happens in Texas.[58] If Texas reduces its emissions from industry, it has the existing manufacturing infrastructure needed to produce a significant amount of low- or zero-carbon goods for global export.

Export Capacity: About 20% of all US exports, by dollar value, originate from Texas.[59] The Port of Houston handles the most total tonnage and the sixth most shipping containers of all US ports.[60] The Dallas-Fort Worth and George Bush Intercontinental airports rank as the 10th and 18th busiest US cargo airports, respectively.[61] Texas has more freight rail miles and more freight rail workers than any other state, and 68% of trade between the U.S. and Mexico - our largest trading partner - crosses the Texas border. [34,35] [64,65] If Texas produces low-carbon goods to sell, it will have the freight capacity to export them.

Renewable Energy Resources: Texas already leads the US in wind-generated electricity, and it has capability to produce much more. Texas technical potential for onshore wind is significantly greater than its current capacity (about 1,900 gigawatts, or GWs, of potential compared to about 35 GW installed), representing 17% of total U.S. technical potential; Texas also has about 35% of U.S. technical potential for solar (utility-scale and distributed PV).[66] Texas might also have considerable geothermal capacity, possibly 384 GW of technical potential for enhanced geothermal systems (EGS), and geological logs for mapping it.[67,68] Additionally, Texas has nine nautical miles of ocean under its control compared to 3 for most other states, giving Texas ample leeway to capitalize on offshore wind or solar resources and locations to store carbon. These offshore resources are conveniently close to major load centers such as Houston, Corpus Christi and other gulf coast industrial complexes.[69] Although integrating these resources into the electric grid has its challenges, and would likely require some substantial structural shifts, the Texas grid system would be expected to evolve to meet these additional challenges.

Texas is already taking steps towards climate leadership. When the U.S. withdrew from the Paris Agreement, the cities of Austin, San Antonio, Dallas, Houston, and Laredo, and Dallas and Travis counties pledged to continue working towards fulfilling the original commitment.[70] The mayors of Houston and Austin are both members of the C40 Cities Global Climate Leadership Group, a global network of mayors committed to climate action with performance-based requirements for membership.[71] The cities of Austin, San Antonio, Dallas, and Houston all have net-zero targets by 2050, with Austin recently releasing their Austin Climate Equity Plan that also accelerated their net-zero goal up to 2040.[72–75] The state-wide Transportation Energy Reduction Plan has been successful in abating emissions from Texas vehicles, reducing over 180,000 tons of nitrogen oxide emissions, and the program has room to be even more impactful.[76]

Texas institutions, policymakers, and industry leaders can leverage Texas' strengths to pursue a low-carbon future that helps Texas avoid the risk of dwindling oil & gas and industrial sectors, realize the economic benefits of becoming a clean-energy exporter, and show the world that Texas is a global leader for energy that includes for a low-carbon future.

Net-Zero Texas: Potential Pathways to Decarbonization by 2050

Texas is no stranger to leading energy revolutions. We rose to energy prominence on our vast resources: first in the 1800s from agriculture, then in the 1900s from our rich reserves of oil & gas. Texas can do it again by leveraging our longstanding energy expertise and vast renewable resources that greatly exceed energy demand. Texas wind and solar technical potential alone exceeds state-wide demand by over two orders of magnitude, which doesn't even include other abundant sources like bioenergy or geothermal energy.[77] All of these underutilized resources can be harnessed to supply clean electricity, converted into dense energy carriers, or used to manufacture zero- or low-carbon goods. As governments and consumers around the globe are taking actions to reduce their greenhouse emissions, Texas can lead the way and expand our own industrial economy in the process.

There are many pathways to decarbonize the Texas economy by 2050. This report presents four options and quantitatively compares those pathways to business as usual (BAU) conditions, revealing key policies, technological developments, economic impacts, and important environmental trade-offs. These are not intended to predict the future. Rather they are intended to illustrate a range of options and we anticipate the future is likely to bring a hybrid of these pathways. Importantly, policies that have an outsized impact on future emissions or are present across multiple pathways should be strongly considered in the near term as win-win decisions Texas can make now while future technology development and market conditions continue to unfold. While these pathways are not prescriptive, modeling multiple scenarios and comparing their impacts both shows that a net-zero future for the Lone Star state is achievable and provides key insights on the different options for getting there.

2.0 Background

Texas has a vibrant economy spanning a variety of industries and sectors. This section provides high-level background and context on the end-use emission sectors including agriculture, buildings, industry, transportation, and electricity. Information on the various advantages and challenges to decarbonization for each and sector-specific policies that could reduce carbon emissions are discussed.

Agriculture and Land Use

Texas has more farms than any other state and, with approximately 5.5% of all US agricultural sales, is the fourth-largest agricultural producer in the country.[78] [79] [80] More than 248,000 farms and ranches in the state span 127 million acres and generated approximately $25 billion in revenue in 2017. [81] One in seven working Texans has an agriculture-related job, and 90% of farms are small, family-owned businesses. [81]

Texas's agricultural sector is dominated by cattle, which made up almost half of revenue for the sector in 2017. The next top commodities include cotton, milk, broilers (chicken), and corn that together made up almost $9 billion in revenue in 2017.[81]

Agriculture consumes a considerable amount of direct and indirect energy and is responsible for 10.2% of national greenhouse gas emissions due primarily to crop cultivation, livestock and enteric fermentation*, and fuel combustion.[82] Energy in the sector is consumed directly via gasoline, diesel, natural gas, propane, and electricity for farm equipment, heat, and onsite power. While energy use on farms varies depending on the commodity being grown, fuel and electricity comprise between 7 to 16% of farm expenses nationally.[83] In addition, agriculture's indirect energy expenses (primarily for fertilizers and pesticides manufactured from fossil fuel-based feedstocks) range from 16 to 36% nationally.[83] In 2017, of the almost $23 billion of Texas's farming expenses, 4% was spent on fuels and oils, 22% on feed, 4% on fertilizers, and 3% on chemicals.[81] Nationally in 2014, agriculture was responsible for about 1.75% of all primary energy use between direct and indirect energy use.[83]

Because Texas has abundant and diverse energy resources, a significant number of farmers and ranchers lease their land for energy production, including oil, gas, wind, or solar.[84] Onsite energy production provides an additional revenue stream for these businesses and increases Texas's overall energy production.

There are several ways to reduce greenhouse gas emissions in the agricultural sector, including electrifying on-site equipment, reducing fertilizer use or changing the way fertilizers are made, adjusting feed composition or timing to reduce enteric fermentation, capturing methane on-site,

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*Enteric fermentation is a digestive process in ruminant animals such as cattle where digestion produces methane.

and employing soil management techniques that increase carbon sequestration.[85] Emissions related to agriculture's indirect energy use are tallied in the industry sector, so decarbonization of fertilizer and pesticide production will be critical to reducing both sectors' overall emissions impact.

Residential and Commercial Buildings

Due to a variety of reasons, including the region's warmer climate and lower energy efficiency standards, the average Texas household consumes 26% more electricity than the average U.S. household and uses a greater percentage of energy for cooling than the national average.[86] Commercial buildings in Texas account for a significant portion of the state's economy through direct revenue potential and indirect money spent on construction, management, and materials. In 2018, Texas spent almost $26 billion on commercial building construction yielding $62 billion in direct and indirect benefits which generated $21 billion in personal earnings and supported the equivalent of more than 400,000 jobs (roughly 3% of the Texas labor force).[87,88]

Because buildings account for 40% of the U.S.'s primary energy usage, a significant portion of emissions related to the electricity sector are driven by consumption from buildings.[89] Based on EIA data, burning fossil fuels for cooking and heating in buildings and homes accounted for approximately 12% of U.S. carbon emissions in 2020.[90] In 2017, Texas ranked eighth in building emissions and emitted 22.2 million metric tons of CO_2e in building-related greenhouse gases.[91] In addition, from 2010 to 2018 natural gas usage in buildings in Texas grew by about 6%.[91]

In contrast to previous projections of increasing emissions, the 2022 EIA Annual Energy Outlook now forecasts a slight reduction in energy-related residential and commercial building emissions out to 2050.[92,93] Depending on the energy-efficiency of future appliances and building codes related to insulation and other efficiency measures, significant reductions in emissions could be achieved in residential and commercial buildings.[92] However, factors such as population growth, increases in square footage of buildings, and increased use of appliances might cause growth in energy consumption to outpace gains in efficiency, resulting in a small net increase in emissions. These competing effects could be ameliorated by use of low-carbon substitutes (such as renewable or synthesized natural gas) in place of fossil natural gas or through greater electrification supplied by clean power.[94,95]

Eliminating gas combustion–even of low-carbon gases–in buildings could achieve significant health benefits.[96] A study analyzing the role of cooking with gas indoors on children's health found that children in homes with gas stoves had a 42% increased risk of experiencing asthma symptoms and a 24% increased risk of being diagnosed with asthma.[97] Approximately four million people die prematurely each year due to pollution from cooking with solid fuel or kerosene, and nearly half of pneumonia-related deaths in children under five are attributable to inhalation of indoor particulate matter pollution.[98]

Two major strategies are often discussed when decarbonizing buildings: 1) full electrification of building energy use, and 2) the use of alternative low- or zero-carbon fuels. In both strategies, emissions could be driven down through increasing efficiency of heating/cooling systems, building appliances, and lighting, which would decrease energy consumption and emissions. In addition, higher efficiency for fuel-based appliances (e.g., gas stoves and gas water heaters) could decrease direct emissions and improve human health.

Retrofitting existing buildings to increase their energy efficiency is not only more cost-effective than constructing brand new energy-efficient buildings, it also reduces consumption of new materials, providing environmental benefits through decreased water and energy use associated with material production.[89] Since Texas consumes more energy for cooling than the national average, significant improvements to insulation in the building envelope of structures and efficiency of cooling systems and non-cooling appliances (e.g., washers, dryers, refrigerators, etc.) would impact Texas household energy consumption more than other states.[86,99] However, opportunities to upgrade to more efficient heating systems might not be cost-effective for Texas households. As such, the carbon emitted by heating systems may be harder to reduce without alternative fuels or full electrification powered by renewable energy sources. Notably, with 61% of home heating coming from electricity in 2019, compared to 39.5% on average nationally, the majority of residential heating systems are already electrified in Texas and the state is already a leader.[100]

Several alternative fuels exist that could play a role in decarbonizing Texas, though their role in the buildings sector remains uncertain. Key alternative fuels which could replace fossil fuels in the buildings sector include synthetic or renewable natural gas or hydrogen. These fuels offer carbon-free production processes (hydrogen if made through electrolysis and clean electricity), though these might not be commercially viable in all cases and face challenges such as potential leaks.[89] In addition, renewable and synthetic natural gas do not resolve onsite emissions that can be harmful to human health. To secure the benefits achieved by alternative fuels in the long-term, decisions must be made in the coming years about the scale of infrastructure which will be built out to support alternative fuels.[101] Some suggest the full potential of alternative fuels, particularly hydrogen, would be best achieved if all sectors are included in a large-scale infrastructure buildout.[89,102]

Overall, decarbonization options for buildings may be considered on a more local, or even building-by-building basis – in conjunction with local and regional building codes – as building owners consider whether the potential benefits of each method outweigh the costs, whether retrofitting and reconstruction would involve significant exposure to toxic or hazardous materials, and whether options for recycling and material reuse are presented.[89] Texas is well positioned to utilize energy-efficient technologies to reduce electricity and fuel consumed by cooling systems and appliances and may look to deep electrification, alternative fuels, or a combination of the two to eliminate carbon emissions in the buildings sector.

Industry

The Texas industrial sector is large and multifaceted. At $2 trillion in the third quarter of 2021, Texas has the second highest gross domestic product (GDP) of all states in the U.S. and the twelfth largest economy in the world.[103,104] In addition to total energy production, Texas leads the nation in refining and chemical production.[105] In 2019, Texas exports generated $328.8 billion in revenue, more than California ($174 billion) and New York ($75.6 billion) combined.[106–108] All together, two-thirds of Texas's exports are oil & gas (22.9%), petroleum and coal products (15.2%), computer and electronics products (14.9%) and chemicals (13.6%).[109] Almost 30% of Texas's GDP relies on energy-intensive manufacturing and mining, quarrying, and oil & gas extraction as of 2020.[110] This productivity is energy intensive; thus, while Texas produces the most energy of any state, it also consumes the most.[111]

Just over half of all energy consumed in Texas is in the industrial end-use sector, whereas the U.S. average is only 35%.[112,113] Most of our industrial energy consumption comes from fossil fuels.[111,114] Nationally, the National Renewable Energy Laboratory (NREL) found that large consumers accounting for 37% of total industrial energy use are located in Texas, Louisiana and California.[111] The same study found that ten counties accounted for 14% of total industrial energy use, with seven located in Texas and Louisiana.[111] Thus, Texas is also the leading state in industrial emissions.[115]

Texas industry directly emitted 228 million metric tons (mmt) of carbon dioxide in 2017, over 100 mmt more than the next-highest state, Louisiana.[115] At the national level, industry accounts for about 26% of energy-related U.S. carbon dioxide emissions by end-use compared to 34% in Texas.[93,115] Current trends indicate that the Texas economy, and thus industry, will continue to grow in the future. More companies relocate to Texas than to any other state, partly because of access to affordable energy, affordable housing, and less restrictive labor and environmental laws.[116,117] This growth has environmental ramifications. Researchers at The University of Texas at Austin found that future build outs of oil & gas infrastructure in the southwest and gulf regions, including Texas and Louisiana, could spur more than 500 million metric tons of additional emissions each year by 2030.[118] And because industrial facilities typically last decades, those additional emissions would continue to add up over time.

Industry has been repeatedly identified as a crucial but particularly difficult sector to decarbonize, due in part to long facility lifetimes often exceeding 20 years, the requirement of large amounts of heat, and both the variety and inherent nature of industrial processes that depend on specific chemical transformations (e.g., converting limestone to clinker for cement).[119–121] A McKinsey report found that 45% of emissions resulting from feedstocks cannot be abated by switching the input material and can only be reduced by changing the process itself, likely necessitating changes to other highly integrated processes within the facility.[122] Furthermore, many industrial processes require large amounts of high-temperature heat, which is difficult to produce from non-fossil resources like low-carbon electricity without major furnace redesign.[122] Approximately 21% of global carbon dioxide emissions in 2016 were from the combustion of primarily fossil fuels to produce industrial heat, which often exceeds 800 °C and can reach over 1,400 °C.[121,123] Industry also physically produces many of the technologies that would be in demand in a low-carbon future, like electric vehicles, wind turbine blades, alternative cement clinkers, or chemical solvents that can be used for CCUS. As Rissman, et al (2020) point out, these industrial pathways should aim to be in line with the zero-carbon future their products support.[124] However, there are ways to decarbonize the industrial sector.

The Intergovernmental Panel on Climate Change (IPCC) has previously identified six broad categories of industrial decarbonization efforts: energy efficiency, emissions efficiency, material efficiency in production, material efficiency in product design, using products more intensively, and reducing overall demand for product services.[125] Options to reduce overall material consumption include production-level efforts like lightweighting vehicles or increasing material reuse, as well as consumer-level efforts to reduce product demand or use the same products for longer.[125] Other frequently discussed technologic options for decarbonization include energy efficiency improvements, fuel-switching to electricity or hydrogen, replacing conventional feedstocks with biomass-based alternatives, and CCUS.[125–128] Some of these choices are attractive for their ability to be integrated with existing industrial operations, like CCUS, but might be limited to those processes with a defined 'smokestack' of emissions. Hydrogen can replace fossil fuels for heat generation, and clean low or zero-carbon hydrogen can replace hydrogen currently used as a chemical feedstock (e.g. for ammonia production). While most hydrogen today is made from steam methane reforming (SMR), several alternative production methods exist. And while still relatively expensive compared to SMR, green hydrogen, made from renewable-powered electrolysis of water, or blue hydrogen, made from SMR coupled with carbon capture, are becoming more available.[119,123,129]

Transportation

Texas's transportation sector was responsible for 23% of end-use energy consumption in 2018 and 32.6% of total state emissions in 2017. [130,131] With hundreds of miles between major cities, and more miles of roads and rail than any other state, it is no surprise that Texans are tenth in the nation for most traveled miles per capita despite having several of the nation's largest metro areas.[132,133] Transportation is the state's second highest greenhouse gas-emitting sector after industry.[115] Transportation emissions in Texas are the highest of any other state due to our high population, our preference for large trucks and cars, and our propensity for driving more miles.[134] Texas has the second highest vehicle miles traveled (VMT) of any state, just behind California.[135] The last decade has also seen a steady increase in VMT, passenger miles, and freight-ton miles, all of which correlates with a steady increase in transportation energy demand.[136,137] At the same time, there has been a decline in the energy required per mile traveled (i.e., energy intensity) of the technologies in the sector largely due to federally mandated fuel economy standards and energy efficiency standards. While decreases in energy intensity are expected across the transportation sector into the future, emissions from the sector will likely continue to be substantial without more aggressive changes or disruptions to the sector. [138,139]

Texas has state-level and county-level transportation-related policies that could help with decarbonization efforts. The Texas Emissions Reduction Plan is a state-level transportation-related policy that offers grants to replace or upgrade older, less efficient heavy-duty vehicles (HDVs), rebates for electric or natural gas light-duty vehicles (LDVs), and rebates for the construction of alternative fueling facilities.[140,141] This plan is organized through the Texas Commission on Environmental Quality. There are also county-specific policies such as on-road vehicle emissions limits that promote decarbonization through increased vehicle efficiency, and various public transit policies (light rail, buses, walkable cities, bike lanes, flexible work weeks, etc.) that promote decarbonization through reduction in VMT.[142]

Policies that focus on improvement of vehicle efficiency, increasing the share of electric vehicles, smart urban planning—which includes alternatives to driving a vehicle (such as walkways, protected lanes for scooters and bicycles, and mass transit)—and research and development in alternative fuels (e.g., hydrogen, hydrogen carriers, and biofuels) could further accelerate the decarbonization of the transportation sector. While alternative fuels could help decarbonize on-road emissions they are not currently deployed at-scale the way electric vehicles have been gaining traction. That said, those low-carbon fuels could be promising options for aviation and marine applications.

Strategies aimed at reducing LDV emissions are critically important in a decarbonized future because LDVs represented about 57% of transportation sector energy consumption. [135] Some possible approaches include fuel fees and feebate policies, government procurement of electric buses, electric vehicle policies (e.g., subsidies, rebates, or tax incentives to reduce the purchase cost, policies to increase the number of charging stations), smart urban planning, and travel demand management.*

Electric Power Sector

Texas is the only state in the contiguous U.S. that has its own self-contained electricity grid. The Electric Reliability Council of Texas (ERCOT) generates about 90% of Texas load, serving over 26 million end users (businesses and people).[143] Of the approximately 135 GW of power plant capacity in all of Texas, about 84% is part of the ERCOT grid.[144] The majority of load centers (e.g. large cities and industrial centers) in Texas are also in ERCOT. However, though all of ERCOT is inside Texas, not all of Texas is inside of ERCOT. Figure 2.1 illustrates the ERCOT service area and regional interconnections. Some areas of the Texas panhandle and far east parts of Texas are connected to the Eastern Interconnection, and the far western region of El Paso is connected to the Western Interconnection.

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* Travel demand management provides reductions in vehicle miles via public transit, rideshare, bicycle and pedestrian facilities, and traffic system management, which improves the operational efficiency of the existing transportation network by optimizing traffic light timing, pre-staged wrecker service to clear accidents faster, or traveler information systems.

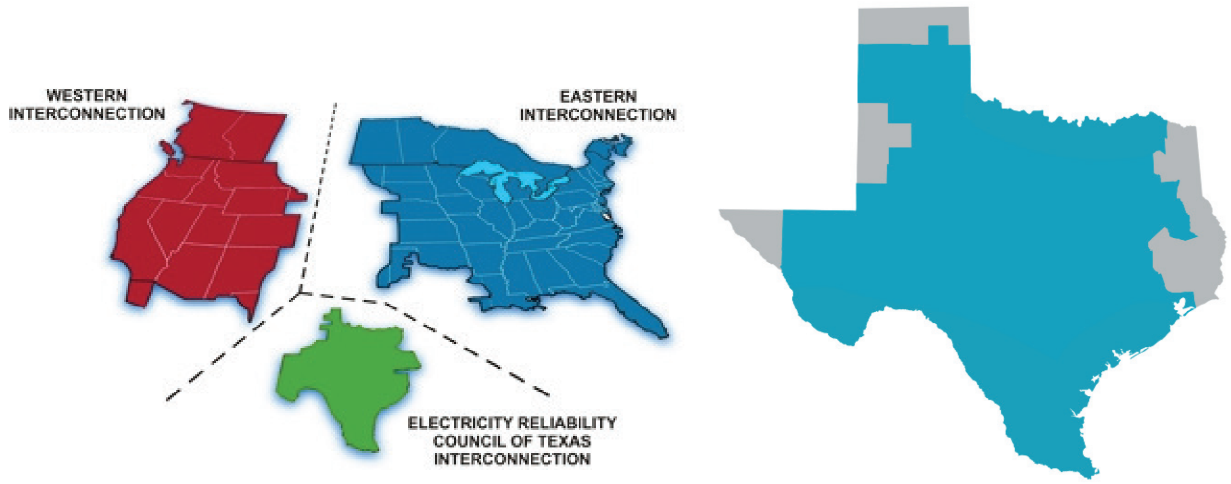
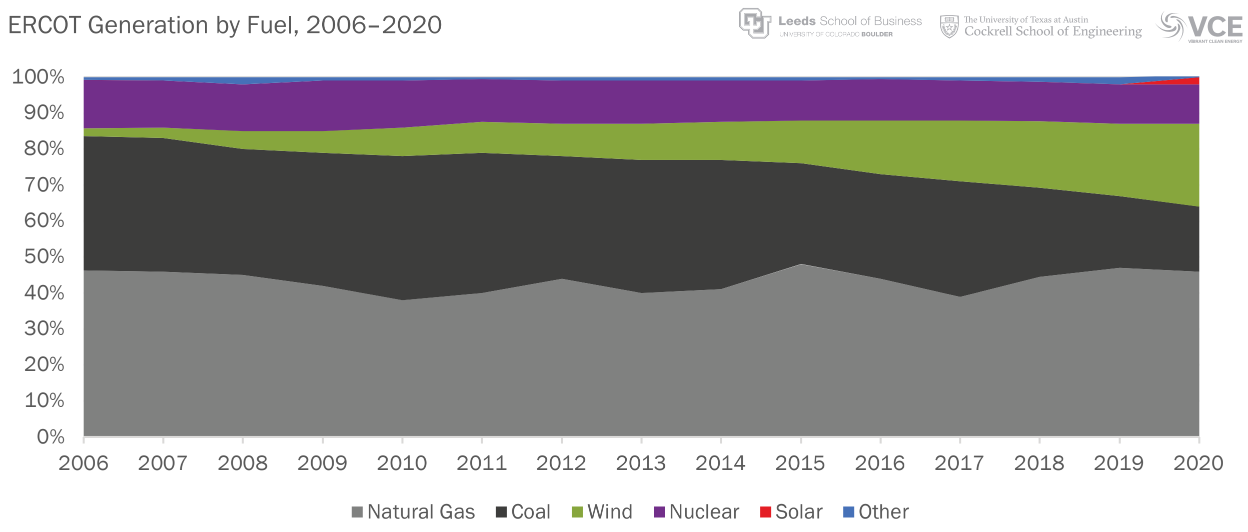


Figure 2.1: The three main US interconnections (Western, Eastern, and Texas, left) and a closer view of the ERCOT footprint within Texas (right).[143,145] The ERCOT footprints in the above images differ slightly based on where loads and generation sources are located.

Because ERCOT lies wholly within the boundaries of Texas, its operations are not subject to as much oversight from the Federal Energy Regulatory Commission (FERC) as other interstate grids are. However, the non-ERCOT regions in Texas are under FERC jurisdiction. Also, because all three of the major interconnections serve parts of Texas, the Public Utility Commission (PUC) of Texas is the only state agency that interacts with all three interconnections.

The ERCOT system is also one of the most competitive electricity systems in the US, having both wholesale generation and retail sales competition.[146] Wholesale competition means that power plant owners have to compete in a least-cost auction to provide power and are not guaranteed a rate of return for their assets. Furthermore, most customers have retail choice and can choose their electricity provider.[147] However, the transmission system remains a fully regulated entity.

In 2020, about 46% of ERCOT's electricity was generated from natural gas, 23% from wind, 18% from coal, about 11% from nuclear, and roughly 2% from solar. However, the ERCOT electricity grid fuel mix has changed over time as the cost of natural gas and renewables have fallen and large amounts of coal have retired. Figure 2.2 illustrates the change in fuel mix over time, highlighting the rapid growth in wind power since 2006 and the more recent rapid growth of solar starting around 2018.



Joshua D. Rhodes, PhD | @joshdr83 | The University of Texas at Austin and IdeaSmilths LLC

Figure 2.2: Figure showing the changing fuel mix in ERCOT for the past 15 years.

Texas generates and consumes more electricity than any other state.[148] In 2019, power plants in Texas generated over 483 million megawatt hours (MWh) of electricity, 89% of which was consumed within the state.[149] Texas also ranks first in total electric sector emissions, emitting almost 143 thousand metric tons of sulfur oxides, almost 163 thousand metric tons of nitrogen oxides, and over 196 million metric tons of carbon dioxide.[149] Though Texas has the highest overall emissions, our emissions intensity (i.e., emissions per unit electricity generated) is comparable to other states.[150]

The Texas grid is becoming cleaner with respect to both emissions intensity and total emissions, even as total energy generation increases. For example, comparing 2019 to 2005, Texas power plants produced 22% more electricity while reducing sulfur dioxide emissions by 74%, NO_x emissions by 34%, and carbon dioxide emissions by 24%.[151] This change is largely because of the reduction in coal consumption and the substantial growth in renewable energy resources. Thus, the Texas grid is already following the global trend toward cleaner electricity.

Texas is known as a business-friendly state with minimal regulations, but this regulatory landscape is not incongruous with decarbonization. Texas has a binding renewable portfolio standard set in 1999 that mandated 5,000 megawatts (MW) of non-hydro renewables be installed by 2015 and set a non-binding target of 10,000 MW by 2025, including a 500 MW non-wind carveout.[152] These mandates helped stimulate demand, which grew faster than the mandates required: Texas had over 30,000 MW of wind and solar installed by the end of 2020, eclipsing the legislative requirements. Continued growth of renewables is expected given the state's vast renewable resources, market structure, and business friendly atmosphere.

The regulatory landscape in Texas, particularly the ERCOT part of Texas, also facilitates the construction of transmission lines. One of the largest drivers of deployment of renewable energy in

Texas was the development of the Competitive Renewable Energy Zone (CREZ) lines that allowed the populated centers in the central and eastern parts of the state to access the areas of high wind resource in the western part of the state. [153] Additional benefits of these lines, like geographic diversity for resources and rural economic development, are likely to be realized with further solar development given wind and solar's complementary nature.[154] *

In general, most, if not all, deep decarbonization plans are centered around growing and decarbonizing electricity while simultaneously electrifying as much of the economy as possible.[16,120,155–159] While some parts of the economy, such as chemical processes, are hard to decarbonize, the electricity sector is unique in that it has the ability to fully decarbonize the sector with existing technologies. That these technologies are also rapidly declining in cost and are generally cheaper than their dirtier counterparts is helpful. Even without climate mandates, it is likely that the electricity sector would likely continue decarbonizing, but we anticipate policy support will be required to fully decarbonize on an accelerated timeline.

Fuels and Energy Resources

Rich in coal, natural gas, crude oil, and renewable energy potential, Texas leads the country in energy production and energy consumption.[160] As the makeup of the Texas fuel economy has shifted over time, so have the emissions associated with fuel production.

Texas is the top coal and natural gas consumer in the nation.[160] Texas is also the second-largest lignite coal producer in the country and is estimated to have more than 9 billion tons of total recoverable coal reserves.[160] Technological innovations associated with the shale revolution, such as horizontal drilling and hydraulic fracturing, have led to a drastic increase in natural gas production and a reduction of prices.[161] This shift has made natural gas more cost competitive compared to coal and contributed to a decrease in coal production since the early 2000s.[162] Much of this natural gas production occurs in the Eagle Ford and Permian Basin regions.[160] Texas is well connected to national markets, with more than 17,000 miles of interstate natural gas pipelines to move gas.[160] This pipeline network allows for Texas to not only be the largest consumer of natural gas in the U.S., but also to be a large international and interstate importer and exporter of natural gas.[160,163]

Texas has also led crude oil production in the nation for every year but one since 1970.[160] Though most of the crude oil production occurs in the west and south-central regions of the state, Texas contains about 40% of the U.S.'s proven oil reserves.[160] Like gas, crude oil production in Texas has increased rapidly since 2010.[160] The state is also a large consumer of petroleum products, mostly for the industrial and transportation sectors.[160]

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* Wind and solar are complementary. Typically, as wind output falls midday, solar is at its peak. As the sun sets, wind production often picks up.

Though coal, natural gas, and crude oil are large contributors of greenhouse gas emissions at point-of-use, there are also upstream emissions associated with their extraction and transportation. More than 250 billion cubic feet of natural gas was vented or flared in Texas in 2019, about 5% of Texas' total consumption.[160,164] The Energy Information Administration (EIA) predicts that greenhouse gas emissions from natural gas drilling operations in the U.S. could reach 165 million tons of CO_2 equivalent in 2025, which is an increase of 27.4% from 2018 levels.[165] To put this into context, 2025 projected emissions from natural gas operations are equivalent to emissions from 35 million passenger vehicles.[166] Methane emissions from coal mining and abandoned coal mines accounted for about 7% of the national methane emissions in 2020.[82] These fugitive emissions exacerbate the negative environmental impacts of traditional high carbon fuels.

Biofuels are a possible alternative to fossil fuels. Texas has four ethanol plants, four biogas fuel plants, eight biodiesel producers, and two biomass wood pellet plants.[160,167] Though biomass fuels account for less than 0.5% of Texas's electricity generation, the liquid biofuel plants produce almost 400 million gallons of ethanol and 375 million gallons of biodiesel per year.[160]

Texas sits on a wealth of carbon-free and renewable energy resources, putting the state in a great position as demand for low-carbon fuels and products increases around the country and the world. Texas has two nuclear power plants and has recently restarted uranium mining in sandstone deposits in the Gulf Coast region.[112] Texas also has some of the best wind and solar potential in the US.[160] With almost 34 GW of installed wind capacity as of 2021, only four countries have more installed wind power than Texas.[168–170] By contrast, the state only had 2.5 GW of installed wind capacity in 2000.[170] This drastic increase in wind capacity in Texas follows global trends of decarbonization and is feasible due to the construction of transmission lines across the state, connecting remote wind farms to urban centers (as discussed in the electricity sector above).[160] In addition to the vast wind resources in the state, there are high levels of solar resources across Texas that provide the state with an excellent solar energy potential.[160] As of April 2021, solar capacity in Texas had grown to almost 10 GW in Texas with expectations of further growth.[171]

According to the U.S. Department of Energy, Texas has the potential to produce 18,000,000 MWh per year of hydropower, but only 2,900,000 MWh per year would be feasible due to economic and environmental constraints.[172] There are fewer than two dozen hydroelectric power plants currently operating in Texas; low levels of rainfall combined with small elevation changes across the state restrict the hydroelectric potential.[160] Similarly, Texas's 'reasonable depth' geothermal energy potential is limited, as most of the geothermal resources close to the Earth's surface are less than 100° C. However, the extensive oil & gas drilling infrastructure provides Texas with a unique geothermal potential; geothermal resources that can be accessed from current or abandoned wells indicate temperatures from 180° C to 200° C that have a potential 500 to 2000 MW of capacity.[173] However, recent advancements in geothermal technologies could raise this potential much higher.[68] Geothermal resources can also have the dual advantage of being able to supply both firm renewable generation capacity and industrial heat, which is difficult to decarbonize.[68]

Texas is one of the largest producers of hydrogen in the world, producing large amounts for its own chemicals industry. As of January 2020, Texas produces about 291 million cubic feet per day, needing to neither import nor export much of the fuel.[174] The majority of this hydrogen is produced through steam methane reformation, which has associated carbon dioxide emissions.[175] Due to the great renewable energy potential in the state, there is a high potential for 'clean' hydrogen to be produced via electrolysis with these resources.[175]

Currently, much of Texas's energy fuel consumption and production is centered around fossil fuels such as crude oil, natural gas, and coal. But, with extensive wind, solar, geothermal, and clean hydrogen resources, Texas is well positioned to become a leader in carbon-free and renewable energy resources.

3.0 Results

This analysis used a combination of three modeling approaches. The Texas Energy Policy Simulator (TX-EPS) was developed in partnership with Energy Innovation, LLC and based on the national Energy Policy Simulator (EPS) to quantify energy use and emissions in Texas under the various scenario conditions. The TX-EPS uses the EPS model architecture but adapts all baseline conditions to Texas conditions. The EPS utilizes a system dynamics model to track energy and resource flows throughout the different economic sectors of the state. Within the EPS, policies can be applied that impact these resource flows and reduce emissions.

A baseline business as usual (BAU) scenario was first constructed for Texas, driven primarily by underlying demographic and other trends. Policies within the TX-EPS were then used to create each net-zero scenario. Though named as policy levers in the TX-EPS, many of these policies are for technologic changes (e.g. building and appliance efficiencies, EV adoption, industrial electrification, etc) and can be achieved through policy changes, market outcomes, or other means. The TX-EPS was used to set the scenario assumptions about technology adoption, electrification, transportation fuel demand, hydrogen demand, efficiency improvements, and other decarbonization efforts like preventing leaks from industrial equipment or improving end-of-life practices for industrial F-gases ('clean-up-your-act' policies). In the Hydrogen and Carriers scenario, demand for synthetic natural gas and ammonia were calculated separately because the TX-EPS does not isolate ammonia production nor feedstock hydrogen consumption and also does not include synthetic natural gas as an option.

Statewide electricity demand and leftover emissions profiles for each scenario were used as input into the WIS:dom-P model, created by Vibrant Clean Energy, LLC (VCE®). The WIS:dom-P model was used to provide detailed power sector and unit commitment modeling as well as to deploy carbon capture and removal technologies to abate any emissions not first reduced through policy pathways developed in the TX-EPS, making each scenario truly net-zero. WIS:dom-P determines the least-cost power sector that also achieves net-zero by 2050, choosing the generation mix, carbon capture and removal capacities, and hydrogen production pathway (i.e. steam methane reforming or electrolysis).

Finally, industry cash flow changes, fuel production changes, and power sector costs from the TX-EPS and WIS:dom-P models were used as input to the Regional Economic Modeling, Inc. (REMI) policy insights (PI^{+}) model to provide detailed economic impacts analysis. This modeling was performed in partnership with the University of Colorado, Boulder.

For the power sector and economic modeling portions of this analysis, Texas was condensed from the 12 economic regions into ten, combining Upper Rio Grande with West and Upper East with Southeast. The TX-EPS is an aggregate, statewide model and does not have regional fidelity. Figure 3.1 shows the twelve economic regions of Texas, as defined by the Texas Comptroller's office, and the ten used in this analysis.

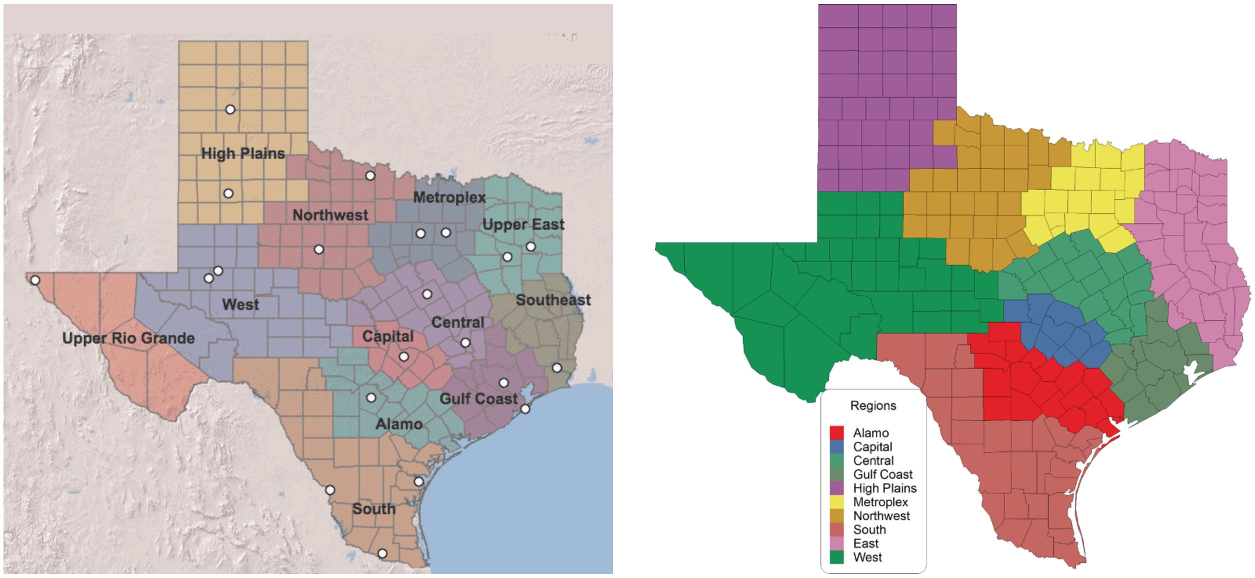

Figure 3.1: This figure shows the (a) twelve economic regions of Texas, as defined by the Texas Comptroller's office (https://comptroller.texas.gov/economy/economic-data/regions/2015/) and (b) ten regions used in this analysis, in which the state was condensed into ten regions, combining Upper Rio Grande with West into one 'West' region and combining Upper East with Southeast into one 'East' region. WIS:dom-P models the ERCOT system but is able to build transmission and access generation in non-ERCOT regions.

There are multiple ways Texas can reach net-zero, and the scenarios we developed are four possibilities. They are not predictive, but rather meant to illustrate that it is possible for Texas to reach net-zero emissions by 2050 and to show what might be needed to achieve it.

3.1 Energy Demand

Decarbonization can improve the overall energy efficiency of Texas. As the economy develops and changes to reach net-zero, electricity demand increases, but total energy demand grows more slowly. Total energy demand in 2050 is less than the BAU scenario for all net-zero scenarios except Extensive Capture. The rise in energy demand for the Extensive Capture scenario is driven by increasing electricity demand to power a significant number of DACS systems. But, in the other net-zero scenarios, the rate of total energy demand increase is lower than in BAU due to increasing electrification as well as energy efficiency policies. Figure 3.2 shows total energy demand and electric end-use demand for Texas.

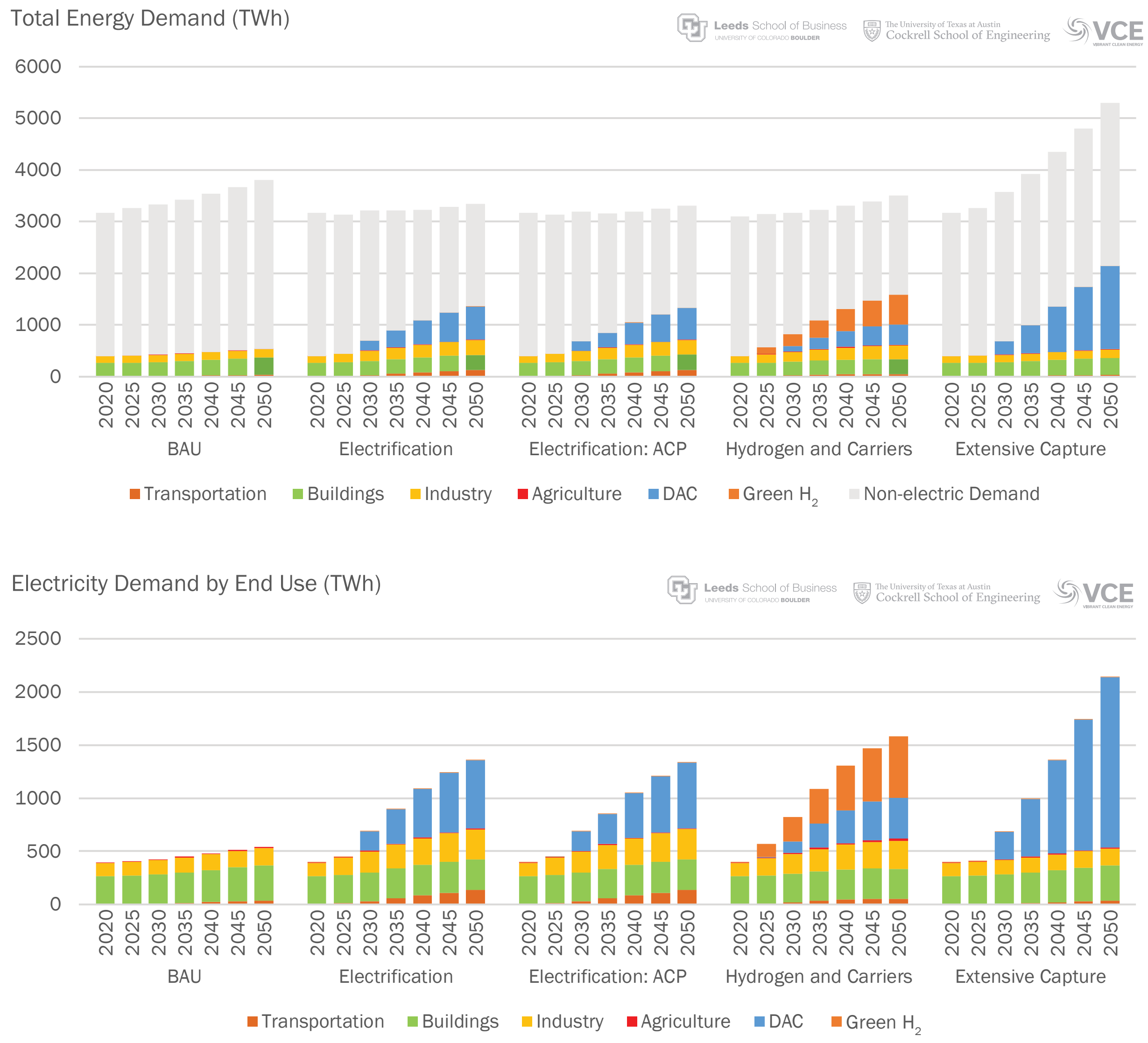

Figure 3.2: This plot shows the total economy-wide energy demand (top panel) and end-use electricity demand (bottom panel) by sector for each scenario. Grey bars in the top panel represent state-wide primary energy demand from fuels not used for creating electricity, whereas the colors denote electricity demand (which is isolated for the bottom panel). Overall electricity demand by 2050 more than doubles compared to 2020 for all net-zero scenarios. Also for all net-zero scenarios, the largest share of new demand comes from DACS or increasing production of hydrogen through electrolysis. Electricity demand increases relative to BAU for transportation and industry in all net-zero scenarios except Extensive Capture, reflecting increasing electrification of these sectors. Buildings are similarly electrified, but the effects are smaller. Electricity for transportation increases primarily in the Electrification and Electrification: ACP scenarios as all new vehicle sales and some aviation become electric by 2050. All net-zero scenarios, except Extensive Capture, are more energy efficient overall in 2050, as shown by lower total energy demand in the top panel, compared to BAU.

As an increasing portion of the economy electrifies in each net-zero scenario, there is less demand for other fuels. Detailed estimates for fuel consumption for transportation, industry, and buildings (residential and commercial), by scenario, are included in Appendix D. Additionally, electrification of certain end-uses, like transportation and home heating, has inherent efficiency benefits compared to other fuels. Electric vehicles require less energy than gasoline- or diesel-powered vehicles due to the increased efficiency of electric drive-train components and regenerative braking. Energy efficiency improvements in all sectors also help reduce total energy demand growth, particularly in the industrial sector.

Electricity Demand

Demand for electricity drives the development of the technologies deployed in each scenario. Growth in electricity demand by sector is presented in Figure 3.2. Even in the BAU scenario, electricity use in ERCOT increases by about 38%, from approximately 412 billion kilowatt hours (kWh) to 570 billion kWh by 2050. The scenarios that include decarbonization goals use significantly more electricity, but displace other non-electric forms of energy for all but the Extensive Capture scenario. The Electrification and Electrification: Accelerated Clean Power scenarios each increase electricity use by about 250% to 1.4 TWh by 2050, the Hydrogen and Carriers scenario consumes 290% more (1.6 TWh by 2050), and the most electricity-consuming scenario is Extensive Capture which increases electricity use by about 430% to 2.2 trillion kWh in 2050. The latter value is a little over half the entire U.S. usage of nearly 4 TWh of electricity in 2021 (though nation-wide electricity consumption in the United States is also projected to grow significantly).[176]

Demand increases significantly in the decarbonization scenarios because many end-uses, such as transportation and heating, use electricity over time to displace direct use of fossil. Additional demands for fuels such as hydrogen also increase electricity demand as the model finds it more advantageous to create hydrogen via electricity-driven hydrolysis than via steam methane reforming paired with CCS (or more DACS).* Some DACS (also driven by electricity) is required in all scenarios to get emissions to net zero, but is featured most prominently in the Extensive Capture scenario. Also, in addition to increasing electrification of the economy, further electricity is also required to produce fuels and chemicals like ammonia, fertilizer, and synthetic natural gas (SNG) in some scenarios.

Though other net-zero studies have also shown that electricity use more than doubles as the economy electrifies, growth in electricity demand (and thus, generation) is somewhat higher than growth projected in other net-zero studies.[155] The *Net-Zero America* report sees national electric generation growth between about 100-280% across the five net-zero scenarios modeled, and the International Energy Agency's (IEA's) net zero scenario sees growth of almost 170%. [155] [177] Much of the high growth in this analysis can be attributed to substantial increases in DACS and electrolysis capacity, depending on the scenario, driven by Texas's large industrial sector. DACS capacities

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* Electrolysis and steam methane reforming with CCS are two low-carbon hydrogen production pathways that are the most common today (though production from both is dwarfed by SMR without CCS), but it's entirely possible that other methods such as pyrolysis, photolysis, metal redox cycles, or biological production pathways will mature sufficiently before 2050 to outcompete electrolysis and steam methane reforming. Those production pathways will have a different impact on electricity demand than electrolysis.

by 2050 in this work are on the higher end of estimates from similar studies (see Appendix A), and are fully electric rather than a mix of electric and gas-powered, further adding to electricity demand.

Tighter efficiency standards can also keep demand lower than it otherwise would be in the net-zero scenarios even though total electricity demand substantially increases due to widespread electrification of end uses. For example, a recent report from the American Council for an Energy-Efficiency Economy found that a combination of residential efficiency and demand response measures deployed over five years could reduce 7,650 MW of peak summer and 11,400 MW of peak winter load in the current Texas economy.[178]

DACS

DACS represents a large, new source of electric load on the grid in all four net-zero scenarios. In the Extensive Capture scenario, where almost all emissions are reduced through DACS exclusively, electricity demand for DACS reaches 1,600 terawatt hours (TWh) in 2050 (figure 3.2). Electricity demand for DACS is overall lower in the other net-zero scenarios as fewer emissions are abated through DACS compared to the Extensive Capture scenario. Much of the additional wind generation in the net-zero scenarios can be attributed to the increased demand from DACS. The primary difference in electricity demand between the BAU and Extensive Capture scenarios is the deployment of DACS, and in response, the 2050 electric mix features wind and solar resources much more heavily in the Extensive Capture Scenario. DACS is discussed in further detail in Section 3.4.

Hydrogen and Ammonia

WIS:dom-P was given the option to pick either electrolysis (often referred to as 'green hydrogen' when paired with zero-carbon electricity) or steam methane reforming to make non-feedstock hydrogen. We did not look at hydrogen used as a feedstock or hydrogen produced and consumed on-site for industrial or cogeneration purposes because the TX-EPS focuses on primary energy consumption. Emissions from feedstock and on-site hydrogen are included in overall industrial sector emissions and not isolated. The only exception is in the Hydrogen and Carriers scenario, in which hydrogen demand for ammonia was separately estimated based on industrial ammonia production rates and stoichiometry and included in the WIS:dom-P modeling. Other hydrogen production methods, such as pyrolysis, photolysis, metal redox cycles, or biological pathways, were not evaluated, though it's reasonable to expect that one or more of them could mature swiftly enough to compete with electrolysis or steam methane reforming before 2050. Of those, pyrolysis is the most advanced. Pyrolysis converts methane into hydrogen and solid carbon. However, this method is not without greenhouse gas emissions and is dependent on the emission intensity of the supplied natural gas and the electricity or process heat needed.[179]

Given the choice between electrolysis and SMR, the model chooses to for the vast majority (more than 98%) of non-feedstock hydrogen to be produced via electrolysis. Slight amounts of hydrogen are produced via steam methane reforming in later years for each scenario as production and thus costs rise. More steam methane reforming-based hydrogen is purchased in later years in the Hydrogen and Carriers scenario (about 7%) because the hydrogen demand is so high that it becomes cheaper to purchase the SMR hydrogen than to build out more renewables to power increased electrolysis. Because of the net-zero constraint, if the model picked steam methane reforming-based hydrogen, it would have to make up for the carbon emissions via either CCS or additional DACS. Also, hydrogen is easier to store for long durations than electricity and thus doesn't have to necessarily be produced in real-time like electricity. One of the benefits of electrolysis (and similar for DACS) is that the systems can ramp quickly. This feature allows the system to turn down hydrogen production at will (as long as all hydrogen demands are met) and free up electricity that was meeting hydrogen loads for other, less flexible demand. Figure 3.3 shows the difference between steam methane reforming hydrogen ('grey'), steam methane reforming hydrogen with CCS ('blue'), and hydrogen produced through electrolysis with renewable energy ('green').

Hydrogen Production Pathways: Grey, Blue, and Green

Although hydrogen is the most abundant element in the universe, on Earth, it's mostly tied up with oxygen in the form of water, or carbon in the form of fossil fuels. Hydrogen is produced today primarily from natural gas through an energy-intense process called **steam methane reforming (SMR)**. Hydrogen can also be produced using electricty and water by **electrolysis**, a process that emits no greenhouse gases.

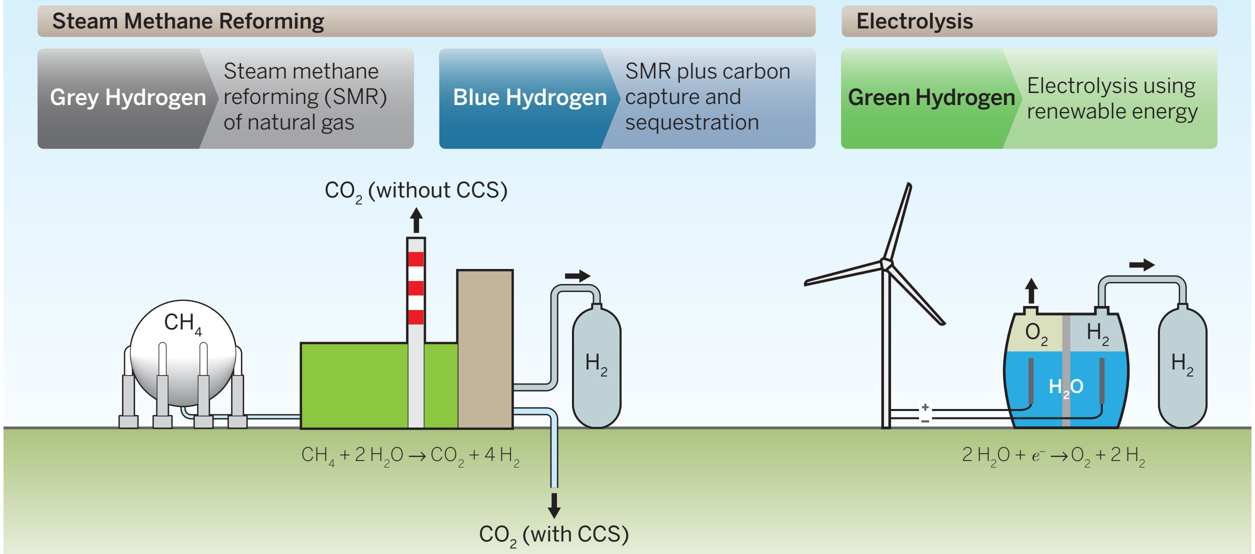


Figure 3.3: Grey, blue, and green hydrogen production pathways have different inputs and outputs.

Increased production through electrolysis greatly adds to power sector demand and consumes large quantities of water (see Section 3.5), but when tied to a low-carbon grid, it provides a flexible and low-carbon fuel and feedstock.

One prominent use of feedstock hydrogen is to make ammonia, which is used both on its own and to make ammonium nitrate fertilizer, among other products. Conventional ammonia production is carbon intensive, releasing around 2 kilograms of carbon dioxide per kilogram of ammonia produced when using steam methane reforming-based hydrogen. [180] In the Electrification, Electrification: Accelerated Clean Power, and Extensive Capture scenarios, all feedstock hydrogen for ammonia is assumed to be produced using natural gas. In the Hydrogen and Carriers scenario however, ammonia demands are met using low-carbon hydrogen as feedstock.

Ammonia production increases in the Hydrogen and Carriers scenario as it begins to replace heavy fuel oil for cargo shipping, ramping up to supply 100% of cargo shipping fuel demand by 2050. The model also has 'Power-to-X' capabilities, whereby excess electricity generation ("Power") during periods of high renewable resource availability (e.g. wind and solar) is used to produce energy carriers or fuels ("X"). These fuels can be used as they are or can be used down the line to produce electricity in an 'X-to-Power' pathway. While the model does use Power-to-X to produce hydrogen and ammonia or ammonium nitrate, it does not choose to use X-to-Power. Multiple energy conversions and efficiency losses makes the X-to-Power pathways more expensive overall than simply building out more storage and firm generation.

Hydrogen demand grows substantially in the Hydrogen and Carriers scenario. In this scenario, Texas hydrogen production could represent about 2% of global demand in 2050 (compared to less than 1% in the others) based on projections from the Hydrogen Council (which estimates total demand near 660 mmt in 2050).[181] Three percent is high but not unreasonable for Texas, which produces roughly 2% of global GDP.[103,104] Texas can also meet the rising electricity demand from electrolysis with low-cost wind generation, lowering system costs. Furthermore, Texas is also well-suited to support green hydrogen because of our existing hydrogen and oil & gas infrastructure and expertise. The Hydrogen Council notes three types of 'cluster' areas (surrounding large hydrogen users) that can help scale infrastructure and reduce costs: 1) port areas for fuel bunkering, port logistics, and transportation, 2) industrial centers including refining, power generation, and fertilizer and steel production, and 3) export hubs.[182] All of these areas exist within Texas.

Synthetic Natural Gas

Synthetic natural gas (SNG) replaces natural gas for use in buildings in the Hydrogen and Carriers scenario. All SNG in the model is made via the Sabatier reaction which produces methane and water from hydrogen and carbon dioxide. This production method is also frequently referred to as Power-to-Gas because excess electricity can be used to power the upstream hydrogen production through electrolysis. SNG can also be made through anaerobic digestion of organic matter, including at landfills, wastewater treatment facilities, and agricultural operations, but this pathway was not included in the WIS:dom-P model. The model can either build SNG capacity in Texas or purchase SNG on the market. The vast majority of the SNG in this scenario is purchased, though a small amount (maximum annual production of 30 metric tons) is produced in-state, primarily due to cost considerations. The Sabatier reaction is exothermic and power producing, but there is a negligible impact on the grid given the minor in-state production capacity.

Residential and commercial buildings consume about 10% of the natural gas consumed in Texas.[183] Replacing traditional natural gas with SNG in buildings would have less of an impact than reducing its use in the industrial sector and for electricity generation, but would still reduce the amount that is conventionally produced.

Flexible demand/non-critical loads, storage, and resilience

Significant amounts of wind and solar are constructed across all four net-zero scenarios. This renewable capacity generates clean electricity for everyday energy needs and also generates electricity for new, non-critical, flexible consumers such as electrolysis for hydrogen, DACS, many types of data centers, and consumers with built-in storage like electric vehicles can consume electricity on a more flexible timeline than traditional loads. The flexibility of these load sources means that, during times of grid strain, they could be turned off to close the gap between critical load and available power. Electric heating and cooling can also be used as a form of demand management through mild cycling of compressors statewide.[184] Demand response measures are included within the WIS:dom-P model (See Appendix F). The resilience benefits of demand response (primarily seen through peak demand reductions) can be very large, but are not specifically quantified in this analysis for that purpose.

In our analysis, 53% of transportation electricity demand (and 25% of total transportation energy demand) in 2050 for the Electrification scenario comes from passenger and freight LDVs and HDVs as well as passenger motorbikes. These vehicles could act as distributed storage in times of grid strain. In the Electrification scenarios, electrolyzers and DACS have lower capacity factors due to the need for their flexibility. However, electrolyzers in the Hydrogen and Carriers scenario have a higher capacity factor (about 85%), so might have less flexibility as they need to run more frequently to meet higher hydrogen demand. DACS systems are flexible and generally run when excess wind resources are available. DACS systems are not considered critical because the capture of carbon does not have to be temporally matched with its emissions elsewhere to achieve a net-zero economy.

This combination of significant renewable capacity and non-critical loads produces three benefits for the electric grid. First, flexible electricity demand reduces the need for firming power. In a system without flexible demand, traditional firm power plant capacity and/or energy storage technology must ramp up and down to balance the renewables' intermittent output. But in a system with large flexible, non-critical loads, these loads can also ramp up and down to balance generation.

Second, flexible, non-critical loads also reduce the need for energy storage and their associated losses. The ramping up and down of flexible demand is similar to the charging and discharging of energy storage in that it balances the misalignment between variable generation and everyday electricity consumption. We show this outcome in our Extensive Capture scenario, which has very high wind and solar capacity but relatively low energy storage, because the flexible DACS operation balances the wind and solar output.

Third, flexible electricity demand can also improve electric grid resilience. When the electric grid is struggling to produce enough electricity to meet total demand, it must either turn on new sources of power or turn off load (for example, in a worst-case scenario disconnecting electricity consumers against their will in forced outages). Most Texans observed this reality first-hand during the extreme winter weather event in February 2021, when millions of customers lost power for multiple days. However, in an electric grid with significant renewable capacity and non-critical loads, there is a higher likelihood that more energy generation will be available and that significant amounts of non-critical load can be shed to keep households, infrastructure, and critical loads online. While the resilience impacts of non-critical load were not directly captured in the model, more detail on resiliency measures that were included are available in Appendix F.

3.2 Electricity Generation

Figure 3.4 shows the increase in generation and the change in generation mix out to 2050 for all scenarios. Throughout each of the scenarios, some common themes appear. Even in the BAU scenario, all coal retires by 2035. In the net-zero scenarios, all coal retires by 2025. In the net-zero scenarios, because shutting down coal plants is one of the easiest ways for the model to reduce carbon emissions, this option is selected first. Coal retires in the BAU scenario due to market forces and declining costs of renewable generation.

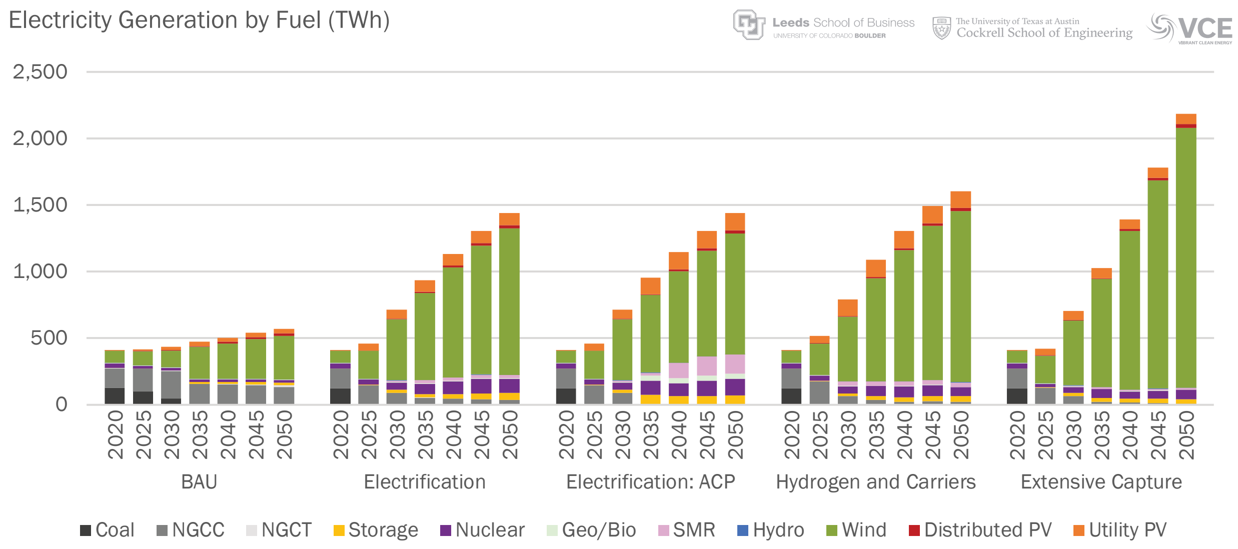


Figure 3.4: This plot shows the generation mix over time by scenario. The highest growth in generation occurs in the Extensive Capture scenario, with generation exceeding 2000 TWh in 2050, primarily to power DACS systems. For all scenarios, onshore wind experiences the highest growth across all generating technologies due to its favorable economics and vast resources, as well as its ability to better match ramping profiles with electrolyzers and DACS. Coal retires by 2035 in the BAU scenario due to existing market forces and by 2025 in all other scenarios. Natural gas generation declines, but some peaker plants remain in all scenarios except Electrification: Accelerated Clean Power. The highest growth in advanced generating technologies like SMR nuclear and enhanced geothermal is also seen in Electrification: Accelerated Clean Power to add firm generating capacity to a grid that will be fully decarbonized by 2035. Solar thermal was available but not chosen by WIS:dom-P for any scenario because of its relatively higher costs.

All net-zero scenarios except Electrification: ACP keep between 2 and 45 GW of natural gas generation (combined cycle, combustion turbine, and combined cycle with carbon capture) for firm capacity needs in 2050. The capacity factors of these power plants are low, but it is cheaper within WIS:dom-P to use them to match supply and demand in real-time (hour-by-hour) and use the DACS to reduce the carbon emissions at a later time (calculated on an annual basis) than other solutions. When the entire economy is constrained to net zero, some time periods (hours in this analysis) can be carbon positive as long as other periods are carbon negative. The scenario with the lowest amount of residual fossil generation is the Electrification: Accelerated Clean Power scenario because it must reach a net zero electricity sector by 2035, and DACS is still relatively expensive at that time. Figure 3.5 shows the installed capacities in 2050 for each scenario, including DACS, and their shares of generating capacity.

Figure 3.5: This plot shows the 2050 installed capacity of the different generating technologies in GW (left bars, top panel)) and capacity for electrolyzers and DACS (right bars, top panel) and the percent of total generation met by each technology (bottom plot). In the figure, NGCC is natural gas combined cycle, NGCT is natural gas combustion turbine, Storage is battery electricity storage, Nuclear is conventional nuclear, Geo/Bio is geothermal and biomass, SMR is small modular reactor nuclear, Hydro is hydroelectric, Wind is wind, Distributed PV is distributed solar photovoltaic or DPV, Utility PV is utility-scale photovoltaic or UPV, DACS is direct air capture and sequestration, and Electrolysis is the electrolysis used to produce hydrogen. DACS and electrolysis consume rather than generate power, and so are only present in the top panel of capacity. Each net-zero scenario installs greater wind, solar, and storage resources compared to BAU as well as substantial DACS capacity. All net-zero scenarios except Electrification: Accelerated Clean Power retain some natural gas capacity in 2050 because that is the only scenario requiring a fully zero-carbon grid, and the others keep the gas online for firm generation. Instead of natural gas, Electrification: Accelerated Clean Power use enhanced geothermal and SMR nuclear in addition to conventional nuclear and storage for firm generation.

In general, the model favors the deployment of wind, with some solar and storage as well. Small amounts of SMR nuclear appear in all net-zero scenarios, but it mostly plays a role in the Electrification: Accelerated Clean Power scenario, where capacity exceeds 18 GW. This scenario is also the only one where enhanced geothermal power plants are built. The accelerated grid-decarbonization timeline in this scenario requires rapid deployment of all available technologies by 2035. Based on the cost assumptions used for this analysis, advanced generation technologies (e.g., SMR nuclear and enhanced geothermal) are not cost competitive until after 2035 so do not contribute to pre-2035 decarbonization in this scenario. However, after 2035 when their costs have declined, they are deployed to provide additional firm, dispatchable generation. Besides storage and both conventional nuclear, the other net-zero scenarios all retain some level of natural gas to provide firm generation, but Electrification: ACP does not because it is a fully zero-carbon grid. If SMR nuclear or geothermal technologies see faster cost declines than the model anticipates, then presumably their deployment would happen more quickly than shown here.

Renewables and Storage

In general, wind is consistently found to be the cheapest and most popular option for a vast preponderance of decarbonization for each scenario. Even in the BAU scenario, wind makes up about 60% of total electricity generation (primarily for economic reasons as it is a cheap form of power to install) and close to 90% in the Extensive Capture scenario, though the absolute numbers are much higher in the Extensive Capture scenario (1.9 million gigawatt hours) than the BAU (0.3 million gigawatt hours).

Though solar lines up well with current peak system demands in ERCOT, electrifying transportation, heat, hydrogen production, and the use of large amounts of DACS has the impact of spreading out higher loads to more hours of the day. In general, wind is more available for more hours of the day than solar, making it a more advantageous power source for flexible demands such as hydrogen production, DACS, and electric vehicles. In contrast, solar is only available for a limited number of hours during the day, and more DACS and electrolysis capacity would have to be built to utilize that energy to create the same amount of hydrogen and capture the same amount of carbon dioxide if the grid were solar dominated. Even during times of low wind speeds, a very large wind fleet can still produce high amounts of electricity.

Despite the large amount of wind capacity developed in our model, the geographic area served by ERCOT has additional undeveloped wind resources. One application for these wind resources could be exporting clean electricity to other states and Mexico. One report makes a similar proposal for Australia, another renewables-rich country with significant potential to export clean electricity.[185]

Though the growth in wind is most striking, all renewables, grid-scale storage, and nuclear experience growth out to 2050 (Figure 3.6). Utility-scale solar grows almost 3,000% compared to 2020 values in the Electrification and Electrification: Accelerated Clean Power scenarios. Interestingly, distributed solar resources in each net-zero scenario and BAU grow by the same amount out to

2050. In all the scenarios, additional load to the utility load (e.g., DACS and hydrogen production via electrolysis) is significantly larger compared to the increase in load due to electrification in the distribution grid. As a result, WIS:dom-P builds much more utility-scale generation in order to meet this load; it is cheaper to use this large utility-scale generation along with distributed storage to meet the load rather than build additional distributed solar. Compared to the BAU scenario, distribution system costs are reduced slightly in Electrification and Electrification: Accelerated Clean Power and substantially reduced in the Hydrogen and Carriers scenario as WIS:dom-P uses the utility-scale generation along with distributed storage to optimize the distribution system.

Storage grows the most in Electrification: Accelerated Clean Power to support a grid that has greater renewable resources deployed earlier to reach zero-emission by 2035. In this scenario, WIS:dom-P deploys long duration storage on both the utility and distribution grids between 2030 and 2035 to meet the zero-carbon goal for the electricity sector. The long duration storage is needed to meet demand during periods of low wind generation, which can last multiple days. No new storage (energy capacity) is added after 2035 in this scenario as electrification, in addition to deployment of DACS, provides enough flexible demand to work with the existing storage on the grid and ensure the installed generation can meet load during periods of high system strain. In the BAU scenario, about 75% of the storage is installed on the distribution grid to optimize the distribution grid with utility-scale generation. In the net-zero scenarios, however, storage power and energy capacities are almost equally divided on the distribution system and the utility-grid.

For all scenarios, almost all the new storage installed after 2025 is installed on the distribution network. The reason for this is that storage behind the 69-kV substation works along with other distributed energy resources (DER), such as distributed photovoltaic (DPV) and demand-side management (DSM), to not only reduce the peak power passing through the utility-scale and distribution-system interface, but also reduces the total energy crossing the interface. As a result, upgrades to the distribution system from increasing demand can be deferred or are completely eliminated. In addition, due to less energy crossing the utility-distribution interface, the wear and tear on the distribution infrastructure is reduced, thereby further reducing costs. This co-optimization helps reduce electricity system costs as well as retail rates.

Advanced generation resources like enhanced geothermal systems (EGS) and SMR nuclear have the highest growth rates in Electrification: ACP to help provide zero-carbon firm generation after 2035. The other net-zero scenarios see some growth in SMR nuclear (generating between 11 and 34 TWh in 2050), but most of the growth in nuclear for these scenarios is conventional nuclear (Figure 3.4). Besides SMR nuclear, zero EGS is built in the other three net-zero generation scenarios investigated, and neither option is built in BAU. As such, Electrification: Accelerated Clean Power has the most diverse energy generation mix by 2050 compared to the other scenarios and the lowest percentage of wind generation in 2050 after BAU (see Figure 3.5). Given the rapid decarbonization of the electric grid in this scenario, there is a need for cleaner electricity sooner and faster. Existing technologies are deployed quickly to reach the 2035 goal, and advanced options come online after 2035 to provide firm, dispatchable generation when their costs decline. The other net-zero scenarios do not have a zero-carbon grid and can retain some natural gas for firm generation in addition to storage and nuclear, but Electrification: ACP relies solely on zero-carbon options. In Electrification: Accelerated Clean Power, more SMR nuclear capacity is projected compared to EGS because of SMR nuclear's higher energy density and greater flexibility compared to EGS. Both conventional and SMR nuclear are built in some scenarios to take advantage of the different ramp rates, with SMRs having higher ramp rates than conventional.

Grids with high levels of variable renewable electricity generation can encounter challenges managing the variability of resources like wind and solar. These challenges, as well as costs, can increase nonlinearly as variable renewable resources approach 100% of generation.[186,187] Part of the reason for increased system costs is the overbuilding of renewable resources to ensure sufficient power during periods of low resource availability. This overbuilding can lead to high levels of curtailment when the wind or solar resource is high, lowering overall utilization rates.[187] Even so, transmission, storage and flexible demand can be used to mitigate the amount of overbuilding that is needed.

Figure 3.6: This plot shows the changes in resource capacities out to 2050 for all five scenarios, with 2050 capacity compared to the 2020 historical baseline for onshore wind, nuclear (both conventional and SMR), utility-scale photovoltaic (Utility PV, or UPV) solar, distributed photovoltaic (Distributed PV, or DPV) solar, geothermal and biomass (Geo/Bio), and storage. Nuclear, storage, and all renewables see strong growth in each net-zero scenario. The exception is geothermal, which only sees substantial capacity growth in the Electrification: Accelerated Clean Power scenario, where it is used to support a zero-carbon grid with firm generation. The zero-carbon grid is also why the same scenario sees the highest growth in storage capacity. The growth in distributed solar is equivalent between all scenarios because Distributed PV achieves optimal growth in Texas under BAU conditions; there is higher utility-scale demand in the net-zero scenarios, prompting the model to install more utility-scale resources rather than distributed. Nuclear capacity grows in all net-zero scenarios. The 2020 storage baseline is less than 0.5 GW.

Though the growth rates in all net-zero scenarios are high, Texas has a proven track record of scaling rapidly. Solar installations in Texas doubled between 2019 and 2020, and nearly doubled again between 2020 and 2021.[188] Production in the Permian Basin nearly quintupled for oil and quadrupled for gas in a single decade between 2012 and 2022.[189] These recent examples show that Texas is well-positioned to handle steep growth curves, particularly in the energy industry.

Given the steep growth curves and rapidly changing technology landscape, the actual future generation mix in Texas will likely look different from our scenarios. As of February 2022, the ERCOT queue already has over 52 GW of storage and 105 GW of solar, exceeding many of the 2050 estimates in the net-zero scenarios.[190] The interconnection queue for ERCOT also shows another 21 GW of wind in some stage of development over the next few years, which is very rapid, but a bit slower than the pace necessary for the net-zero scenarios as analyzed here. WIS:dom-P builds out the least-cost power sector while ensuring net-zero emissions by 2050; it does not consider any other reasons for building or not building resources. In practice, Texas might choose different technologies for different reasons. For example, Texas might choose not to build out any further nuclear generation, but this analysis does not take any political or social limitations into account for generating technologies. Additionally, part of the reason wind generation sees such astounding growth in these scenarios is its ability to pair well with the electric DACS systems in this analysis (see Section 3.4), but Texas might choose to develop a different portfolio of carbon mitigation strategies and removal technologies in the future. The same can be said for hydrogen production; this analysis assumes that production will shift from steam methane reforming to electrolysis, but alternative pathways or a mix of pathways might be used in practice. Both technology choices and political and social pressures will affect the future generation mix.

Table 3.1 shows the curtailment rates for each scenario in 2050. Interestingly, the BAU scenario results in the highest level of curtailment, with almost 17% of total wind and solar energy curtailed. The other scenarios have less curtailment because the additional electric loads and DACS provide more demand-side flexibility to the grid. However, these scenarios would likely also see high levels of curtailment if demand were not as flexible.

Firm low-carbon generation, like SMR nuclear, EGS, or natural gas with CCS, can obviate the need for overbuilding renewables and provide clean electricity during periods of low renewable resource availability. Deploying these technologies can help mitigate the risks of high renewable penetration and potentially lower costs. Further, research has also found that firm generation can also reduce total system costs of net-zero electricity systems.[191,192]

Table 3.1: Percent of total generating resources curtailed in 2050 by scenario*

	Wind	DPV	UPV
BAU	11.1%	2.8%	3.0%
Electrification	0.2%	0.3%	0.2%
Electrification: ACP	0.1%	0.1%	0.1%
Hydrogen and Carriers	0.2%	0.4%	0.3%
Extensive Capture	0.1%	0.2%	0.1%

**Within WIS:dom-P, DPV is allowed to be curtailed similar to UPV if it cannot be used to charge distributed storage or meet load.*

All scenarios in our analysis retain some firm generation, either in the form of natural gas plants or advanced generation. Texas has about 100 GW of firm generation capacity in 2020, comprised of coal, natural gas, hydropower, geothermal, and conventional nuclear. Firm capacity declines to varying degrees by 2050 in all scenarios, but is supplemented with gains in storage capacity. Firm generating capacity and storage are both dwarfed by renewable (wind and solar) capacity by 2050 in the net-zero scenarios. Wind represents up to 90% of the generation mix in the net-zero scenarios, with much of it used to power DACS systems that are better able to ramp to match the wind generation profile than solar in WIS:dom-P. The use of DACS to improve wind utilization combined with low-cost Texas wind power might abate some of the negative impacts of high shares of renewable generation. Firm generation capacity, wind and solar capacity, and with peak load (with and without DACS or electrolyzers for hydrogen production) in 2050 for all scenarios is presented in Table 3.2.

Table 3.2: Firm and VRE capacity, storage, and peak load in 2050, by scenario

Scenario	2050 Firm Generating Capacity (GW)	2050 Storage Capacity (GW)	2050 Wind and Solar capacity (GW)	2050 Peak Load without DACS or Electrolysis (GW)*	2050 Peak Load with Dacs and Electrolysis (GW)
BAU	64	24	145	100	100
Electrification	63	57	380	148	320
Electrification: Accelerated Clean Power	42	79	350	164	304
Hydrogen and Carriers	45	44	455	121	358
Extensive Capture	27	43	600	104	495

**state-wide peak load including all end-use sectors*

One of the biggest differences in this study and other net-zero studies is the lower amount of firm generation left by 2050, which is a result of the large amount of DACS that is also deployed. Most of the DACS load is met by wind power given that wind is generally available for more hours of the day than solar PV. However, because the DACS is also flexible, it can turn off during times of high demand and even if wind capacity factors at that time are low, the large amount of installed wind capacity on the system still produces a large amount of power. This arrangement allows the system to remain stable even with lower levels of firm generation resources. See Appendix F for further detail.

It is possible that assuming different future price curves for technologies would result in other technologies, such as more natural gas with carbon capture would be chosen instead. However, these technologies would still need DACS to take care of any fugitive upstream emissions and the residual emissions that are not captured with the CCS equipment. Geothermal or EGS might be able to provide firm, zero-carbon generation as well as industrial heat, though this connection was not modeled in WIS:dom-P.[68]

Transmission

As demand for electricity grows, additional transmission will be required to deliver the power to residential, commercial, and industrial customers. The WIS:dom-P model adds to existing transmission as required for optimal capacity expansion and dispatch. All transmission added is modeled as new construction, therefore actual transmission costs could be lower than modeled if existing transmission pathways can be upgraded. Transmission build outs include inter-region (between the ten regions modeled) and in-region (within an individual region). Within WIS:dom-P, the ERCOT region of Texas is allowed to build transmission and access generation in the non-ERCOT regions of Texas.

In all scenarios, the majority of the inter-region transmission buildout happens in the High Plains region (frequently called the 'panhandle' of Texas) primarily to bring wind generation to the Northwest and Metroplex regions, but also to power installed DACS systems (see section 3.5 for land use details). Substantial transmission is also built connecting the Gulf Coast, Central and Capital regions to bring power to load centers in Austin and Houston. Inter-region transmission buildout in all scenarios follow a similar trend, with only a 10% difference between scenarios by 2050 (all between 4,800 and 5,800 GW-miles). The lowest inter-region transmission buildout occurs in the Extensive Capture, and the largest buildout occurs in Electrification.

The BAU scenario adds the least amount of in-region transmission adding 5,729 GW-miles of new transmission by 2050. The Extensive Capture scenario adds the most (32,974 GW-miles) because this scenario installs the most generation to power DACS. The two electrification scenarios install approximately the same amount of in-region transmission at 19,000 GW-miles because renewable generation is added to meet electrified loads as well as power DACS. The Hydrogen and Carriers scenario installs slightly more, 23,233 GW-miles, to connect renewable generation to both electrified load centers and hydrogen and synthetic fuel manufacturing facilities. For more detail on transmission build out, please see Appendix F.

Power Sector System Costs and Electricity Rates

Under BAU conditions, system costs for the power sector change only slightly over time as capacity undergoes turnover, with the older fossil generation replaced with new variable renewable generation. System costs are $30 billion in 2020 and drop to their lowest value of $29 billion in 2030 because most of the coal generation is retired along with some of the older natural gas combined cycle (NGCC), natural gas combustion turbine (NGCT) and nuclear generation. System costs rise again after 2030, reaching $32.6 billion in 2050. In contrast, all net-zero scenarios see a rapid rise in total electricity sector costs because of increasing end-use electrification and the addition of DACS. Extensive Capture has the highest total system cost by 2050 of all scenarios because it deploys the most DACS of all scenarios. The Electrification scenario results in the lowest system cost of all the net-zero scenarios, while Hydrogen and Carriers, which initially (2025) has the highest system costs as it builds out the infrastructure needed for producing hydrogen and other synthetic fuels, ends up costing less than Extensive Capture.

Retail rates were calculated assuming the cost of installing and powering the DACS is spread out over all electric customers. In the BAU scenario, the retail rates fall about 1.4 ¢ per kWh by 2050. The largest increase in retail rates is in Extensive Capture, where the retail rates increase about 5.6 ¢ per kWh by 2050 as a result of the large DACS deployment. The Electrification scenario has only a modest increase in retail rates, with retail rates rising 0.2 ¢ per kWh by 2050, as electrification and decarbonization of the electricity sector reduces the need for DACS deployment and the excess generation needed to power it. Electrification: Accelerated Clean Power results in a short-term spike in retail rates in 2035 as a result of 100% decarbonization of the grid by 2035, but the retail rates reduce again after 2035 for a total net increase of 0.6 ¢ per kWh by 2050. This also shows that earlier decarbonization goals in Texas might not have a drastic increase in cost to the customer in the longer term. The Hydrogen and Carriers scenario results in the largest reduction in retail rates of all scenarios, falling 2.5 ¢ per kWh by 2050. Hydrogen and Carriers sees the lowest retail rates because it minimizes the need for DACS and spreads investments in all sectors of the economy that it aims to decarbonize, resulting in lower burden for electricity sector customers. More information on power sector costs and retail rates can be found in Appendix F.

3.3 Economic Impacts

All four net-zero scenarios see economic benefits compared to the BAU. Economic impacts were split into four categories: the power sector, the fuel sector, the non-energy industries, and emission costs. The power sector includes any impacts related to electricity generation and distribution; the fuel sector includes any impacts related to the production of non-electric fuels (such as oil, gas, and hydrogen); non-energy industries refers to all other industry categories (i.e. non-power sector and non-fuel sector, such as steel and cement); and emission costs refer to economic impacts associated with greenhouse gas and criteria pollutant emissions.

To calculate the overall economic impacts, we used a two-step process: 1) impacts to the Texas economy including the power sector, fuels sector, and non-energy industry were calculated using the REMI modeling platform by the team at The University of Colorado Boulder (full REMI results available in Appendix E), and 2) the cost of emissions was calculated by the UT Austin team and incorporated with REMI results. These emission costs are substantial and typically left out of economic analyses. Emission costs include those for CO_2e using the Social Cost of Carbon (SCC) with a starting value of $50 per metric ton and 3% discount rate.[193] The marginal costs of criteria pollutant emissions (SO_2, NO_x and $PM_{2.5}$) were calculated using the Estimating Air pollution Social Impact Using Regression (EASIUR[194–196]) reduced-form air pollution model and incorporated with REMI results. Marginal emission costs were calculated on a regional basis for the power sector and state-wide for the rest of the economy due to the differing scales of WIS:dom-P and TX-EPS. Costs for CO_2e emissions, while borne globally, were incorporated into Texas GDP estimates as a way to internalize to state GDP a global externality of Texas industrial activity. Though the mechanisms might vary, it is unlikely that emissions will be able to continue into the future without consequence, so pricing these emissions into our analysis acts as a proxy for that expected reality.

All of the net-zero scenarios call for an increase in capital expenditures in Texas, which subsequently increases economic activity in Texas. Some scenarios also enable a decrease in operating expenditures, which might mean lower operational costs for consumers but also reduces economic activity in Texas. However, a decrease in customer rates is a reduction in costs for utility customers, which would free up money to facilitate additional spending in other industries. These competing effects are non-obvious, so data were analyzed collectively to consider if the scenarios provide a *net* economic benefit to Texas. Given that Texas is rich in native energy production (wind, solar, oil, gas, and coal), it experiences a more significant economic impact with changes in energy production compared to other states that have fewer natural energy resources. Figure 3.7 shows the net impacts to GDP compared to BAU.

The Hydrogen and Carriers scenario sees the highest relative benefits, primarily due to a growing electyrolysis industry that helps offset losses that occur from declining production and consumption of fossil fuels. Essentially, the Hydrogen and Carriers scenario fares the best among the scenarios mostly because the energy sector's picot would be easiest with that trajectory; the hydrocarbon industry would become more of a hydrogen and carbon management industry. Texas GDP in the Hydrogen and Carriers scenario is 7.9% higher in 2050 than the BAU scenario. Because this scenario shows substantial economic benefits while retaining much more space for the incumbent energy industry's fuel sector, it looks like an appealing low-carbon pathway for the Texas economy.

Similarly, the Extensive Capture scenario benefits from maintaining the status quo within the energy industry and investing heavily in DACS; the Extensive Capture scenario sees the second-highest benefits to GDP (2050 GDP is 4.6% higher than BAU). Even so, all scenarios have trade-offs, and the economic and distributional equity dimensions of a shrinking fossil fuel industry should not be ignored. These dimensions are discussed further in Section 3.6.

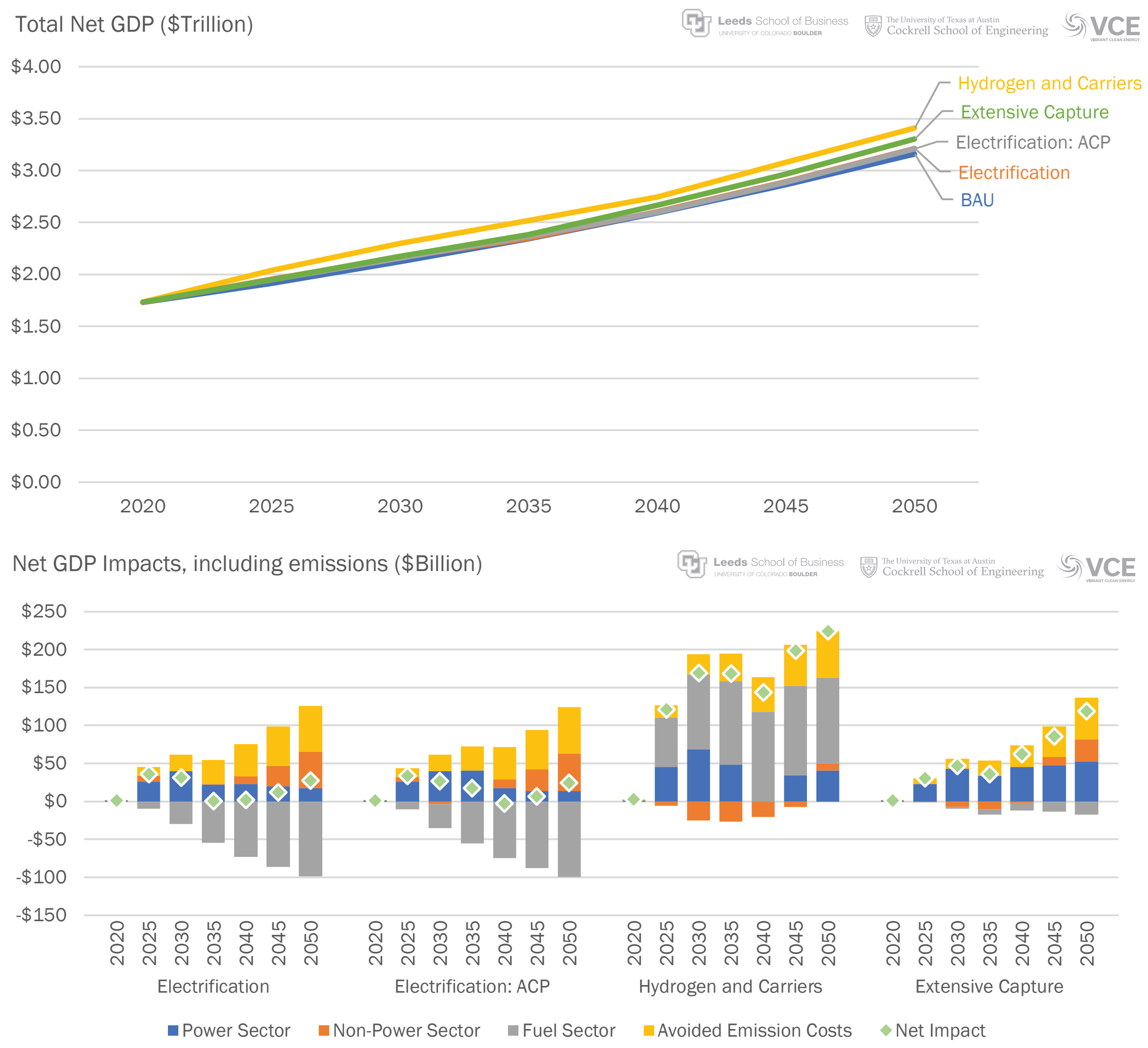


Figure 3.7: This plot shows the total net GDP by scenario, including economic impacts for the power sector, the fuel sector, the non-energy industries (top panel), and a breakdown of relative impacts by sector for each scenario (bottom panel). Net GDP is higher in all net-zero scenarios compared to BAU. Across all net-zero scenarios, benefits from lower emission costs (relative to BAU) offset negative impacts from decreased economic activity in the non-energy industry or fuel sectors, leading to net economic benefits overall. Net-zero scenarios also see increased economic activity in the power sector. The Hydrogen and Carriers scenario sees substantial economic benefits compared to the BAU scenario, primarily due to increased activity in the fuel sector from a growing electrolysis industry. The Extensive Capture scenario sees net benefits as well, mostly due to spending on a large DACS build out in the power sector, which offsets slight losses in the fuel sector from lower fossil fuel production for power generation. Benefits from lower emission costs in the Electrification and Electrification: Accelerated Clean Power (ACP) scenarios offsets the economic losses from the fuel sector, which sees negative impacts from the decline of fossil fuel consumption and production without the commensurate benefits of growth in alternative fuel production, as in the Hydrogen and Carriers scenario. Note that 2020 GDP differs about 4% from the Bureau of Economic Analysis estimates as REMI internally calculates baseline (BAU) GDP.[104]

Even if the value of avoided emission costs are ignored, both the Hydrogen and Carriers and Extensive Capture scenarios still see net economic benefits, with average annual GDP 4.9% and 1.4% higher than BAU, respectively. The Hydrogen and Carriers scenario has an average net economic benefit of $122 billion to the state of Texas compared to the BAU scenario and adds 766,000 jobs over the 30-year horizon, driven by extraordinary capital investment in the power sector and increased fuel sector revenue (primarily for electyrolysis) compared to the other scenarios. Extensive Capture sees the second-largest positive impact (average $34 billion benefit and 204,000 additional jobs above BAU), primarily driven by investment in the power sector. The Extensive Capture scenario assumes BAU conditions with all emissions abated through capture technology or power sector decarbonization, so the energy industry and fuel production remain about the same (other than the slightly decreased fossil fuel production due to a more renewables-heavy grid), but the renewable power sector and carbon capture industries grow on top. While the large build out of DACS increases electric retail rates for consumers, DACS benefits from low electricity prices (WIS:dom-P assumes DACS can purchase electricity at the marginal cost) that drive down the overall cost of capture (see Section 3.4); if Texas uses a different DACS technology or capture prices are higher, operating costs would likely be higher and mute the benefits of power sector investment in this scenario.

Texas 2050 GDP in both the Electrification and Electrification: Accelerated Clean Power scenarios is 1.6% higher than BAU. If the economic costs of emissions are ignored, GDP in these scenarios is 0.6% lower in 2050 than in BAU. These scenarios both see net benefits to the power sector and non-energy industries that are offset by losses from decreased fossil fuel production. For this analysis, volumetric fuel production is assumed to decrease commensurate with decreased domestic consumption within Texas; each barrel of oil no longer consumed in state means one less barrel of oil would be produced. However, for this analysis, exports were assumed to stay constant at BAU levels in all scenarios. Realistically, it is possible that exports will fall in the future if the market for fossil fuels dwindles in a net-zero world (there are already high-profile export deals that did not come to fruition because of environmental concerns by overseas customers). In that case, the BAU reference might be overly bullish; if the fuels sector is set to shrink anyway, that would change the conclusions about the net effect of the electrification scenarios. It's also possible that exports would increase to fill the gap of declining domestic production. In that case, the electrification scenarios would yield significant economic benefits over BAU. Further, these two scenarios see the greatest social benefits from reducing emissions.

The net-zero scenarios see substantial reductions in the cost of CO_2e emissions economy-wide, though these costs are not included in the GDP estimates. Our energy system has multiple environmental impacts on land, air, and water. Greenhouse gas emissions are no exception. The cumulative costs from these impacts can be significant. However, they are often borne external to the market (that is, the environmental damages to ecosystem or public health show up in health care premiums, taxes, lost economic productivity, etc. but are not directly part of the transactions for purchasing energy) and thus are considered market externalities.

Because of the immediate risk posed to human health, air pollution impacts have received significant regulatory attention with bipartisan support for more than 50 years. These emissions historically have focused on criteria pollutants that cause acid rain, smog, and other near-term local or regional risks and particulate matter, which causes significant harm to human health.[197] More recently, emissions concerns have expanded to include greenhouse gas emissions, whose impact is usually significantly delayed many years from the time of release into the atmosphere and whose impacts are not necessarily in the same geographic location as the emissions.

Decarbonizing the energy system will change the nature of these impacts. In particular, reducing greenhouse gas emissions will provide commensurate environmental co-benefits from reductions in emissions of other pollutants and reduced water use, but with a trade-off of increased surface land use. The environmental consequences of changes to land- and water-use are discussed in Section 3.5, though most of this analysis focuses on air emissions. Estimated emission costs for all scenarios are presented in Figure 3.8.

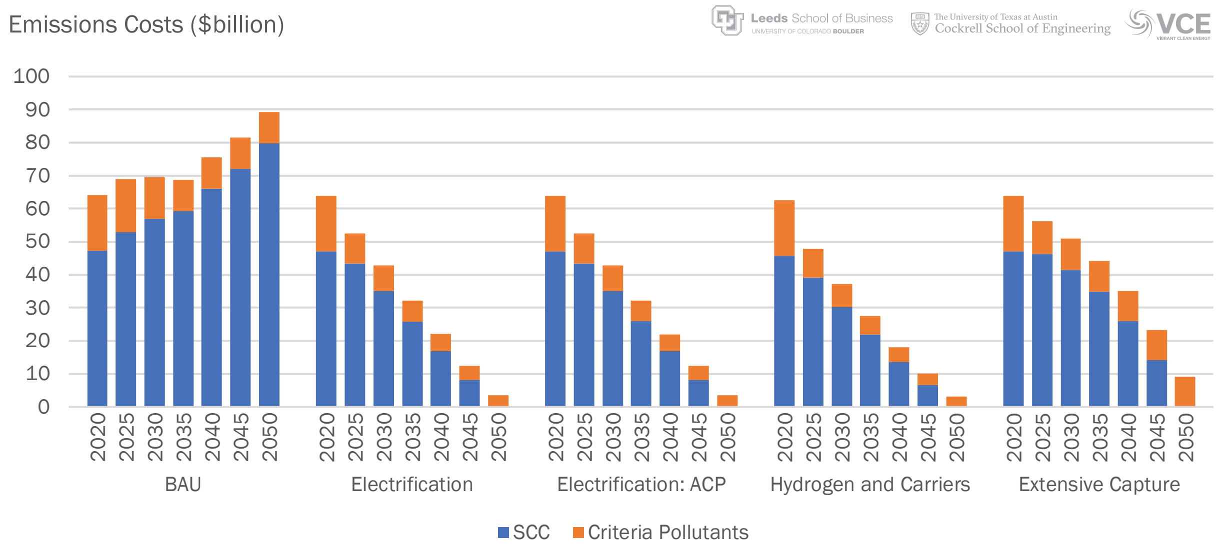


Figure 3.8: This plot shows the cost of economy-wide emissions costs for each scenario. Emissions costs includes mortality and morbidity impacts of criteria pollutant emissions (SO_2, NO_x, and $PM_{2.5}$) and the social cost of carbon (SCC). Criteria emissions decrease in all scenarios, including BAU, as the grid decarbonizes, but carbon equivalent emissions continue to increase unabated in the BAU scenario.

Some of the biggest impacts from decarbonizing the Texas economy are the reductions of greenhouse gas emissions from 930 mmt CO_2e a year to net-zero by 2050. In 2050, emissions from the BAU scenario cause almost $90 billion in damages, rising from approximately $60 billion in 2020. Cumulatively, the BAU scenario generates about $2.3 trillion in damages across the 30-year time horizon compared to $0.9-1.3 trillion for the other scenarios. Hydrogen and Carriers scenario has the lowest cumulative emission costs and Extensive Capture the highest, while both Electrification and Electrification: Accelerated Clean Power cause cumulative damages around $1 trillion each.

While preparing for a declining fuels sector and ensuring the sector's ability to pivot (e.g. in the Hydrogen and Carriers or Extensive Capture scenarios) has significant economic benefits, reducing emissions from BAU levels also provides substantial economic benefits that might offset the negative impacts from a shrinking fuel sector. All scenarios have associated emission costs, but because the net-zero scenarios reduce emissions, they save money relative to BAU in later years.

Also worth noting is that the costs of criteria pollutant emissions might actually be larger than presented in this analysis. Health impacts from air pollution are cumulative and tied to background concentrations, making them dependent on chemical transport of the different pollutants and highly localized. Criteria pollutant emissions in this analysis were determined by region in WIS:dom-P and state in the TX-EPS and costs estimated using the reduced-form EASIUR model, which might underestimate costs slightly relative to more detailed models.[194] Previous studies have also found the co-benefits of reduced greenhouse gas emissions to be the same or greater than the benefits of reducing the greenhouse gas emissions themselves.[198,199] Underestimating these costs might unintentionally under-represent some of the benefits of the net-zero scenarios, particularly Electrification, Electrification: Accelerated Clean Power, and Hydrogen and Carriers, which reduce emissions from non-power sectors in addition to the power sector. Future work should investigate the criteria pollution co-benefits of the net-zero scenarios in greater detail.

Impact to Employment

Average annual impacts to total employment for the net-zero scenarios are smaller than those to GDP but follow similar trends. Average annual impact to total employment is low for both the Electrification and Electrification: Accelerated Clean Power scenarios. The primary difference between these two scenarios is that, in the latter, the grid is fully zero-emission by 2035, resulting in slightly greater decreases in fossil fuel production and fuel sector employment than in the Electrification scenario. There is also greater investment in the power sector in 2035 in the Electrification: Accelerated Clean Power scenario for the rapid build out of renewables to achieve said zero-emission grid. The Hydrogen and Carriers scenario sees the largest positive impacts to total employment, mostly from growing hydrogen production in the fuels sector.

A recent study modeled the energy workforce during a net-zero energy transition and found that, in aggregate, gains in low-carbon resource sectors offset losses in fossil fuel sectors.[200] The same study also found that, under their net-zero conditions, there was no net job loss in Texas over time; the Texas energy workforce starts out in 2020 as about 80% oil & gas positions and gradually shifts to 80% low-carbon jobs by 2050, primarily concentrated in the grid, wind, and solar sectors, with some natural gas and oil jobs retained. Those results are similar to those presented here.

All net-zero scenarios see net employment benefits from the non-energy industries except the Hydrogen and Carriers scenario. The Electrification and Electrification: Accelerated Clean Power scenarios see the highest employment benefits in the non-energy industries likely due to increasing electrification throughout the economy as well as construction growth to support the net-zero transition.

Power sector employment sees net average growth compared to BAU across all net-zero scenarios and all regions save for the Central region in the Electrification: Accelerated Clean Power scenario. Across all scenarios, power sector employment benefits are primarily concentrated in the Metroplex and Gulf Coast regions, which have the two largest economies of the ten regions. Power sector employment benefits are highest in the Hydrogen and Carriers scenario likely because this scenario sees the greatest increase in generation. Power sector employment benefits in the Extensive Capture scenario primarily derive from the substantial DACS build out in this scenario combined with increasing generation to support the DACS systems, while power sector employment impacts in the Electrification and Electrification: Accelerated Clean Power scenarios experience this combined effect to a slightly more modest effect.

Within the power sector, industry-specific employment impacts can be approximated from WIS:dom-P results. Though the REMI analysis did not include industry-specific employment impacts, the WIS:dom-P model conducts its own estimates of employment impacts within the power sector (see Appendix F for more detail). Power sector investment and spending determined by the WIS:dom-P model were used as input for the REMI analysis, so WIS:dom-P employment results can be reasonably compared to those from the REMI analysis. WIS:dom-P employment impacts are presented in Figure 3.9.

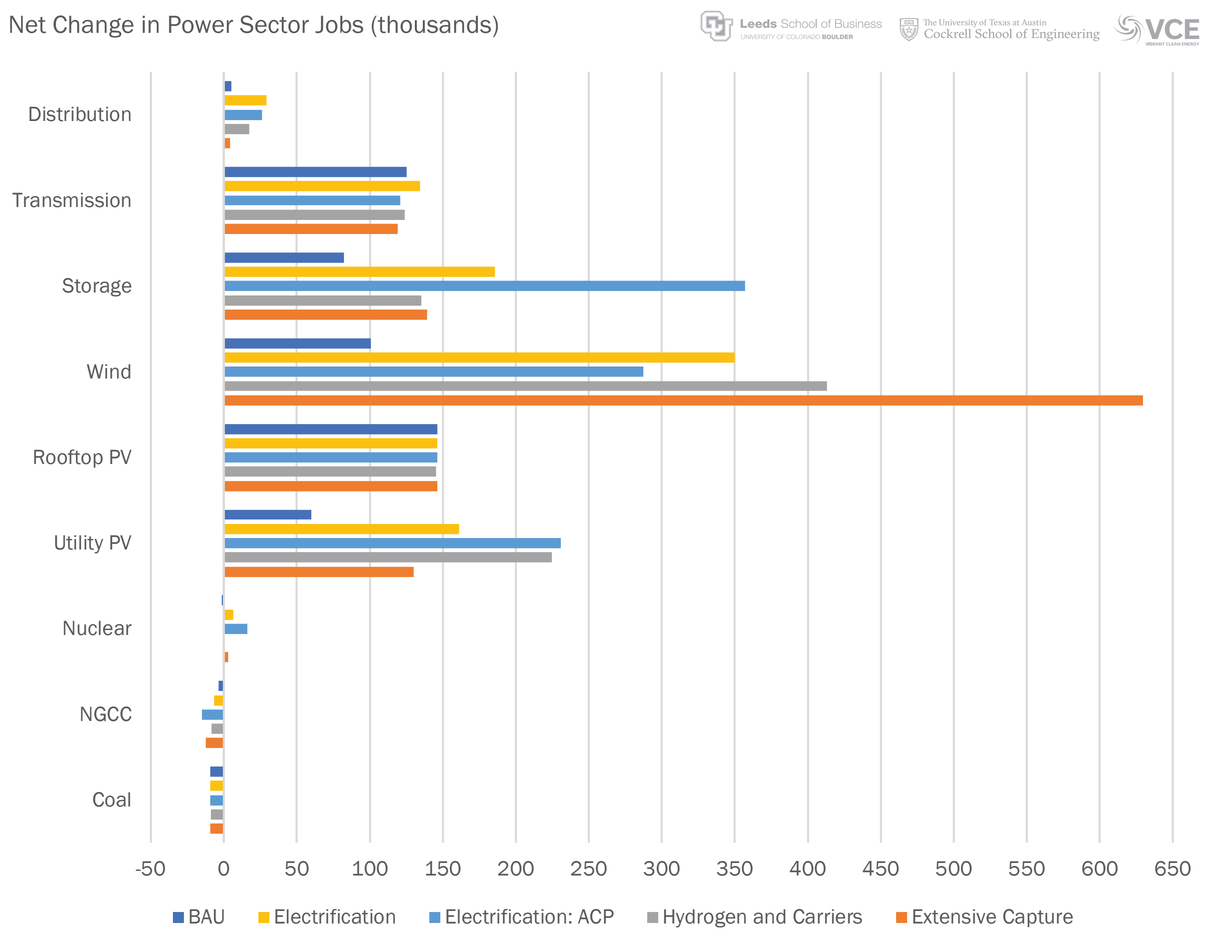


Figure 3.9: This plot shows estimates of industry-specific net employment impacts by 2050 in the power sector by the WIS:dom-P model (separate from REMI analysis). Wind sees the highest job growth over the time horizon, with storage, solar (Rooftop PV, or DPV, and Utility PV, or UPV), and transmission also seeing net benefits. Coal and natural gas (NGCC) power plant operators see net job losses. Storage jobs grow the most in the Electrification: Accelerated Clean Power scenario as the most storage is built in this scenario to aid with the large portion of variable renewables on the grid.

Wind, solar, storage, and transmission see the greatest employment growth within the power sector across all scenarios, including BAU, but growth in these industries is even greater in the net-zero scenarios. Employment growth within the power sector follows growth in generating technology on the grid. Wind-related jobs grow the most in the Extensive Capture scenario, which depends on wind generation more than other scenarios. Employment impacts are equivalent across all scenarios for distributed solar (DPV) because DPV generation grows the same amount across all scenarios (See Figure 3.6). Growth in grid-level storage employment is the highest in the Electrification: Accelerated Clean Power scenario because this scenario builds out substantial storage capacity to support a high-renewables grid. Though all net-zero scenarios see substantial growth in both renewable generation and solar, Electrification: ACP sees the most renewable generation due to its zero-emission grid by 2035. Coal and natural gas employment in the power sector see moderate declines across all scenarios, but most of the employment losses associated with declining fossil generation are associated with extraction and are felt in the fuels sector.

3.4 Emissions Reductions

Texas economy-wide greenhouse gas emissions, expressed in terms of CO_2 equivalent (CO_2e), include carbon dioxide (CO_2), methane (CH_4, GWP of 28), nitrous oxide (N_2O, GWP of 265), and fluorinated gases (F-gases, emissions directly estimated as CO_2e in the TX-EPS) for this analysis.[201,202] Under BAU conditions, total net emissions in Texas, including the effects of carbon sinks from land use, rise from about 930 million metric tons CO_2e in 2020 to about 950 mmt in 2050. For all other scenarios analyzed here, net emissions reach 0 in 2050. However, gross aggregate emissions (i.e., those before land sinks and carbon capture or removal options like CCS and DACS), remain above zero in 2050 for all scenarios and range between 240 mmt for the Hydrogen and Carriers scenario and 920 mmt for Extensive Capture. Figure 3.10 shows the total economy-wide carbon dioxide equivalent emissions for each scenario, net and aggregate.

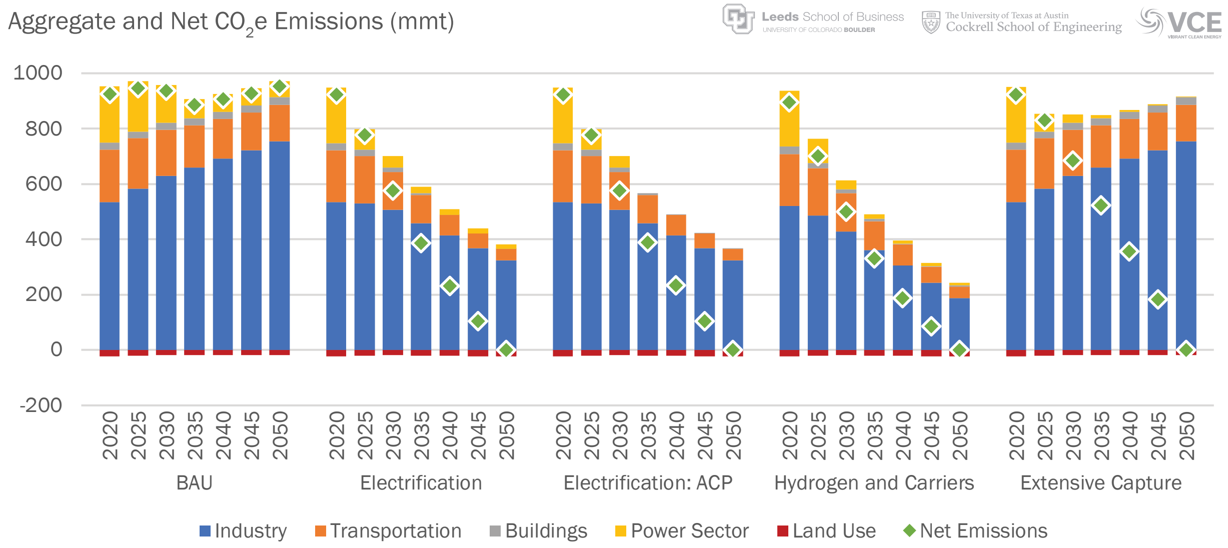
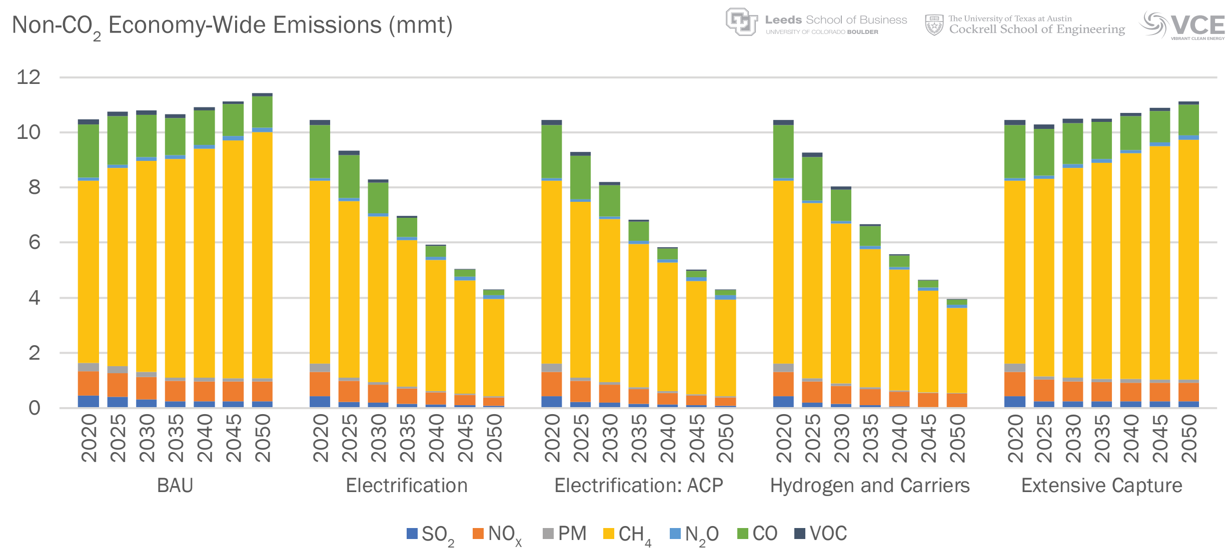


Figure 3.10: This plot shows the net CO_2e emissions (i.e., including the effects of land sinks and carbon removal, top plot) and aggregate CO_2e emissions (i.e., not including land sinks and carbon removal, bottom plot) by sector. Power sector emissions decline for all scenarios, including the BAU, but only reach zero in the Electrification: Accelerated Clean Power scenario. Non-power sector emissions increase out to 2050 in the BAU scenario. Non-power sector emissions rise between 2020 and 2025 in the Extensive Capture scenario because DACS technology is still scaling up and power sector emissions decrease enough to satisfy glide slope constraints. Emissions fall fastest in the Hydrogen and Carriers scenario, likely due to increased electrolysis fuel use in industry for hydrogen production. Throughout the scenarios, industry has the largest share of remaining aggregate emissions before land sinks and carbon removal technologies. Industrial emissions include those from agriculture, oil & gas extraction and production, and industrial process emissions.

Under BAU conditions, economy-wide emissions increase out to 2050 even as power sector emissions decline. Driven by technology advances and cost declines, BAU power-sector carbon emissions decrease 70% between 2020 and 2050 with no new policy interventions. Transportation sector emissions also decrease out to 2050 in the BAU scenario due to existing trends in fuel efficiency gains and electrification. The growth in industrial emissions outweighs the decline in other sectors, causing economy-wide CO_2e emissions to rise overall. In particular, methane emissions grow approximately 35% out to 2050 in the BAU scenario, primarily due to increasing industrial activity. Methane emissions also increase in the Extensive Capture scenario, while they fall by approximately 50% across all other net-zero scenarios. Non-CO_2 emissions, both economy-wide and from the power sector specifically, are included in Figure 3.11.

In contrast to CO_2e emissions, criteria pollutant emissions decline overall in the BAU scenario, though less steeply than in the net-zero scenarios. Criteria pollutant emissions are also included in Figure 3.11. Most of the criteria pollution reductions in the BAU scenario are a co-benefit of a decarbonizing grid that is less reliant on fossil fuel combustion. As the share of renewables on the grid grows, criteria pollutant emissions also fall: sulfur dioxide (SO_2) by more than 99%, nitrogen oxides (NO_x) by 75%, particulate matter ($PM_{2.5}$ and PM_{10}) by more than 99%, carbon monoxide (CO) by 80%, and volatile organic compounds (VOCs) by almost 90%. However, economy-wide, the reductions are more modest, ranging from a 20% reduction in NO_x to about a 55% reduction in both $PM_{2.5}$ and PM_{10}. Even so, these reductions would result in significant air quality and health benefits for local communities.



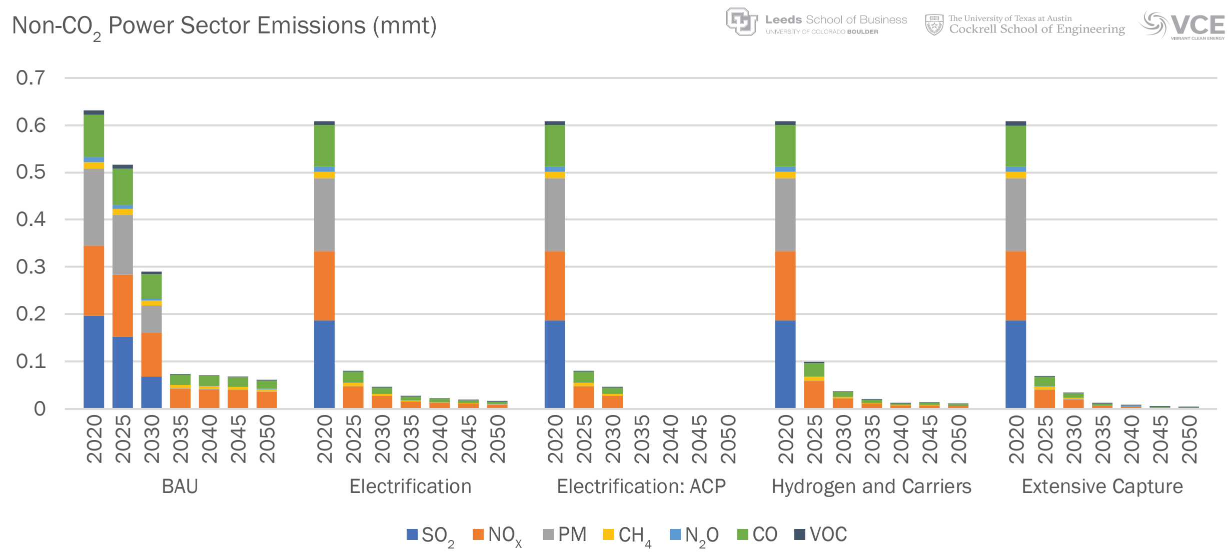


Figure 3.11: This plot shows the non-CO_2 emissions economy-wide (top panel) and only from the power sector (bottom panel). Within the power sector, criteria pollutant emissions as well as methane (CH_4) and nitrous oxide (N_2O) emissions decrease rapidly between 2020 and 2025 in all scenarios, primarily due to the retirement of coal facilities and some gas. Non-CO_2 emissions fall more rapidly in the net-zero scenarios compared to BAU, which keeps more coal and gas facilities online for longer. Some power-sector criteria emissions remain in 2050 for all scenarios except Electrification: Accelerated Clean Power. Economy-wide, carbon monoxide (CO) sees steep reduction primarily due to electric vehicles and industrial electrification/hydrogen fuel use. Electric vehicles also contribute to reductions in VOCs, NO_x, and particulate matter ($PM_{2.5}$ and PM_{10}). Economy-wide CH_4 reductions are mostly due to industrial electrification/hydrogen fuel use, industrial efficiency, and 'clean-up-your-act' policies within industry and oil & gas that prevent leaks and improve end-of-life management. F-gas emissions are only available as CO_2e in the TX-EPS and are omitted from these plots because of their relatively larger scale: F-gas emissions start at 48 mmt CO_2e in 2020 for all scenarios and reach 90 mmt in 2050 for BAU but fall to 0.7 for Electrification, 0.7 for Electrification: Accelerated Clean Power, 0.7 for Hydrogen and Carriers, and 79 in Extensive Capture.

Criteria pollutant emission reductions are larger than those in the BAU scenario for all net-zero scenarios except the Extensive Capture scenario, which sees mostly identical reductions to the BAU because Extensive Capture can only decarbonize through DACS, CCS, and low-carbon electricity. Power-sector emissions, including greenhouse gas emissions and criteria pollutants, fall more than 90% in each net-zero scenario except for Electrification: Accelerated Clean Power, where the grid is required to be fully zero-emission (not net-zero) by 2035. The power sector itself is not required to be zero-emission in the Electrification, Hydrogen and Carriers, and Extensive Capture scenarios, but it is constrained by the overall requirement that the full economy be net-zero in 2050.

Economy-wide criteria pollutant emissions fall more precipitously in the Hydrogen and Carriers, Electrification, and Electrification: Accelerated Clean Power scenarios due to a decarbonizing grid as well as industrial measures and electric transportation. Industrial measures include electrification (as well as using hydrogen as fuel in the Hydrogen and Carriers scenario) and 'clean-up-your-act' policies. Electrification and hydrogen as fuel reduce criteria emissions by preventing fossil fuel combustion, similar to decarbonizing the grid. 'Clean-up-your-act' policies focus on preventing leaks in equipment, preventing fugitive methane emissions at wells, and improving end-of-life measures for greenhouse gases used in industrial processes. Electrification of transportation also contributes to reductions, particularly for NO_x, VOCs, and CO. Transportation contributes to criteria pollution through combustion and non-tailpipe sources like tire and brake wear, which will become the dominant sources as transportation electrifies.[203,204]

Across all net-zero scenarios, common measures that contribute the most to overall decarbonization include power sector decarbonization, industrial electrification and hydrogen fuel use, industrial efficiency improvements, industrial methane and F-gas measures, and electric vehicles. Also common to each scenario is DACS. Many other efforts have small individual impacts on emissions, but combine to reduce about 10% of emissions total by 2050 in each net-zero scenario except Extensive Capture, which implements no changes outside of BAU conditions. Figure 3.12 shows the portion of annual emissions in 2050 abated by each scenario assumption, with multiple small contributors combined together into one category ('Other'). For a complete list of all scenario assumptions, please see Appendix C.

Higher sales of electric vehicles primarily contribute to decarbonization in the Electrification and Electrification: Accelerated Clean Power scenarios. Though incentive programs can be used to help encourage electric vehicle adoption from consumers, the transition to electric vehicles is already well underway because of consumer preferences, municipal and national policies, and auto manufacturers, some of which are planning to stop selling gasoline-fueled vehicles entirely. [205]

Electric transportation also helps reduce a little over 1% of emissions in the Hydrogen and Carriers scenario because most new LDV sales are assumed to still be electric with a small portion (10%) of new sales being hydrogen in 2050. New sales of HDVs are 100% hydrogen by 2050. Hydrogen transportation in the Hydrogen and Carriers scenario helps reduce a little over 4% of emissions by 2050, lower than electric transportation in the other net-zero scenarios both because of electric LDV sales in the scenario and because hydrogen vehicle sales targets ramp up more slowly than those for electric vehicles, resulting in lower fleet turnover.

Hydrogen production through electrolysis primarily benefits the Hydrogen and Carriers scenario because of the increased hydrogen demand for both transportation and industrial fuel use. In this scenario, most new sales of vehicles other than light duty vehicles are hydrogen-based by 2050 compared to electric in the other scenarios (except Extensive Capture).

Industrial fuel consumption in the Electrification and Electrification: Accelerated Clean Power scenarios electrifies as much as possible based on estimated electrification potentials.[10] But in the Hydrogen and Carriers scenario, the remaining, unelectrified industrial fuel consumption is replaced with hydrogen. Using electrolysis to meet an increasing hydrogen demand has a large emission reduction potential because hydrogen produced by steam methane reforming emits between 8 and 12 kg CO_2 per kg of H_2 produced.[206] Fugitive hydrogen emissions, a likely side effect of greater production, are an indirect greenhouse gas through their interactions with hydroxyl radicals in the atmosphere, but the global warming potential (GWP) of hydrogen is about 5.8 compared to methane – between 28 and 36 over a 100-year time horizon (this analysis uses 28[201]). Using electricity or hydrogen for industrial fuel consumption reduces the emissions of carbon dioxide as well as other pollutants, particularly sulfur dioxide and particulate matter.

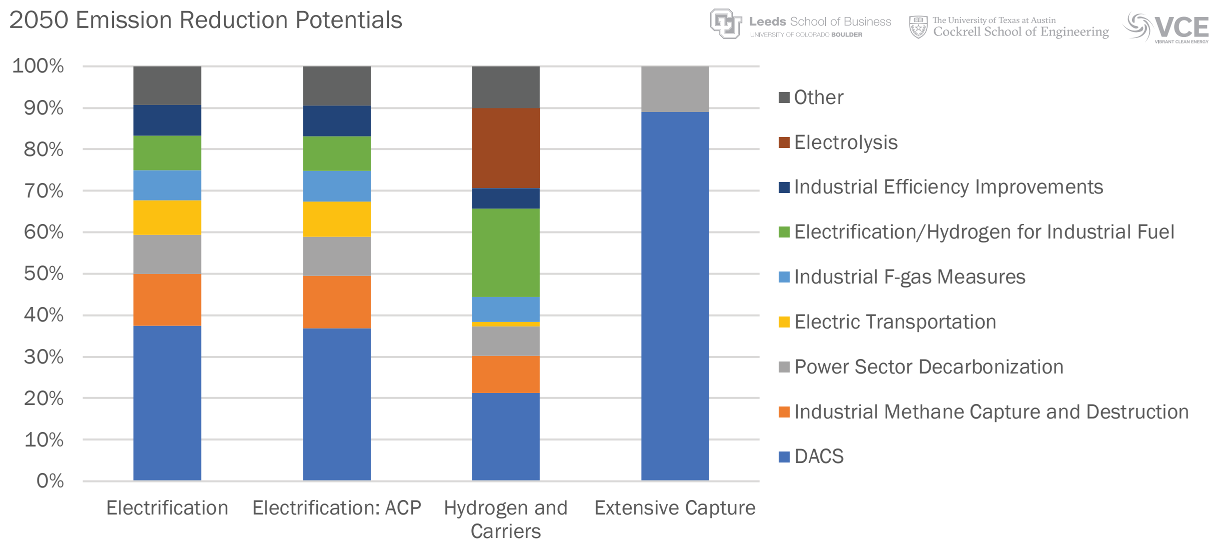


Figure 3.12: This plot shows the intervention impacts on emission reductions for each net-zero scenario. All net-zero scenarios are required by the WIS:dom-P model to achieve net-zero emissions by 2050 and follow a linear glide slope. Emissions can fall faster if it is economic to do so. The discrepancies in 2020 emissions between scenarios (all within 5% of BAU) are due to slight modeling variations in WIS:dom-P, which begins all simulations in 2018. "Other" is the sum of several scenario assumptions including building electrification, building efficiency, research and development fuel use reductions, transportation mode shifting, livestock measures, early retirement of industrial facilities, afforestation and reforestation, hydrogen transportation, green ammonia and fertilizer, and cogeneration and waste heat recovery. Note that wedge 'sizes' were taken from the TX-EPS, which takes interactions between different scenario settings into account when calculating CO$_2$e emission reduction potentials. For a breakdown of the contributions for the 'other' category and attribution methodology, please see Appendix B or the online TX-EPS documentation.

Industrial efficiency measures (including energy efficiency standards, improved system design, and material efficiency/longevity/reuse) might help mitigate 7% of emissions in 2050 in the Electrification and Electrification: Accelerated Clean Power scenarios and 5% in the Hydrogen and Carriers scenario. The standards are the same between scenarios, but they might have a slightly lower impact in the Hydrogen and Carriers scenario because of the greater use of hydrogen as an industrial fuel source, as most of the standards focus on fossil fuel use efficiency and electricity.

These three scenarios also include efficiency standards for building heating, cooling, envelope, lighting, appliances, and other components (included in the 'other' category, full breakdown in Appendix B). Within the TX-EPS, industrial efficiency standards are applied to overall energy use, and building efficiency standards are applied to newly sold components and appliances. These building efficiency standards are combined with increasing in-home electrification and widespread building retrofits to maximize effectiveness and reach. Building efficiency standards combined with increased retrofitting might mitigate 0.5% of emissions in 2050, with an additional 1 to 3% that could be reduced through building electrification. Also included in the 'other' category, which comprises multiple policies with small individual impacts that sum to substantial emission reductions, are afforestation/reforestation efforts and livestock measures to reduce methane from enteric fermentation (represented within the 'Other' category in Figure 3.12).

Another more direct source of emission reductions is in industrial fluorinated gas and methane measures ('clean-up-your-act' policies). Fluorinated gases (F-gases) are strong, long-lived greenhouse gases with many of the highest GWPs of greenhouse gases. They can be used in industrial processes as refrigerants or propellants, or they can be released as byproducts of industrial processes like electronics manufacturing.[207] Emissions of F-gases are primarily reduced through substitution for less harmful or lower-GWP gases or better recovery and/or destruction at the end of service life for various equipment. Full implementation of F-gas measures might help abate between 7 to 10% of emissions in 2050. Federal legislation is already being proposed to limit F-gases, with the American Innovation and Manufacturing Act, 2021 requiring the EPA to reduce hydrofluorocarbon production and consumption 85% in the next 15 years.[208] Methane emissions are reduced through increased capture and destruction efforts in the oil & gas and coal mining industries (considered part of the industrial sector, and includes upstream activities). Industrial F-gas and methane measures have a combined reduction potential between 16 to 22% in 2050.

Across the three policy-forward net-zero scenarios, industrial measures provide a large share of emission reduction potential. But industry is also the primary source of 'leftover' emissions, or those that are not first reduced through policy intervention and are more difficult to abate. These leftover emissions are mostly industrial process emissions. Industrial process emissions are associated with chemical or physical reactions, like converting limestone to lime during calcination in cement production, or producing high-temperature heat. Process emissions are harder to reduce than energy-related emissions because they are frequently predicated on the use of a specific feedstock or highly optimized processes, making it more difficult to switch input materials or change facility configurations. Texas has a large industrial sector with emphasis on manufacturing and refining, both of which are emissions-intensive.

In the Hydrogen and Carriers scenario, using green hydrogen as a feedstock for ammonia production helps further reduce industrial emissions. Ammonia is a major global polluter, emitting about 2 kilograms CO_2 per kilogram NH_3, primarily from the production of hydrogen through steam methane reforming (SMR), which uses natural gas as the feedstock.[209,180] Using other advanced feedstocks or technologies could similarly help reduce process emissions further, but many of these options are still in the development stage and were out of scope for this analysis. Research into technologies for deep industrial decarbonization is ongoing, including more advanced options for process emissions.[119,122,124]

Additionally, some transportation modes like cargo ships and planes are also difficult to fully decarbonize. Jet fuel, for example, could be replaced with biofuel alternatives, electricity, hydrogen, or drop-in fuels synthesized from hydrogen, though the different propulsion systems and aircrafts have varying degrees of technological maturity. In our modeling, a quarter of new airplane sales are electric or hydrogen by 2050, depending on the scenario. The use of carbon removal technologies can help reduce or offset emissions associated with the extraction of the fossil resources that are used for these feedstocks and fuels.

There are also leftover emissions from agriculture in each net-zero scenario. Emissions from agriculture are reduced primarily through replacing on-farm fossil fuel use with electricity or hydrogen and other livestock measures. Livestock measures reduce emissions from livestock cultivation and include interventions like manure management for methane and nitrous oxide mitigation as well as feed supplements to prevent methane from enteric fermentation. Livestock measures reduce about 1% of CO_2e emissions by 2050 in the Electrification, Electrification: Accelerated Clean Power, and Hydrogen and Carriers scenarios. There are other agricultural efforts not considered in this analysis that should be studied further in future work, such as regenerative agriculture for enhanced soil health and carbon storage, soil amendments to both improve carbon storage and prevent nitrous oxide emissions, precision agriculture for more efficient use and application of resources, and various combinations of strategies.[210–218]

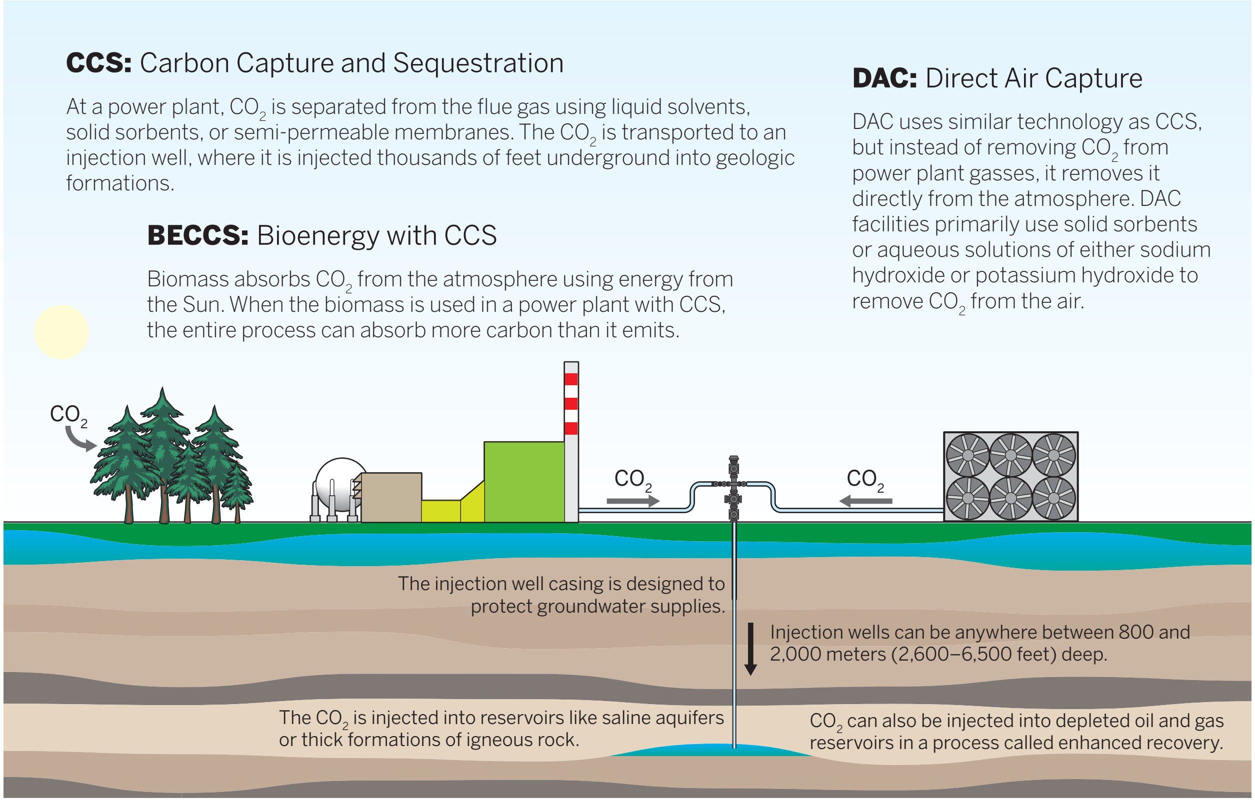
Carbon can be sequestered in the soil or vegetation, and the amount of carbon uptake can be affected by land use, also referred to as land use, land change, and forestry (LULUCF). Carbon sequestered through land use is enhanced in all net-zero scenarios except Extensive Capture through afforestation and reforestation. These efforts help reduce overall state-wide emissions by a little under one percent by 2050 and increase existing carbon sink capacity in Texas by about a third compared to the BAU. Further, in the BAU scenario, land use soil sequestration decreases over time. For the scenarios where they are implemented, afforestation and reforestation efforts help reverse this trend so sequestration potential slightly decreases before then rebounding to a slight increase in sequestration by 2050.

Though all scenarios other than BAU reach net-zero emissions by 2050, the scenarios do not all have equal cumulative emission reductions. The Hydrogen and Carriers scenario has the lowest cumulative net emissions between 2020 and 2050 at 11.7 billion metric tons. Electrification and Electrification: Accelerated Clean Power both cumulatively emit near 13.2 billion metric tons, while Extensive Capture has the most cumulative emissions of the net-zero scenarios at 15.7 billion metric tons. For comparison, BAU cumulative emissions total 28.7 billion metric tons. Extensive Capture has higher cumulative emissions than the other net-zero scenarios because it primarily relies on a decarbonizing power sector and CCS/DACS to reach net-zero, which is more expensive than using a broader suite of approaches to reduce emissions. The linear glide slope (i.e., slope of emission reductions to 2050) set by WIS:dom-P is treated as an upper bound whereby emissions cannot exceed the glide slope in any year, but they can fall faster if it is economic to do so.

Cumulative emissions are slightly lower in Electrification: Accelerated Clean Power than Electrification because of the full decarbonization (i.e. zero-carbon, not net-zero) of the power grid by 2035. Under the Extensive Capture scenario conditions, emissions followed the linear slope as it would be more expensive to scale up carbon capture (primarily DACS) resources any earlier than necessary. Electrification and Electrification: Accelerated Clean Power could further lower emissions because of initial policy interventions that reduced emissions without the need for costly, nascent removal technologies. Furthermore, the Hydrogen and Carriers scenario has the least amount of emissions, partly due to greater deployment of low-emission hydrogen made from electrolysis and low-carbon electricity in addition to other policy measures earlier on, further reducing emissions and staving off the need for removal technologies.

Carbon Management Strategies

Leftover emissions that are difficult to decarbonize with existing technologies, fuel substitutions, or policy levers are abated in our scenarios via carbon management strategies. The TX-EPS can reduce emissions through land use interventions, while WIS:dom-P can deploy DACS or CCS to remove or capture carbon emissions. Bioenergy with carbon capture and sequestration (BECCS) is not yet available in WIS:dom-P and was not included in this analysis. However, BECCS is frequently considered one of the crucial negative emission technologies required to meet mid-century climate goals.[219] Studies also suggest that DACs is a complementary technology that is one of a suite of options meant to work together rather than individually.[220,221] Within our analysis, the carbon management capacities for each scenario can be used as a placeholder for a mix of other low-cost technologies that are currently available or will become available in the future. Other options include coastal blue carbon to increase carbon sequestered in the plants and sediments of marshland and tidal areas, carbon mineralization and enhanced weathering where carbon dioxide is mineralized on exposed rocks on the surface or subsurface, other terrestrial options that enhance carbon soil storage, and various ocean-based approaches.[221,222] Figure 3.13 describes DACS, CCS, and BECCS.



CCS: Carbon Capture and Sequestration

At a power plant, CO_2 is separated from the flue gas using liquid solvents, solid sorbents, or semi-permeable membranes. The CO_2 is transported to an injection well, where it is injected thousands of feet underground into geologic formations.

BECCS: Bioenergy with CCS

Biomass absorbs CO_2 from the atmosphere using energy from the Sun. When the biomass is used in a power plant with CCS, the entire process can absorb more carbon than it emits.

DAC: Direct Air Capture

DAC uses similar technology as CCS, but instead of removing CO_2 from power plant gasses, it removes it directly from the atmosphere. DAC facilities primarily use solid sorbents or aqueous solutions of either sodium hydroxide or potassium hydroxide to remove CO_2 from the air.

The injection well casing is designed to protect groundwater supplies.

Injection wells can be anywhere between 800 and 2,000 meters (2,600–6,500 feet) deep.

The CO_2 is injected into reservoirs like saline aquifers or thick formations of igneous rock.

CO_2 can also be injected into depleted oil and gas reservoirs in a process called enhanced recovery.

Figure 3.13: Description of three major carbon capture and removal pathways: CCS, BECCS, and DACS

Every scenario sees substantial growth in carbon management, the majority of which is supplied by DACS. The largest DACS build out occurs in the Extensive Capture scenario, where DACS removes 95% of BAU-level CO_2e emissions (900 mmt CO_2) a year by 2050. Though emissions are nearly equivalent between the Electrification and Electrification: Accelerated Clean Power scenarios, slightly less DACS is built in the latter due to earlier emission reductions from a zero-carbon grid in 2035. The lowest DACS build out is in the Hydrogen and Carriers scenario, which also has the lowest aggregate emissions. In the Extensive Capture scenario, the only options for getting to net-zero outside of power sector decarbonization are CCS and DACS (this scenario assumes BAU levels of soil carbon sequestration). In the other scenarios, DACS is used to capture the emissions that are not first reduced through policy interventions and trends like electrification, methane and F-gas measures, and efficiency standards. Figure 3.14 shows carbon removal capacity by technology for each scenario. CCS deployment and land use measures are low across all scenarios.

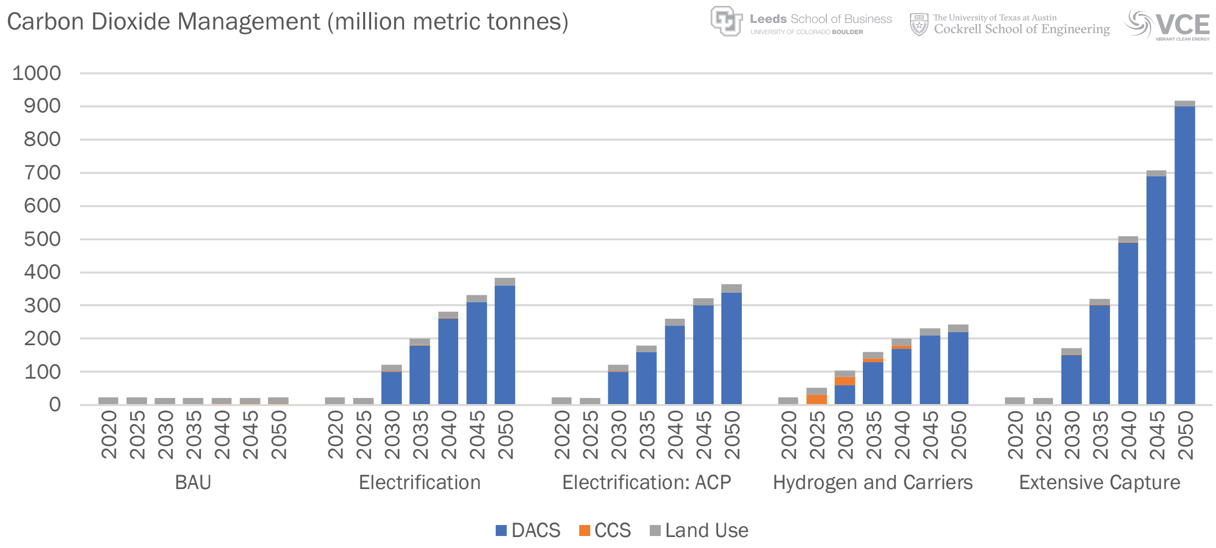


Figure 3.14: This plot shows the total carbon dioxide captured or removed over time through CCS, DACS, or land use management. Carbon management capacity is dominated by DACS across all scenarios with small amounts of CCS deployed and relatively constant sequestration through land use. Within the model, it is less expensive to build out electric-powered DACS with low-cost wind power than natural gas with CCS. The Extensive Capture scenario primarily relies on carbon removal options to reach net-zero emissions so has the highest DACS capacity. CCS removal capacity is highest in the Hydrogen and Carriers scenario in the early years to abate emissions from the increased electricity generation required to meet demand for hydrogen production from electrolysis while fossil resources are still online, but CCS capacity drops off as more renewables go online and DACS resources scale up. Less carbon removal capacity is needed in the Hydrogen and Carriers scenario because more emissions are abated through use of hydrogen for industrial fuel consumption in addition to electricity. Carbon sequestration in the land use sector is mostly constant, but increases slightly in all net-zero scenarios except Extensive Capture due to afforestation and reforestation efforts.

Carbon sequestration from land use is mostly constant for all scenarios but increases slightly in later years in the Electrification, Electrification: Accelerated Clean Power, and Hydrogen and Carriers scenarios due to afforestation and reforestation efforts. In these scenarios, soil carbon sequestration increases by about 5 mmt by 2050 relative to BAU. The most CCS of any year is built in the Hydrogen and Carriers scenario in 2025, where it captures a maximum of about 28 mmt CO$_2$. More CCS is deployed early on in this scenario because of higher electric generation to meet increased demand for electrolysis. DACS is still developing in earlier years (WIS:dom-P does not deploy DACS until after 2025), so the model deploys CCS attached to natural gas power plants to capture the increased emissions from greater generation. Early deployment of CCS can help abate rising emissions from the power sector due to electrification or demand growth in the near-term while other removal technologies are still nascent or too expensive. Recent research shows that there is substantial potential for industrial CCS capacity in the Gulf Coast region.[223] In this analysis, the vast majority of CCS is in the power sector for all scenarios. The model builds very limited industrial CCS capacity, less than 100 metric tons of carbon dioxide in any year for any scenario.

Costs for CCS are the low values from NREL's 2019 Annual Technology Databook.[224] DACS system costs (capital and operational) were taken from the literature and adjusted for inflation, resulting in capital costs of about $990 per annual metric ton with electricity requirements of 1.785 MWh per metric ton, which includes energy required to pressurize the system.[225] Because this technology is currently unproven and not in operation, no technology learning curve was applied to DACS, so all costs other than those for fuel (electricity) stay constant through 2050 in WIS:dom-P. Industrial CCS values were adapted from values in the literature and set at a levelized cost of $76 per metric ton capture in 2020, falling to $68 per metric ton in 2050.[226,227] More details, including costs for storing CO_2, can be found in Appendix F. A cost comparison of various DACS technologies from the literature and industry can be found in Appendix A.

WIS:dom-P chooses to build more DACS than CCS because, in the model, it is overall less expensive to drive the economy to net-zero using electric DACS systems and wind power than build out a combination of NGCC and CCS and industrial CCS. The levelized cost of DACS within WIS:dom-P is primarily driven by the cost of electricity, which can be supplied by low-cost wind and purchased at the margin. Within WIS:dom-P, CCS is weighed down by both a fuel penalty that increases an NGCC plant heat rate by about 14%, and the added emissions from producing and burning the natural gas (our analysis assumes a capture efficiency of 95% for CCS). Building more natural gas with CCS would add emissions that would need to be reduced another way to meet the net-zero requirement in 2050. DACS also becomes a way to handle more extreme conditions, with DACS acting as a flexible load that can be shut down under times of grid strain to allow other demands to be met. DACS also wins out over industrial CCS primarily because of cheap electricity. Figure 3.15 explains DACS processes in more detail.

DAC: Direct Air Capture

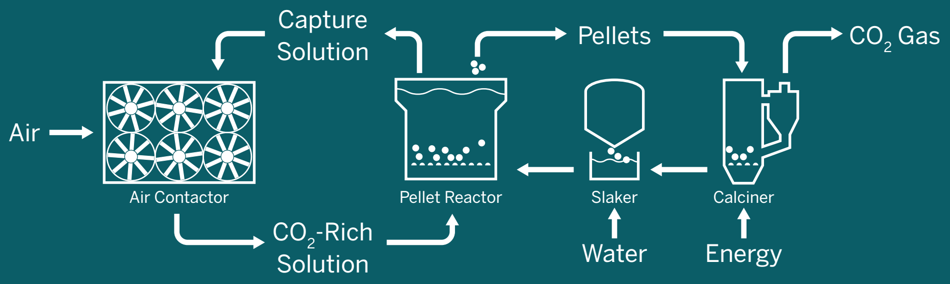
Using Liquid Solvents

The **air contactor** has thin plastic surfaces with sodium hydroxide or potassium hydroxide solution flowing over them. CO_2 molecules in the air bind to the solution and form carbonate salt.

The carbonate salt is precipitated out of the solution in a **pellet reactor** using technology developed for water treatment plants.

The pellets are transferred to a **calciner** where they are heated to release the CO_2 gas. The calciner is similar to equipment that's used at very large scale in mining for ore processing.

The processed pellets are then hydrated in a **slaker** and recycled back into the system to reproduce the original capture chemical.

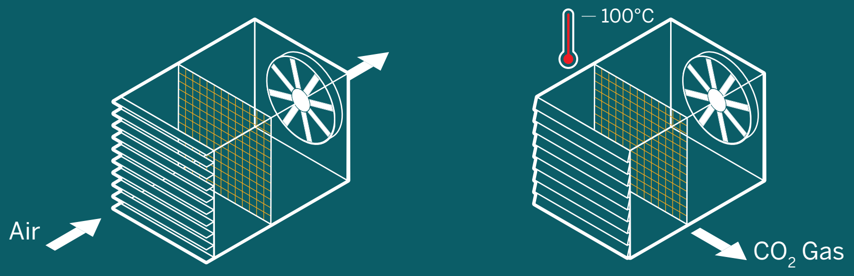


Source: Carbon Engineering, Ltd.

Using Solid Sorbents

Air is drawn into the collector with a fan. Carbon dioxide is captured on the surface of a highly selective filter material that sits inside the collectors.

When the filter material is saturated with CO_2, the collector is closed and heated to between 80 and 100 °C to release the CO_2 gas, which is then drawn off and stored.



Source: Climeworks

Figure 3.15: Description of two major pathways for direct air capture

There are other approaches to CCS not considered in this work, like the Allam-Fetvedt cycle, a novel power cycle which produces electricity from natural gas while capturing all of the CO_2. While conventional CCS requires additional fuel for operation, fully operational Allam cycle plants might be able to operate at 59% efficiency, on par with highly efficient natural gas combined cycle plants (50-60% efficient) while providing a nearly pure stream of CO_2 that can be separated without an operational penalty.[228] A test facility owned by NET Power in La Pointe, TX successfully delivered power to ERCOT in November 2021.[229] Industrial CCS is also modeled in WIS:dom-P as a set levelized cost and is not tied to changing fuels or electricity prices. Additionally, although the cost of industrial CCS in this analysis takes into account the dominant industries in Texas, the competitiveness of industrial CCS will vary more substantially by industry in practice.[230]

DACS benefits in our analysis from being all-electric operation as compared to other DACS approaches that use a combination of electricity and natural gas. In our analysis, based on an all-electric DACS system, the levelized cost of capture for DACS falls to about \$50/tonne of CO_2 by 2050 in all scenarios. This cost is at the low end of CCUS costs in the power sector and about half of current low-end estimates for DACS; one study projects that DACS could fall as low as \$94/tonne, but with a mix of electricity and natural gas.[231–233] Though it is certainly possible that a large build-out of DACS capacity combined with technology learning curves, falling prices, and cheap electricity could result in such a low cost of capture for DACS in the future, this cost is as yet unproven. A cost of \$94 per metric ton CO_2 captured by DACS in our analysis would likely still win out over power sector CCS, however, because of the other benefits previously discussed that make it more attractive in the WIS:dom-P model. Though in this case, industrial CCS would be more cost competitive with DACS, likely resulting in a more balanced carbon mitigation strategy portfolio. The carbon capture capacity presented here can be met by multiple low-cost technologies in the future, with DACS still represented. Our results indicate that an all-electric DACS system coupled with low-cost electricity might have a distinct advantage for Texas if developed, though there might be other benefits to using existing DACS technologies that take both electricity and natural gas.

Some DACS plants run on both electricity and natural gas.[220,225] Occidental Petroleum is partnering with Carbon Engineering, the same firm that projects DACS costs could fall to \$94 per metric ton depending on plant characteristics, to build a large-scale direct air capture facility in the Permian Basin in Texas using electricity and natural gas.[231,234] However, Climeworks in Iceland operates their plant using heat and electricity from geothermal energy.[235,236] Using hybrid electricity-natural gas systems might help carve out another use for Texas natural gas, retaining oil & gas sector revenue and jobs in the process. On the other hand, to reach net-zero, more DACS systems would be required to offset the emissions from natural gas production required to power the DACS.

Texas might also have a uniquely advantageous landscape for DACS development. Texas has large chemical and refining industries that might be difficult and expensive to fully decarbonize through retrofits, process reconfiguration, or advanced techniques. It might be cheaper to partially decarbonize these industries and use DACS to remove the remaining, most difficult or expensive emissions. Texas also has a lot of land and the ability to power DACS with vast wind resources. Research from Decarb America predicts Texas to be the leader in DACS capacity in 2050 for all of its seven net-zero scenarios.[237] Even so, the DACS plant scheduled to begin construction in the Permian Basin in Texas in 2022 is projected to capture a maximum of one million metric tons of carbon dioxide a year.[234] This capacity implies a rapid expansion would be necessary to meet the carbon removal capacity achieved in our scenarios.

In addition to becoming its own industry, large DACS capacity could also theoretically lead to other industries. With a net-zero carbon industrial sector, Texas could become a hub for low-carbon goods and fuels. Research on industrial CCS indicates that establishing a market for low-carbon goods can help support and promote capture efforts.[230] The captured carbon dioxide from

DACS systems could be turned into materials or other fuels like synthetic methane. And though some of the captured carbon dioxide might be used for enhanced oil recovery (EOR), oil produced using EOR can still provide emission reduction benefits that might help lower net emissions while waiting for other reduction technologies to scale.[238,239] These links are worth studying further in future work. Additionally, though BECCS was not included in this analysis, research indicates that integrating BECCS with direct air capture can increase carbon removal and lower system costs, and additional benefits are realized if these integrated systems are co-located with geologic storage sites.[240] Future work should investigate this potential in Texas.

Notably, it is potentially less risky, and less expensive, to decarbonize first and avoid becoming dependent on DACS in the future when time for action is vastly more limited. While there are plants currently in operation, DACS is still a nascent technology with uncertain cost curves and low agreement among projections.[225,232,233] Additionally, removing a ton of carbon from the atmosphere might not completely negate the impact of emitting it in the first place.[241] Preventing the emission of carbon dioxide will also prevent emission of any other gases that might be co-released during combustion or other processes, whereas removal only accounts for the carbon dioxide. In a recent report, the IPCC emphasizes the risk in delaying emissions to a point where we would become reliant on carbon removal technologies to meet emission reduction goals.[233] Large deployment of carbon removal technologies is correlated in the literature with temperatures peaking and then declining, which can trigger permanent negative impacts like destabilization of ice-sheets or release of emissions from the Arctic or Amazon.[242] Additionally, large DACS potentials combined with low but unproven prices mean that the actual economic impacts of leaving over 300 million metric tons of carbon dioxide to be captured through DACS might be much higher.

Leftover emissions (those to be captured or removed through CCS, DACS, or other technologies) in our scenarios can be reduced to about 130 million metric tons in 2050 by setting tighter scenario conditions and faster technology adoption rates in the TX-EPS but without reducing fossil fuel exports. Leftover emissions are higher in the final net-zero scenarios, reflecting a Texan desire to minimize political intervention as well as labor and economic disruptions. Given these aversions, it is important to investigate what a carbon capture- or removal-heavy future might look like. Though there are multiple reasons why the approach taken to carbon capture and removal will be more diverse, including various social, political, and economic priorities, carbon management overall can play a large role in reaching a net-zero Texas.

3.5 Environmental Trade-Offs: Land, Water and Materials

While the main objective of decarbonization is to eliminate greenhouse gas and air pollutant emissions, it is critical we understand the tradeoffs associated with water withdrawals, water consumption, land use, and material inputs for a decarbonized future.

Land use

Land use is a particularly important consideration when transitioning from fossil-based to low-carbon electricity generation because many renewable sources such as hydroelectric, wind, and solar power are relatively diffuse and therefore require more area. Figures 3.16, 3.17, 3.18, 3.19, and Figure 3.20 show the regional change in capacity from 2020 to 2050 for each scenario. These results are illustrative of the modeled scenarios and not predictive. For example, the analysis does not take into account social and political considerations within the local geographies such as tax incentives or siting prohibitions implemented at the country level. WIS:dom-P sites generation based on a weather dataset spanning multiple years at 3-km and 5-minute resolution over the contiguous U.S. Within WIS:dom-P, the whole state of Texas is modeled, and the ERCOT region is able to build transmission and access generation in non-ERCOT regions.

WIS:dom-P deploys wind generation throughout the state to take advantage of the geographic diversity, which provides a more complementary generation profile in addition to generating more energy near the load centers. Significant wind is deployed in each scenario in the High Plains, central Texas, and the Gulf Coast as these regions have high wind capacity factors. Wind is also deployed in the Northwest and West regions to take advantage of diverse generation profiles that helps fill a gap from wind patterns in other regions. Further, significant distributed solar PV (DPV), like rooftop solar, is deployed in the Metroplex and Gulf Coast regions as these areas have large load centers and robust solar resources. DPV generation helps alleviate transmission congestion that routinely occurs in moving energy from remote locations to these regions. DACS (direct air capture systems) resources are co-located with existing oil & gas resources where possible, but also with wind resources, which are the primary source of power for DACS.

WIS:dom-P also locates much of the electrolyzer capacity in the panhandle, partially to be close to retired power plants. However, there is already significant hydrogen production and pipeline capacity in the Gulf Coast region (and the model concludes some new electrolysis capacity is indeed built in this region as well), making it likely that any hydrogen made in the panhandle would require additional transportation resources to reach the Gulf ports. A larger share of future electrolyzer or hydrogen production capacity in general might actually be built closer to existing infrastructure rather than wind-generated electricity sites.

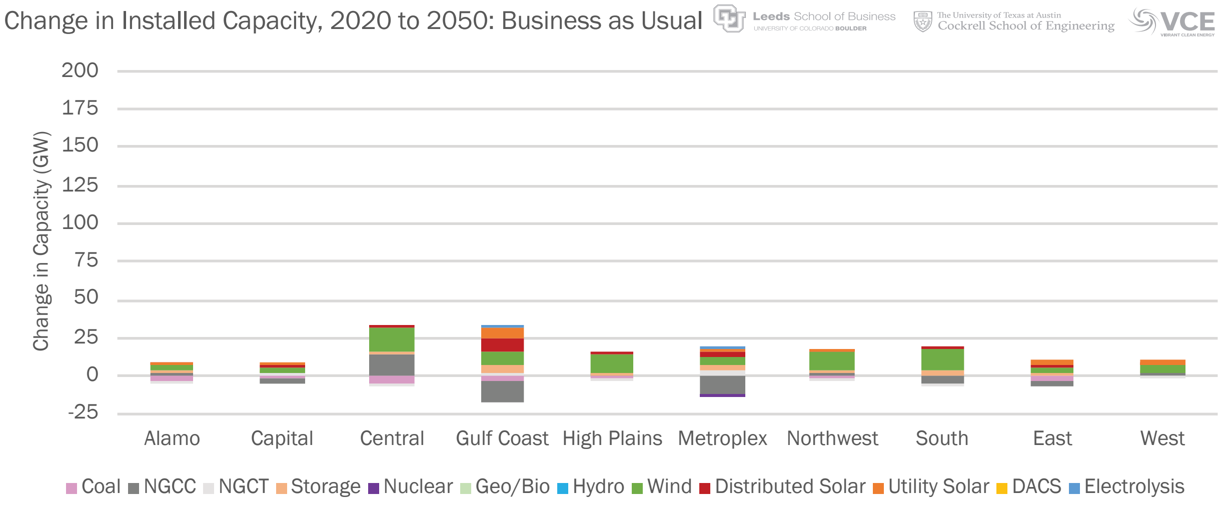


Figure 3.16: This plot shows the change in capacity for the BAU scenario by 2050. The BAU scenario has the fewest capacity additions out to 2050 of all scenarios. Most solar is built in the Metroplex and Gulf Coast regions, home to Dallas and Houston respectively, relieving some transmission congestion to these regions. New wind resources are distributed throughout the regions. In the figure, NGCC is natural gas combined cycle, NGCT is natural gas combustion turbine, Distributed Solar is distributed solar photovoltaic panels (like rooftop solar), and Utility Solar is utility solar photovoltaic.

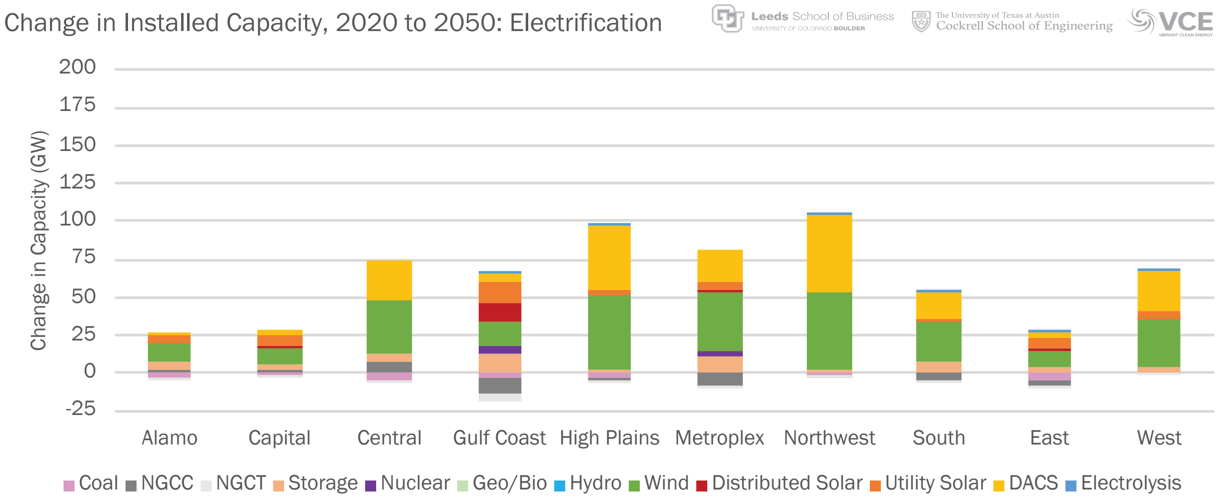


Figure 3.17: This plot shows the change in capacity for the Electrification scenario by 2050. A substantial amount of wind capacity is built by 2050 throughout the state, providing more power closer to load centers. Most solar is built in the Metroplex and Gulf Coast regions, home to Dallas and Houston respectively, relieving some transmission congestion to these regions. Some SMR nuclear is built near Dallas. In the figure, NGCC is natural gas combined cycle, NGCT is natural gas combustion turbine, Distributed Solar is distributed solar photovoltaic panels (like rooftop solar), and Utility Solar is utility solar photovoltaic.

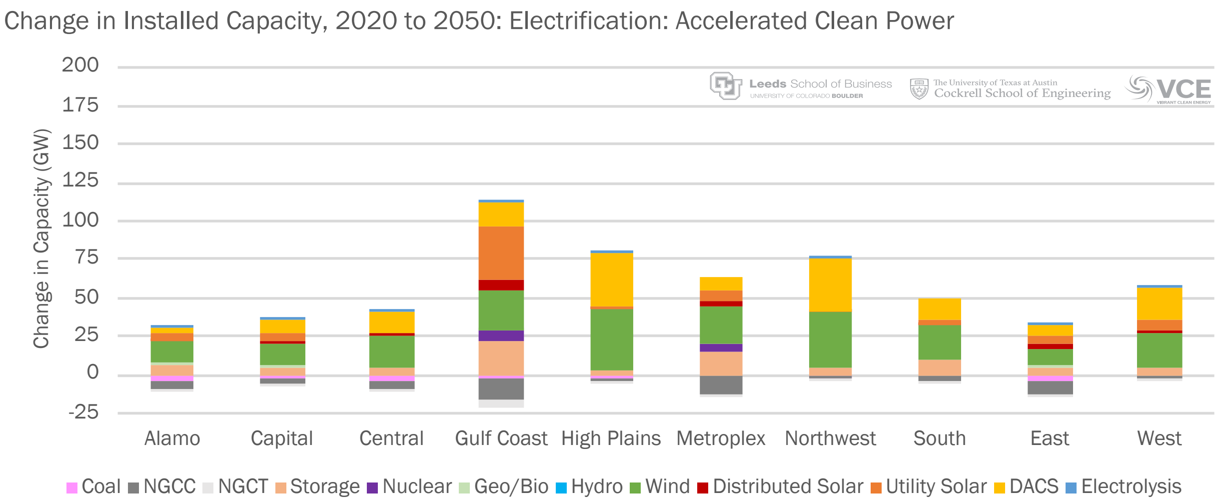

Change in Installed Capacity, 2020 to 2050: Electrification: Accelerated Clean Power

Figure 3.18: This plot shows the change in capacity for the Electrification: Accelerated Clean Power scenario by 2050. A substantial amount of wind capacity is built by 2050 throughout the state, providing more power closer to load centers. This scenario deploys the most solar of all the scenarios in order to decarbonize the grid by 2035. Less wind is deployed in this scenario than Electrification because of the large solar build out. SMR (small modular reactor) nuclear is deployed in El Paso and around the Gulf Coast. EGS is built in the southeast. In the figure, NGCC is natural gas combined cycle, NGCT is natural gas combustion turbine, Distributed Solar is distributed solar photovoltaic panels (like rooftop solar), and Utility Solar is utility solar photovoltaic.

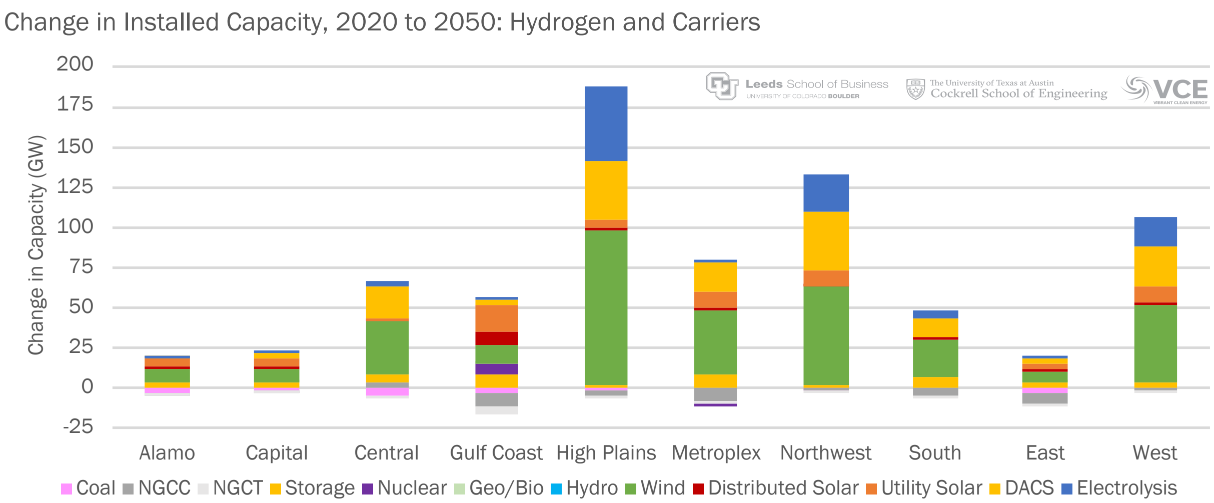

Change in Installed Capacity, 2020 to 2050: Hydrogen and Carriers

Figure 3.19: This plot shows the change in capacity for Hydrogen and Carriers scenario by 2050. A substantial amount of wind capacity is built by 2050 throughout the state, providing more power closer to load centers. Most solar is built in the Metroplex and Gulf Coast regions, home to Dallas and Houston respectively, relieving some transmission congestion to these regions. Electrolysis facilities for hydrogen production are built mostly in the panhandle as they are sited close to retired thermal units, though some are also built in the Gulf Coast region where much of the existing hydrogen infrastructure is located. In the figure, NGCC is natural gas combined cycle, NGCT is natural gas combustion turbine, Distributed Solar is distributed solar photovoltaic panels (like rooftop solar), and Utility Solar is utility solar photovoltaic.

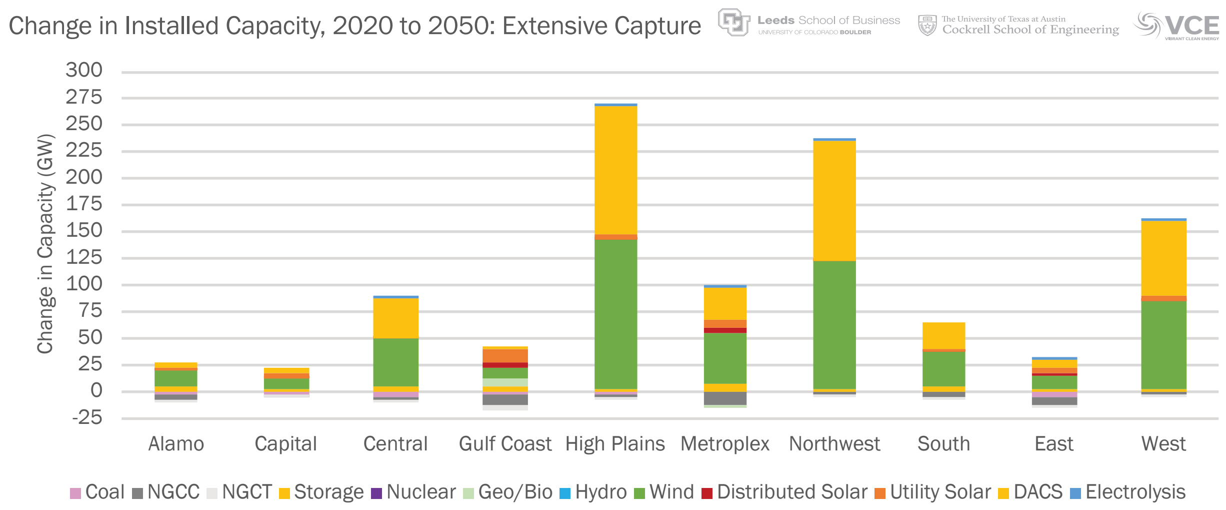


Figure 3.20: This plot shows the change in capacity for Extensive Capture scenario by 2050. The most wind capacity of all scenarios is built in this scenario by 2050, distributed throughout the state, providing more power closer to load centers. The most DACS is also deployed in this scenario and is frequently cited near wind generation. Most solar is built in the Metroplex and Gulf Coast regions, home to Dallas and Houston respectively, relieving some transmission congestion to these regions. In the figure, NGCC is natural gas combined cycle, NGCT is natural gas combustion turbine, Distributed Solar is distributed solar photovoltaic panels (like rooftop solar), and Utility Solar is utility solar photovoltaic.

The High Plains, Northwest, Central, Metroplex, and Gulf Coast regions tend to see larger capacity growth across all scenarios, while the Gulf Coast, Metroplex, and East regions see larger capacity retirements, especially from older, dirtier natural gas and coal-fired thermal plants. Capacity changes in Electrification, Electrification: Accelerated Clean Power, and Business as Usual are also slightly more evenly split between regions, while there are substantially more additions in the High Plains, Northwest, and West regions in the Hydrogen and Carriers and Extensive Capture Scenarios due to larger additions of electrolyzer, DACS, and wind capacity in the regions. Regions with larger capacity additions will have greater land use footprints compared to other regions with more modest additions. However, land use intensity varies by technology.

Compared to BAU, all net-zero scenarios show significant growth in wind and solar, which require greater land area footprints than thermal power generators. Thermal power plants tend to be more space-efficient than intermittent renewables, providing large power output within a relatively small land-use footprint. However, many of those plants require additional space for safety perimeters (e.g., nuclear) or cooling water reservoirs. These reservoirs can sometimes be dual-use (e.g., fishing, other ecosystem support), but some reservoirs, like coal ash ponds, cannot serve additional purposes. Renewable generation sites tend to be more conducive to dual-use. Land that houses wind farms can also frequently be used for agriculture or running cattle. Distributed PV is often installed on rooftops, and research shows crops can thrive if planted in the shade of utility-scale PV.[243] There are also indirect land use requirements for fuel extraction that can be substantial and have adverse environmental impacts. For example, over time, more mines need to be constructed to ensure a continuing supply of fuel. When considering both direct and indirect land use, the land use intensity for coal might be more on par with solar generation.[244]

A recent review compares the land use intensities of different generating sources.[245] When accounting for total land scope (i.e., including land lease bounds and not just direct footprint), biomass and hydropower have the highest land use intensities, measured in square meters per GWh, followed by onshore wind, solar, geothermal, coal, nuclear, and then natural gas with the lowest intensity. In general, the power density (watts generated per square meter) of these technologies are flipped in order, with natural gas having the highest power density. However, the story is slightly different if only looking at direct land use. The direct footprint of onshore wind (e.g. from the turbine towers and their concrete pads) is more comparable to fossil generation, and it is lower than the total footprint for coal. Total system bounds and how the total land scope is used (e.g. dual-use potential versus extractive, polluting practices) are important to consider within land-use intensities.

Additionally, impacts to biodiversity are also important land-use considerations. While combating climate change by decarbonizing is itself an important contributor to protecting biodiversity, the expansion of renewable energy, which requires generating infrastructure and the mines for requisite materials, might overlap with areas important for protection and conservation priorities.[246,247] In some regions however, overlaps with conservation areas might be comparable between certain fossil generation and renewables; in British Columbia, natural gas and wind have similar biodiversity impacts but are both exceeded by those for hydropower.[248] Biodiversity impacts from rapid expansion of wind and solar might be less severe than previously estimated however and mitigated through regulatory and policy controls.[249] Similarly, alternative siting of renewable energy projects might help mitigate biodiversity impacts.[250]

Water

Water is required in many stages of energy production and generation including: 1) uranium mining, 2) coal, natural gas, and oil fuel production, 3) thermal power plant cooling, 4) hydrogen production (via electrolysis), 5) irrigating bioenergy crops, 6) transporting energy by barge or ship, 7) equipment cleaning and fabrication and 8) for hydroelectricity, among other uses. In addition, surface water and groundwater quality can be impacted by energy production, mining, and waste disposal through thermal or chemical pollution. In regions where water is limited and droughts are common, it is critical to understand the impacts of a changing energy mix on water resources. Except for the eastern portion of the state, Texas is mostly an arid or semi-arid climate and is subject to periods of moderate to severe drought. [251]

Thermal power plants require substantial water withdrawals for cooling, which often puts their water needs in competition with municipalities, agriculture, and other industrial activities. Water withdrawals refer to the total amount of water removed from its source. A portion of this water is returned to its source, and another portion is not returned (water consumption). Overall, thermal power plants are responsible for almost 50% of Texas water withdrawals annually. [252] Texas water withdrawals by sector, including thermoelectric power generation, are summarized in Figure 3.21.

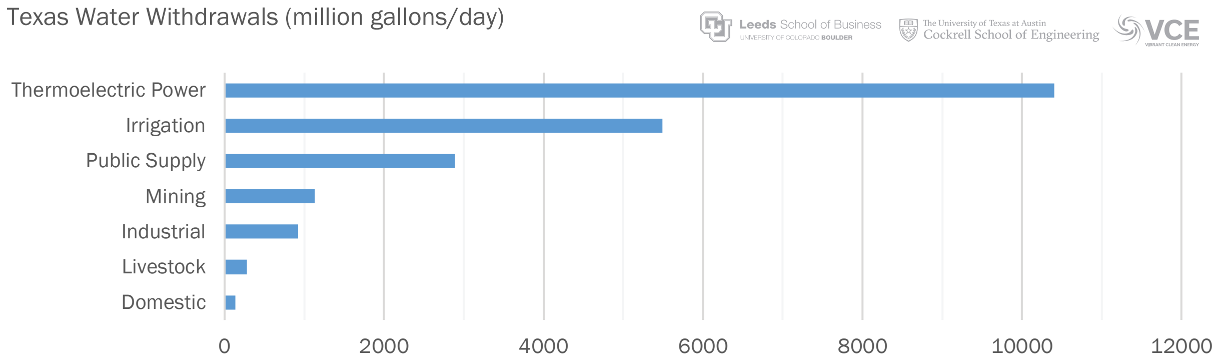


Figure 3.21: Texas water withdrawals by sector, 2015. Thermoelectric power generation accounts for the most water withdrawals, though water intensity will vary with generation technology and cooling strategy. Data taken from USGS.[252]

Water use varies widely among thermal power plants based on fuel type, prime mover, and cooling water strategy.[253,254] As coal and natural gas thermal power plants retire and are replaced primarily by wind and solar, which do not use water for cooling, water withdrawals and consumption for Texas's power sector decline significantly, which frees up water that can be used for other purposes. This reduction in water use is one of the primary environmental co-benefits of decarbonization. However, if nuclear or geothermal power plants are built, they would potentially use some of that water. Estimates for water withdrawals and water consumption for power generation were made for all scenarios in this study and are summarized in Figure 3.22.

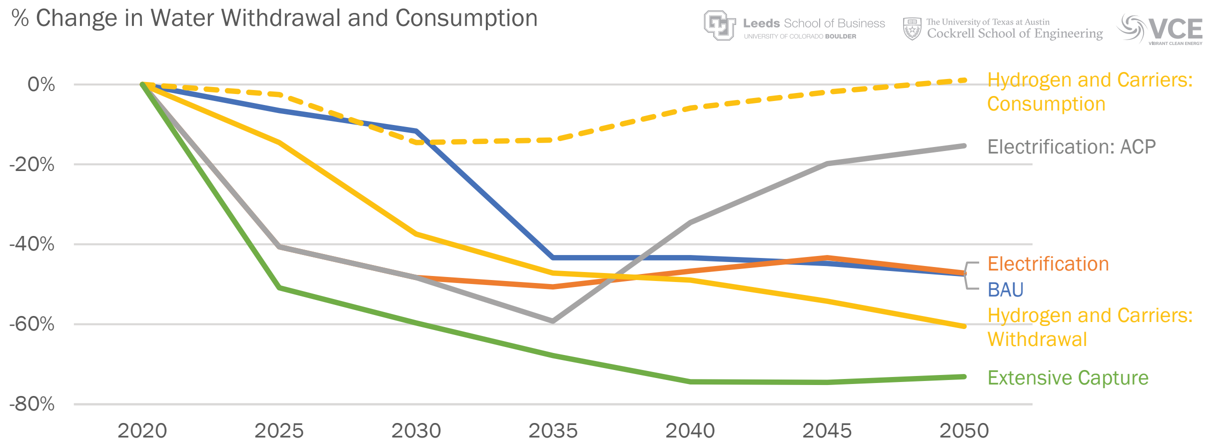


Figure 3.22: This plot shows the percent change in Texas water consumption and withdrawals within the power sector (including electricity-powered electrolysis and DACS) for all scenarios, relative to 2020. Water consumption and withdrawals decline relative to 2020 for most scenarios as the grid decarbonizes and thermoelectric power plants retire. Water usage initially declines in the Electrification: Accelerated Clean Power scenario as renewable generation replaces thermoelectric, but rebounds as advanced nuclear generation comes online. Water usage declines somewhat before rebounding in the Hydrogen and Carriers scenarios as higher water use for hydrogen production (electrolysis) offsets declines from retiring thermoelectric generation. Note: percent change for water withdrawals and consumption are the same for all scenarios except Hydrogen and Carriers.

Figure 3.22 shows that water withdrawals in the Electrification: Accelerated Clean Power scenario drop significantly for 15 years as wind and solar come online then rebound to almost current levels of water withdrawals as advanced nuclear power generation grows in market share. Note that although Electrification: Accelerated Clean Power is the most diverse with respect to its generation fleet, it also has the largest absolute water withdrawals in 2050. The Extensive Capture scenario shows the greatest decline in water withdrawals, which corresponds to the fact that this scenario has the lowest thermal generation by 2050.

Water consumption also declines in most scenarios except Hydrogen and Carriers, which sees a slight net increase in water consumption of 1% by 2050, relative to 2020. Hydrogen production via electrolysis requires 2.38 gallons of water for every 1 kilogram of hydrogen, though other production pathways have different water needs.[255]

Change in water use is a more visible environmental impact than greenhouse gas emissions; changing regional water availability is easier to see, feel, and quantify than the myriad distributed effects of emitting carbon dioxide. Decreased water withdrawals and consumption is a valuable co-benefit of retiring thermoelectric power plants, especially in Texas. However, other technologies that might be beneficial in a low-carbon energy future, like electrolysis for hydrogen production (as exemplified by the findings of this study), require substantial water supplies. Figure 3.22 is also limited to the power sector and does not include water impacts from other sectors, like industry. Being cognizant of the water tradeoffs of low-carbon technologies will be critical in regions like Texas that suffer extensive periods of drought.

Additional Considerations

Changes in our energy system will alter the materials supply chain, which could, in turn, impact supply of critical minerals* as well as the environment and water resources of regions outside of Texas. For example, rare earth elements are required for batteries, wind turbines, and PV panels.[256] Electric vehicles and their batteries also require materials like cobalt and lithium rather than gasoline.[257] Renewable generating technologies have higher material requirements compared to fossil generation (whose requirements are non-trivial to begin with), though the requirements of nuclear, hydropower, and waste biomass might be more comparable.[258] Awareness of the change and growth in use of these resources in each decarbonization scenario is imperative to avoid unintended consequences such as resource depletion, competition, or detrimental impacts to the environment and water resources where the materials are extracted.

Much like energy mining today, mining for many of these materials will take place outside of Texas. As such, the environmental impacts might be felt elsewhere, but also introduces vulnerability from long supply chains that can be disrupted. Today, those risks are felt substantially by the coal and nuclear power plants in Texas whose fuels and components are produced elsewhere. As such, their ability to operate can be disrupted if a nuclear fuel fabrication facility or railway are out of commission far away. These disruptions might also happen to mines or factories for manufacturing wind, solar, and batteries. However, a key difference is that wind and solar plants only have a supply chain for their production, but they do not have a supply chain for their power generation. Once they are built, installed, and operational, they are immune to the out-of-state disruptions as the solar and wind resources are inherently on-site. Natural gas is produced in abundance in Texas, but its components (such as turbines, compressors, etc.) are often produced out of state. In that way, the vulnerability of the gas system to disruption from out-of-state events is similar to wind and solar in that its fuel is mostly produced nearby, but the equipment is not.

Taking the concept further, countries with rich reserves of oil and gas are not necessarily the same ones rich with metals and critical minerals, thus ramping up material mining will have geopolitical impacts.[259] However, there might also be a trade-off between the ongoing need for a steady fuel supply to fossil generators and the large initial requirements of materials for constructing renewables but free fuel (e.g. solar and wind). Increasing renewable generation might decrease the overall material intensity of electricity generation over time as fuel requirements decline. This balance might not be the same for other sectors though, such as transportation, where the increase in material requirements for EVs might offset declines in gasoline consumption.[257] These aspects are worthy of deeper examination in future work.

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* Critical Minerals were defined by the Trump Administration as "1) a non-fuel mineral or mineral material essential to the economic and national security of the United States; 2) the supply chain of which is vulnerable to disruption; and 3) that serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for our economy or our national security."

3.6 Equity Implications and Considerations

The ongoing threat of climate change will not be felt equally across geographies or communities. Research has shown that, among other groups, low-income communities, tribal communities, island communities, and people of color will bear more of the negative impacts of climate change.[260–262] Hotter temperatures might also have stronger negative effects on labor, including weekly earnings, in poorer areas.[263] As average temperature rises and storm systems intensify due to climate change, these skewed impacts will continue to further exacerbate inequities.

Though global decarbonization will, at a macro scale, help prevent the worst effects of climate change and alleviate that burden from vulnerable communities, decarbonization policies are still not always equitably implemented. For example, electric vehicle subsidies might disproportionately benefit already-wealthy consumers, and charging stations are more frequently located in wealthier areas.[264,265] Potential pitfalls like these should be considered when mapping any path to a net-zero economy. This section draws from existing scholarship to discuss possible equity implications of various decarbonization policies, focusing on those that could promote technologies and behavioral changes that make sizable contributions to reaching net-zero in our scenarios. This section does not make specific policy recommendations on how to improve equity, but instead discusses important considerations for policy makers to ensure that any supporting policies remedy rather than exacerbate existing inequities.

Distributed Solar Generation

Each renewable generation source has unique social implications and challenges. The equity implications of rooftop solar panels have been widely studied in the literature.[266–276] High-income communities are more likely to adopt rooftop solar, and so are white-majority communities, even when controlling for income.[271,272] Solar adoption is particularly low in low- and moderate-income (LMI) communities, which might lack either sufficient capital or credit for initial investment, a high enough tax burden to take advantage of certain state and federal incentives, information about installations, or a suitable roof for installation, either because the roof is in poor condition or they do not own their home.[277,278] Renters traditionally pay for utilities but usually are prohibited from making property modifications, such as the installation of solar panels. Landlords, on the other hand, have little incentive to invest in technologies that reduce the utility costs that they do not pay. In Texas, the share of housing occupied by Hispanic and Black populations is 30.6% and 12.5%, respectively, compared to 51.5% for the white population.[279] However, the rate of home ownership among Hispanic and Black populations is 27.7% and 8.3%, lower than the 58.8% ownership rate for the white population. [279]

Though costs have been declining, rooftop solar panels still have a large cost barrier, which leaves many low-income families unable to participate.[266] Subsidies for rooftop solar have historically been disproportionately distributed among high-income households.[273,275] The continued disparity in adoption, even as prices fall, is reinforced through peer effects (i.e., influence of neighbors), customer referrals, and installer marketing behavior that all help to reinforce solar panel adoption near wealthier, early-adopter communities.[272,274] Research in California also indicates that variations in circuit hosting capacity, the capacity of new generation that grid infrastructure can accommodate without needing upgrades, limits the adoption of solar PV in largely Black-identifying and disadvantaged communities.[276]

Incentives targeted to low- and moderate-income (LMI) households, the ability to lease solar panels, and property assessed clean energy (PACE) financing (allowing homeowners to finance solar panels through property tax payments) might help improve adoption in LMI communities.[272] Shared renewable energy programs like Community Shared Solar (CSS), where electricity customers join together to finance a solar installation through purchasing subscriptions or shares of generation, might also help improve solar adoption in communities that cannot afford to purchase their own panels or do not have access to either a suitable roof or solar resources, though they still face some barriers.[277,278,280,281] Some programs in Texas and elsewhere, such as CPS Solar Host San Antonio, TEP Residential Solar, Colorado PAYS and Enel Green Power, are working to overcome these barriers to solar adoption.

Nuclear Generation

There are two primary considerations of nuclear electricity generation as it relates to equity: 1) safety and 2) uranium extraction. Nuclear plants have lower accidents and fatalities per terawatt hour (TWh) of electricity generated than fossil fuel plants (mining, milling, and generation stages) and even some renewables like hydropower, wind, and solar, though the cost of damages from nuclear are much higher.[282,283] There are also equity concerns over uranium extraction and pollution. With the onset of a uranium ore market in the U.S, the Navajo Nation was identified as a location for uranium mining because the Nation's land covered much of the nation's uranium reserves. The impacts of uranium mining activities within these tribal lands are well documented, including increased rates of lung cancer, kidney disease, and other health complications.[284,285] Further, nuclear plants generate nuclear waste, for which the U.S. has no long-term storage plan; as of 2021, the U.S. has about 86,000 metric tons of spent fuel, currently being stored on-site at existing nuclear facilities, awaiting a permanent storage solution.[286]

SMR nuclear has advantages over conventional nuclear, including modularity that enables incremental growth in capacity over time without large upfront investment, cost savings from shorter construction times and standardization of production for smaller components, and potential safety benefits.[287] But though the amount of waste generated will depend on the specific SMR technology design, concerns over uranium mining and nuclear waste still remain.[287]

Wind Generation

Equity concerns over wind generation are mixed. The air quality benefits are a distinct advantage, especially for marginalized populations. However, communities have historically opposed local wind projects due to complaints over noise, vibrations, aesthetics,, and 'strobe effects' from turbine blades moving across the sun.[269,288,289] Previous research has found that the presence of a wind turbine is associated with negative externalities (e.g. lower satisfaction), though these effects are limited to households that have a turbine within about a 4,000 m radius and for a duration of about five years.[290] There are multiple studies investigating the planning process and procedural justice implications of utility-scale wind project development, where procedural justice refers to the fairness in processes for resolving disputes and allocating resources.[288,289,291,292] Transparency from developers and community engagement and participation in the planning process can help mitigate opposition to wind development and improve public satisfaction.[288,291,293] Private landowners might be more easily able to participate in the planning process through contract negotiations, improving both feelings of control and engagement as well as overall satisfaction with the developments.[292] This consideration might be particularly relevant to Texas, which has primarily privately-owned land and allows surface and mineral rights to be owned and sold separately, which might also lead to conflict between separate developers.[294,295] Other states have specific wind and solar 'easements' that allow property owners to also own the rights to wind that flows over their property or protect them from neighbors blocking their sunlight.[296]

Fossil Fuel Generation

Fossil fuel consumption declines in all net-zero scenarios in this analysis, including Extensive Capture, though to a lower extent. Fossil fuel consumption declines primarily due to widespread end-use electrification and a decarbonizing grid. In our analysis, fossil fuel production declines commensurately with consumption, though we assume exports of fuel do not decline. Low-carbon electrification of end-use sectors contributes substantially to decarbonization and criteria air pollutant emission reductions in all net-zero scenarios. Buildings and transportation are discussed in the following sections.

Fossil fuel extraction, refining, and use makes up about 15% of the Texas economy.[297] Retiring fossil generators would reduce emissions and air pollutant emissions, benefiting surrounding communities that have higher rates of preterm delivery and low birth weights, asthma and other respiratory illnesses, and childhood cancers.[298–300] Additionally, reducing fossil fuel consumption at industrial facilities would have substantial air pollution benefits. A study of industrial emissions in Texas found that areas with a higher share of Black population were associated with exposure to excess emissions, both at the census tract level and facility level.[301] Excess emissions are also correlated with lower population density and fewer college graduates, though there is a positive correlation with median income potentially due to local economic benefits from industrial activity.[301] Though reducing fossil fuel consumption at industrial facilities would ameliorate air pollution impacts, exposure to chemicals in air pollution from industrial plants in Texas is also linked to low birth weight.[302] Older, less efficient industrial facilities are retired in most net-zero scenarios and either or both electricity and hydrogen are used for fuel consumption, but these efforts might not impact chemical pollution, which is an important consideration for Texas given its large chemicals industry.

Shutting down fossil fuel operations (mining and electricity generation) introduces multiple challenges for both individuals and the surrounding communities. In addition to job loss, finding new employment might require substantial commute distances, and the new positions, if available, might introduce wage and knowledge gaps from the prior positions.[269] Additionally, impacts to the local community can be significant and go beyond economic loss to include erosion of culture, community identity, and sense of place.[269] In Texas, the majority of counties with coal mines and gas wells that would be affected by closures are rural and white, with some predominantly Hispanic or Latino.[303–306] The markets are already moving away from coal. Previous analysis found that many coal plants across the nation would no longer be economically competitive with natural gas or renewables if they were upgraded with modern pollution control measures, and coal plants continue to close in Texas due to competition from cheap gas and renewables.[307–310] Sites near retired facilities or the sites themselves could become prime locations for new construction of solar, wind, or other green energy technologies due to the existing connections to the grid and proximity to load centers in certain areas; analysis from the National Academies of Science, Engineering, and Medicine (NASEM) has found that repurposing existing fossil fuel infrastructure can lower the costs associated with decarbonizing the energy system.[156]

Texas also has significant renewable energy resources, leading the nation in wind power generation and coming in second in solar power.[160] Locations that have both fossil energy expertise and rich renewable resources might not only offer vast economic potential in the energy transition, but might also minimize workforce disruption and displacement. Existing proposals, such as one by the Brookings Institution, suggest that Texas, where fossil fuel infrastructure and a large renewable energy potential overlap, is a prime location for policies like retraining workers, clean energy investment incentives, and increased funding in research and innovation.[311] But, in addition to minimizing new disruptions, policy makers should also be mindful of transferring existing inequalities within the fossil fuel industry, which is predominantly white and underrepresents Black, Hispanic or Latinx, and female employees, to a new clean-energy economy.[312–314] However, according to report prepared for the National Association of State Energy Officials, the U.S. renewable and non-fossil fuel energy sector might already face some of the same diversity challenges as the fossil fuel industry and feature similar levels of racial and gender representation across technologies.[314]

The tax revenue impact of decreasing fossil fuel production should also be considered, as this revenue is often used to fund public services. For example, the Permanent University Fund that Texas uses to fund the University of Texas and A&M systems is tied to revenue from state-owned leases on mineral rights on University lands. Historically, fossil fuel production has provided the vast preponderance of those royalties, benefitting Texans greatly. Those funding streams have had a positive impact of keeping costs of public education low, which is good for achieving many equity-related goals. However, commodity price swings and changes in production volumes year-to-year can dramatically affect the amount of money available to the state. Notably, many renewable resources are already built on public lands and do not face the same risks of depletion or commodity price volatility as fossil fuels, so it's possible that these decarbonization pathways provide more stable and non-depleting revenues to support Texas education initiatives. At the same time, existing utility-scale wind and solar projects in Texas might generate $4.7 and $5.7 billion in tax revenue for local communities in their lifetime, with over 70% of the taxes and landowner payments going to rural counties.[315]

Research shows that there isn't one solution for a just transition from traditional fuels to renewable energy, and a whole suite of policy levers including economic development, workforce development, public benefits, and updating infrastructure will be pivotal to this energy transition.[316] Federal efforts to alleviate the burden on communities like these include the White House Justice40 Initiative, which establishes an Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization to coordinate and assist efforts in coal, natural gas, and power plant communities.[317] A recent consensus study by NASEM provides comprehensive recommendations for decarbonizing the U.S. energy system, including establishing task forces and offices within the White House focused on supporting displaced workers and affected communities as well as training and educational initiatives.[156]

Building Electrification, Demand Management, and Efficiency

Across all net-zero scenarios except Extensive Capture, newly sold building appliances and components are electrified, building efficiency standards are improved, and older buildings are retrofitted with more efficient appliances. There are many benefits to be realized through building electrification and efficiency measures. Beyond the overall decarbonization impacts, there are positive health impacts of removing combustible fuels from cooking and everyday use.[24,97,318] Low-income families also devote an outsized share of their income to energy and would stand to benefit significantly from more efficient appliances and reduced energy bills. The portion of income spent on energy costs is referred to as the 'energy burden.'[319] Black and Latino households pay around the same or less in utility costs as white households, but these costs make up a much greater proportion of their overall family income. The median energy burden for Black households is 64% greater than white households, and for Latino households it is 24% greater than white households on average.[320] Black and Latino communities are also four times more likely to have their electricity disconnected due to nonpayment; the number of households experiencing disconnections doubled for these communities during the Covid-19 pandemic.[321] These financial strains can lead to Black and Latino communities experiencing more uncomfortable living conditions, with these residents reporting feeling uncomfortably cold for at least 24 hours at a rate 50% higher than the average Texan.[322] These conditions as well a high energy burden or energy insecurity can all lead to adverse physical and mental health outcomes, which in turn leads to higher living costs.[318,323]

Fossil fuel-powered stoves, water heaters, furnaces, dryers, fireplaces, and ovens can all impact indoor air quality and resident health.[318] Electrification of in-home heating in particular has received much attention in recent years for its ability to improve efficiency and reduce emissions.[95,318,324–328] About 21% of U.S. households might benefit economically from replacing their existing heater with an electric heat pump and 70% would reduce their emission damages (including carbon and criteria pollutant emissions), though benefits vary by location and local grid mix.[324] Analysis from the National Renewable Energy Laboratory has found that, among different residential efficiency improvements, Texas could see the most benefits from adopting heat pumps.[329,330] Heat pumps can also be a source of flexibility for the electric grid, providing demand response opportunities.[328]

Demand response strategies help reduce peak electric demand, which can lessen stress on the electric grid. Demand response programs have been shown to reduce utilities peak demand by an average of 10%.[331] There are numerous demand response policies, including consumer incentives for using energy outside of peak times, such as with Consumers Energy Smart Hours Rate and Portland General Electric's Peak Time Rebates.[332,333] Certain demand management approaches like using price signals might discriminate against low-income consumers who might not be able to avoid peak time energy use or would be more likely to sacrifice either comfort or other household expenses like food to do so.[334,335] Some strategies might be more effective in low-income households than others, like critical peak pricing, but low-income households might still be less responsive to price signals in general.[336,337] Technology interventions can help enhance demand response strategies and enable changes in consumption; in home displays and web portals can provide consumers with readily accessible information on pricing while appliances like smart thermostats can be even more effective at changing electricity use.[337] However, not all households will have access to these technologies. Low-income households and households of color are more likely to live in less efficient homes and appliances that lead to higher energy consumption, and these households might be more vulnerable to impacts from rising electricity prices and changing weather patterns.[269]

Improving the efficiency of commercial buildings has the potential to improve equity indirectly by lowering electricity or fuel costs and saving the companies' money, which could then be passed on to the consumers or be used to invest in new jobs and opportunities for local communities. However, the power to bring about equity improvements ultimately rests with the commercial entity.[338] In contrast, residential building efficiency standards more directly impact families and communities, and therefore might have a greater impact on equity. After previously having the oldest residential and building codes in the nation, in 2021, Texas updated its building codes to reflect the most up-to-date standards.[339] Many cities in Texas, such as Austin, institute additional policies or codes beyond the state building code standards to further increase energy efficiency.[340,341]

Bringing all US households up to the median household efficiency would eliminate 35% of the excess energy burden, which is the difference between a specific household's energy burden and the average energy burden.[320] Lowering the energy burden is especially important in Texas, where low-income households who earn less than $25,000 annually spend 12.5% of their income on energy. Conversely, households that make more than $25,000 a year spend only 4% of their income on energy.[342] Homeownership status impacts the likelihood of efficiency projects being completed. While renters would see the primary benefits and savings from improving household efficiency, the owners are the ones who decide whether or not to make the improvements. Homeowners might not be motivated to take on the cost burden of upgrading their homes if they aren't the ones who then also see the benefits. There are two federal programs aimed specifically at reducing the energy burden of low-income households: the Department of Health and Human Services'

Low Income Home Energy Assistance Program (LIHEAP) and the Department of Energy's Weatherization Assistance Program (WAP). While these programs have been found to be effective at helping to reduce energy consumption (leading to lower bills, less draftiness, and improved health), they are also both underutilized.[269]

Transportation Electrification and Demand Management

Transportation significantly electrifies in all net-zero scenarios except Extensive Capture, though Hydrogen and Carriers sees a higher portion of hydrogen-based transportation. These three net-zero scenarios also feature transportation demand management, aiming to reduce the emission intensity of transportation through reducing the demand for personal transport and shifting modes to less intensive options like mass transit or bikes. Electric transportation has documented environmental and public health benefits and is a key component of many decarbonization pathways.[155,156,158,177,343,344] This is especially important in Texas, where transportation-related carbon emissions have increased 52% since 1990.[345] Transportation emissions in Texas are the highest of any other state due to our high population, our preference for large trucks and cars, and our propensity for driving more miles.[134] Texas has the second highest vehicle miles traveled (VMT) of any state, just behind California.[135] Texas also has more miles of roads and rail than any other state.[132,133]

There is substantial literature on both the cost effectiveness and distributional equity of electric vehicle subsidies.[275,346–354] Electric vehicle subsidies have primarily gone to already wealthy buyers or those that would have purchased an electric vehicle anyways.[275,346] An analysis of the Clean Vehicle Rebate Project in California found that rebates have primarily been given to high-income buyers, and the share of rebates given to disadvantaged communities is disproportionately low, with the bottom 75% of households by median income receiving only 38% of total rebates.[264] Analysis of historic tax expenditures on clean energy technologies found that the top income quintile received 90% of electric vehicle credits since 2006.[275] Federal tax credits for electric vehicles can also be inaccessible for low-income consumers who do owe sufficient taxes to qualify.[355] Almost half of American households do not owe any federal income tax; this group is largely made up of low-income households, mainly those that are elderly people, people with disabilities, or students.[356] Recent analysis finds that income-based subsidies are more effective and equitable than uniform subsidies, though interactions with other policies can both reduce efficacy and increase progressivity of the subsidies.[347] Additionally, a review of the Enhanced Fleet Modernization Program in California found that the majority of the subsidy was realized by low- and middle-income consumers.[353] In addition to federal tax credits, Texas currently incentivizes electric transportation through the Texas Emissions Reduction Plan (TERP), which offers rebates on qualifying electric, natural gas, and hydrogen fuel cell vehicles.[357]

Transportation demand management strategies reduce emissions from the transportation sector by reducing the aggregate amount of miles traveled or redistributing miles traveled among different, lower-emission modes. Air quality benefits from reduced traffic congestion would be primarily felt in urban areas, which currently have the highest levels of air pollution and are home to Black and Latino populations at a rate almost double that of rural areas.[343,358] Additionally, there are oftentime cost benefits associated with these strategies for disadvantaged communities due to the reduced cost burden of high-density transportation compared to owning a vehicle, as well as additional benefits like improving neighborhood connectivity. [359] Another transportation demand strategy is the construction of infrastructure to encourage the adoption of lower-emitting vehicles, such as the construction of EV charging stations, or zero-emission options like bike lanes.

Several states have early-stage programs that address rising demand for EV charging stations through the encouragement of investor-owned utility (IOU) programs or policies directed by state public utility commissions (PUCs).[360,361] For example, in California the three largest IOUs in the state carried out EV pilot programs. Of these, the program that benefited the highest number of disadvantaged communities provided EV infrastructure and financing needed to create and run a new charging station while allowing customers to maintain and own these charging stations. [360] States can address market gaps by encouraging EV infrastructure in underserved communities, whether that be multifamily housing, low-income communities, or other areas. This concern is especially timely as major EV manufacturer Tesla plans to open up its fast-charging EV charger network to other automakers as soon as 2022.[362] Charging accessibility could ease range anxiety and increase charging availability, some of the most prominent barriers to the adoption of EVs.[363]

Carbon Management

Large amounts of carbon management are included across all net-zero scenarios, composed primarily of DACS and lower amounts of CCS and land use efforts like afforestation and reforestation. There is a lack of research on the social implications of rapidly scaling carbon management technologies, particularly DACS, though the literature is more developed for CCS and BECCS.[364–368] Concerns over BECCS tend to surround land, water, and fertilizer requirements. CCS has had difficulties scaling for a variety of reasons, including public acceptance, credibility of revenue, and competition from renewables.[364,369] Similar concerns for BECCS and CCS will likely exist for DACS in terms of social acceptance and procedural justice during deployment. Local opinion of storage operations will also play a role, as storage has received pushback in the past from communities located near storage facilities.[365] There might be fewer land and natural resource use concerns related to DACS than BECCS, which requires the production of biomass. DACS facilities are anticipated to have a smaller footprint and more flexibility in their location, but a rapid deployment and widespread deployment will substantially increase the required footprint and sorbent demand.

A primary concern over these technologies is cost.[364,367,369–371] Raising the price of electricity would disproportionately affect low-income households and those that already spend a substantial portion of their income on energy. In this analysis, system costs for DACS are passed onto consumers. Impacts to electricity rates vary by scenario, the highest retail rate increases are associated with the Extensive Capture scenario because almost all emissions are reduced solely through DACS. Electricity rates fall in the Hydrogen and Carriers scenario because decarbonization is spread throughout multiple sectors of the economy and the added capacity for clean hydrogen and fuels helps reduce the need for DACS. The impact of carbon management technologies on electricity and energy prices, particularly DACS, is an area in need of further study.

3.7 Summary and Conclusions

This report drew on three separate modeling techniques to develop four different pathways to reach economy-wide, net-zero emissions in the state of Texas by 2050. Economy-wide energy flows, electricity demand, and emissions under Business as Usual (BAU) and net-zero conditions were developed using the TX-EPS simulator. Detailed power sector and unit commitment modeling for each scenario was completed using WIS:dom-P to identify the least-cost mix for each pathway, and the economy-wide economic impacts of going net-zero were modeled using REMI, with the cost of emissions calculated separately.

All net-zero scenarios see positive economic impacts compared to the BAU. Compared to the BAU, average GDP in 2050 is 7.9% higher in the Hydrogen and Carriers scenario, 4.6% higher in Extensive Capture, and 1.6% higher in both the Electrification and Electrification: Accelerated Clean Power scenarios. If the benefits of reducing emissions are ignored, the Hydrogen and Carriers and Extensive Capture scenarios both see greater GDP in 2050 compared to BAU conditions (4.9% and 1.4%, respectively). The Hydrogen and Carriers scenario sees the largest economic benefits of the four net-zero scenarios in part because of a vibrant zero-carbon hydrogen industry that would develop from the traditional fuels industry. These results indicate that there are multiple ways Texas can achieve economy-wide net-zero emissions by 2050 and spur economic growth.

Electricity demand increases substantially across all four net-zero scenarios due to increasing end-use electrification from transportation, buildings, and industry, as well as deployment of DACS and electyrolysis. While all renewable resources and storage see substantial growth out to 2050, the majority of 2050 generation in each net-zero scenario consists of onshore wind. Texas has rich renewable resources, which, when coupled with flexible DACS, are complementary for decarbonization as DACS can help improve the utilization of otherwise variable renewable resources as their percentage grows within the generation mix. DACS can also help capture the most expensive and hardest-to-abate emissions, like industrial process emissions or aviation fuels. All net-zero scenarios retain some natural gas with CCS in 2050 for peaking capacity and firm generation except Electrification: Accelerated Clean Power, which requires a fully zero-carbon grid by 2035. This scenario sees rapid deployment of wind, solar, and storage to reach zero-carbon and also builds advanced generation resources like SMR nuclear and enhanced geothermal to provide zero-carbon firm capacity after 2035 when costs for these technologies become more competitive.

End-use electrification as well as efficiency standards and 'clean-up-your-act' policies that focus on preventing leaks and improving end-of-life management for high GWP greenhouse gases are important throughout all scenarios. However, across all net-zero scenarios, the industrial sector stands out as critically important for decarbonization goals. Policies affecting the industrial sector—electrification and hydrogen fuel use, efficiency standards, or preventing methane leaks, etc.—have the largest combined impact on reducing (or preventing) emissions. However, most of the 'leftover' emissions that are abated by DACS are industrial process emissions, which are harder to curtail. While a tonne of carbon removed from the air might have different climate impacts than a tonne of carbon never emitted, DACS systems can help capture these difficult leftover emissions and alleviate the strain of reconfiguring highly optimized industrial processes or developing advanced feedstocks while positioning Texas as a leader in carbon removal. Similarly, using hydrogen as an industrial fuel source and shifting hydrogen production to electrolysis can reduce the capacity of DACS needed to reach net-zero while also making Texas a leader in hydrogen production from electrolysis and providing substantial economic benefits. Each of these new industries can make Texas a technology leader with the ability to export our expertise to other countries.

Future work should expand on DACS to evaluate the potential of other carbon removal technologies, like BECCS, within Texas. This analysis models an all-electric DACS system, but other technologies use both electricity and gas. These systems should also be studied to further gauge the impact on net-zero ambitions and the fuel sector. The scenarios in this study also lean heavily towards variable renewable resources, in particular wind. Future work should further evaluate firm low-carbon resources within Texas, like enhanced geothermal power. Future work should also expand criteria emission accounting to capture those from other sectors like transportation.

4.0 Methodology

This analysis used a combination of three modeling techniques to capture the effects of an economy-wide net-zero transition by 2050. The three models were used in sequence, with outputs of one serving as inputs into the next. The Texas Energy Policy Simulator (TX-EPS) was the first modeling approach used; the TX-EPS captures energy and resource flows throughout the state under Business as Usual (BAU) conditions and then quantifies and illustrates how policy interventions change those flows. The TX-EPS was used to develop all five scenarios, which include the BAU and net-zero scenarios. Electricity demand, and leftover emission profiles (i.e., emissions that were not reduced through initial policy intervention in the TX-EPS) were then used as input into the WIS:dom-P model, which modeled the power sector in greater detail and deployed additional technologies (including DACS and electrolysis for hydrogen production) to achieve fully net-zero emissions by 2050. Changes in spending within the power sector (capital costs, fixed and variable costs, etc.) from WIS:dom-P and changes in revenue from non-energy industries as well as non-power sector energy industry (i.e., 'fuel sector') from the TX-EPS served as input into the Regional Economic Modeling, Inc. (REMI) model for statewide economic impact analysis. The rest of this section provides more detail on each modeling technique and how they were combined.

4.1 The Texas Energy Policy Simulator (TX-EPS)

The Energy Policy Simulator (EPS) is a free, open-source, and interactive computer model created by Energy Innovation LLC that lets users control numerous policies across all economic sectors and determine the policy impacts on various energetic, environmental, and economic metrics. The simulator is a system dynamics model built using open-source data in the software program Vensim and is developed for fifteen different regions, including the US. Vensim is a tool produced by Ventana Systems for the creation and simulation of system dynamics models.

To gauge the impact of policy intervention, the EPS must first determine Business as Usual (BAU) conditions. The EPS builds this BAU scenario based on a set of input data that are customized to the region being modeled. These underlying input data files are available for download at https://texas.energypolicy.solutions/docs/. EPS users can then add different policies with varying implementation timelines and levels of efficacy achieved, creating new scenarios. For a more detailed methodology and complete list of EPS functionalities, please refer to the EPS documentation, available at https://us.energypolicy.solutions/docs/.

For the purpose of this study, the EPS was adapted to Texas and used to construct multiple net-zero emission pathways across the complete Texas economy. Input data to the EPS were updated to establish BAU conditions for Texas, and the resulting Texas-specific EPS (TX-EPS) was used to build the policy scenarios and obtain the resulting electricity demand and emission profiles. In some cases, demand for various other fuels (e.g., freight shipping fuel or hydrogen) were also isolated. As all the underlying relationships between sectors, policies, and output metrics were already established for the National-level EPS framework, adapting the EPS to Texas greatly simplified the process of building a state-level model of Texas energy use and emissions under various policy conditions.

TX-EPS Sectoral Accounting

The EPS defines five primary sectors: buildings, district heat and hydrogen, electricity, industry, and transportation, with detailed subdivisions within each sector. The EPS also defines separate land use and geoengineering sectors that represent negative emissions (though they are not limited to negative emissions). Emissions resulting from the generation of electricity for end-use sectors are accounted for in the electricity sector. For example, emissions resulting from an increase in electric generation due to more electric vehicles would not be added to the transportation sector. This applies to all sectors; increasing electrification of buildings, industrial processes, and transportation shifts emissions away from the end-use sectors and to the electric sector. Additionally, vehicles used for industrial purposes, such as farm tractors, are accounted for in the industry sector. Detailed information on EPS sectoral accounting is available online in the Energy Policy Simulator Documentation, available at https://us.energypolicy.solutions/docs/index.html.

4.2 The WIS:dom-P Model

The WIS:dom® (Weather-Informed energy Systems: for design, operations and markets) optimization planning model is the state-of-the-art energy model developed by Vibrant Clean Energy, LLC (VCE). It is the first commercial co-optimization model of energy grids that was built from the ground up to incorporate vast volumes of data, starting with high-resolution weather and demand data.

WIS:dom-P simultaneously co-optimizes the capacity expansion requirements (generation, transmission, and storage) and the dispatch requirements (production cost, power flow, reserves, ramping, and reliability) for the entire electric (energy) grid of interest (in this case, Texas). Not only does WIS:dom co-optimize these critically linked properties, it was developed from the ground up to work with "big data." The model can determine the cost/benefit ratios for new high-voltage direct current transmission lines, compared with other technologies. It can also determine the risk and rewards from retiring existing generators for the topology of the transmission infrastructure, simultaneously determining how more variable generation is deployed to replace them.

WIS:dom utilizes high-resolution (spatially and temporally) weather data to determine resource properties over vast spatial-temporal horizons. Thus, WIS:dom can be used on scales as small as campuses, cities, counties or states/provinces; but uniquely can also be used for sovereign entities and continents. Moreover, these scales can be nested, allowing high-fidelity local modeling accompanied with lower-fidelity larger areas to create feedbacks within the model that simulate outside influences on local markets.

The model relies on publicly available data where possible, and contains default values for generators, transmission, storage, production cost and resource siting. However, WIS:dom was designed from the beginning to allow "plug-and-play" capability, whereby it can take advantage of customized datasets required for detailed modeling of specific questions, markets or balancing areas, such as higher-resolution weather data over a utility or Independent System Operators or proprietary heat rates for generators within a utility.

The modeling framework is unique and consistent across various scales facilitating more transparent analysis between results derived. With WIS:dom new opportunities are identified due to the co-optimization detecting patterns ignored by other modeling endeavors.

The WIS:dom optimization model allows datasets to be added for specific local interests. For example, WIS:dom can be deployed for any country or continent around the globe. The model requires the local datasets (or uses the default global one) and then can study various questions of interest, such as greenhouse gas emission, high-voltage direct current transmission links, variable generation and reliability, water consumption, air pollution, electric vehicle penetrations, electric heating, jobs and tax revenues, and more. Detailed methodology for the scenario analyses in this report are available in Appendix F.

4.3 The REMI Model

We used the Regional Economic Models, Inc Policy Insight (REMI-PI$^+$) model for economic forecasting, which REMI describes as a structural economic forecasting and policy analysis model. It integrates input-output, computable general equilibrium, econometric, and economic geography methodologies. The model is dynamic, with forecasts and simulations generated on an annual basis and behavioral responses to wage, price, and other economic factors. For a complete description, further documentation is available at https://www.remi.com/model/pi/ .

We used the 160-sector REMI-PI$^+$ model for the analysis, which was constructed using national and local economic and demographic data specifically for the state of Texas and 10 regions within the state. The REMI-PI$^+$ model used for this analysis is a 10-region, E3+ model 2.4 specifically designed for energy analysis. We combined the 12 economic regions of Texas, as defined by the comptroller (Figure 3.1) into 10 based on similarities in location, population size, and economies. We combined Upper East and Southeast into the 'East' region, and combined Upper Rio Grande with West to make the 'West' region.

The REMI-PI$^+$ model consists of thousands of simultaneous equations with a structure that is relatively straightforward. The exact number of equations used varies depending on the extent of industry, demographic, demand, and other details in the model. The overall structure of the model can be summarized in five major blocks: 1) Output and Demand, 2) Labor and Capital Demand, 3) Population and Labor Supply, 4) Compensation, Prices, and Costs, and 5) Market Shares. Figure 4.1 visualizes these blocks and their interactions, which are further described below.

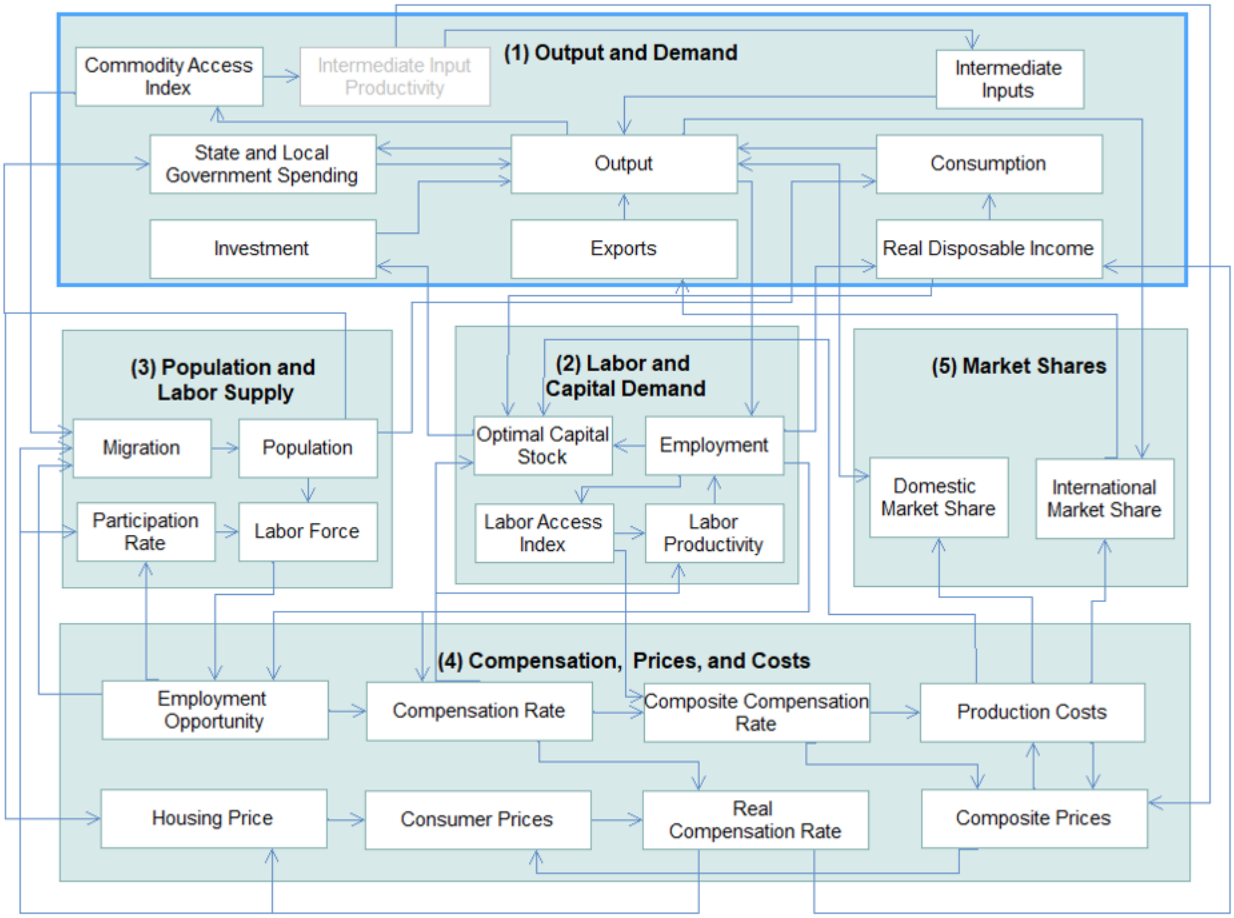

Figure 4.1: This figure shows the different component blocks of the REMI-PI$^+$ model calculations and their interactions.

Block 1: Output and Demand

This block includes output, demand, consumption, investment, government spending, import, product access, and export concepts. For each industry, demand is determined by the amount of output, consumption, investment, and capital demand on that industry. Consumption depends on real disposable income per capita, relative prices, differential income elasticities and population. Input productivity depends on access to inputs because the larger the set of inputs, the more likely that the input with the specific characteristics required for the job will be formed. In the capital stock adjustment process, investment occurs to fill the difference between optimal and actual capital stock for residential, non-residential, and equipment investment. Government spending changes are determined by changes in the population.

Block 2: Labor and Capital Demand

The Labor and Capital Demand block includes the determination of labor productivity, labor intensity and the optimal capital stocks. Industry-specific labor productivity depends on the availability of workers with differentiated skills for the occupations used in each industry. The occupational labor supply and commuting costs determine firms' access to a specialized labor force.

Labor intensity is determined by the cost of labor relative to the other factor inputs, capital and fuel. Demand for capital is driven by the optimal capital stock equation for both non-residential capital and equipment. Optimal capital stock for each industry depends on the relative cost of labor and capital, and the employment weighted by capital use for each industry. Employment in private industries is determined by the value added and employment per unit of value added in each industry.

Block 3: Population and Labor Supply

The Population and Labor Supply block includes detailed demographic information about the region. Population data is given for age and gender, with birth and survival rates for each group. The size and labor force participation rate of each group determines the labor supply. These participation rates respond to changes in employment relative to the potential labor force and to changes in the real after-tax compensation rate. Migration includes retirement, military, international and economic migration. Economic migration is determined by the relative real after-tax compensation rate, relative employment opportunity and consumer access to variety.

Block 4: Wages, Prices, and Costs

This block includes delivered prices, production costs, equipment cost, the consumption deflator, consumer prices, the price of housing, and the wage equation. Economic geography concepts account for the productivity and price effects of access to specialized labor, goods and services.

These prices measure the price of the industry output, taking into account the access to production locations. This access is important due to the specialization of production that takes place within each industry, and because transportation and transaction costs of distance are significant. Composite prices for each industry are then calculated based on the production costs of supplying regions, the effective distance to these regions, and the index of access to the variety of output in the industry relative to the access by other uses of the product.

The cost of production for each industry is determined by cost of labor, capital, fuel and intermediate inputs. Labor costs reflect a productivity adjustment to account for access to specialized labor, as well as underlying compensation rates. Capital costs include costs of non- residential structures and equipment, while fuel costs incorporate electricity, natural gas and residual fuels.

The consumption deflator converts industry prices to prices for consumption commodities. For potential migrants, the consumer price is additionally calculated to include housing prices. Relative to their initial level, housing price changes depend on changes in income and population density.

Compensation changes are due to changes in labor demand and supply conditions, and changes in the national compensation rate. Changes in employment opportunities relative to the labor force and occupational demand change determine compensation rates by industry.

Block 5. Market Shares

The Market Shares equations measure the proportion of local and export markets that are captured by each industry. These depend on relative production costs, the estimated price elasticity of demand, and effective distance between the home region and each of the other regions. The change in share of a specific area in any region depends on changes in its delivered price and the quantity it produces compared with the same factors for competitors in that market. The share of local and external markets then drives the exports from, and imports to, the home economy.

The Labor and Capital Demand block includes labor intensity and productivity as well as demand for labor and capital. Labor force participation rate and migration equations are in the Population and Labor Supply block. The Wages, Prices, and Costs block includes composite prices, determinants of production costs, the consumption price deflator, housing prices, and the wage equations. The proportion of local, inter-regional and export markets captured by each region is included in the Market Shares block.

4.4 Connecting the Models

The TX-EPS model was used to determine state-level electricity demand and emission profiles for the BAU and net-zero scenarios. The WIS:dom-P model was used to determine the full transformation of the power sector required to meet the projected electricity demand while reaching net-zero carbon emissions by 2050 in all scenarios other than BAU. The only difference in electricity demand between the models is based on increases in electric load due to the added use of low-carbon technologies (e.g., electrolysis for hydrogen production and DACS), all of which were determined in WIS:dom-P and then matched as closely as possible in the TX-EPS using the corresponding policy levers. Input data sources and assumptions were matched as closely as possible between the two models for consistency.

Economic results from both the TX-EPS and WIS:dom-P models were used as input for the REMI-PI$^+$ modeling. Power sector system costs including capital expenditures, operating expenditures, and consumer spending on electricity were taken from the WIS:dom model for detailed, region-specific economic analysis. Changes in statewide fuel production and non-power sector industry cash flows (statewide, not region-specific) were taken from the TX-EPS. International Standard Industrial Classification of All Economic Activities, or ISIC, codes used in the TX-EPS were mapped to North American Industry Classification System, or NAICS, codes for REMI-PI$^+$ analysis.

Emission costs were calculated for both greenhouse gas emissions and marginal criteria pollutant emissions. Marginal criteria pollutant emissions were determined on a regional basis in WIS:dom-P for the power sector and at an aggregate, state-wide for all other economic sectors in the TX-EPS. Marginal costs for $PM_{2.5}$, NO_X, and SO_2 were determined using the EASIUR reduced-form model.[195-197] The cost of emissions of CO_2, CH_4, N_2O, and F-gases were calculated by converting all emissions to CO_2e using their associated GWPs and then scaling by the social cost of carbon using the 3% average discount rate.[193]

4.5 TX-EPS and WIS:dom-P Discrepancies

The Hydrogen and Carriers scenario is included in the publicly available TX-EPS simulator as a pre-set scenario available to all users. Due to methodological differences, the TX-EPS and WIS:dom-P scenario results contain some minor discrepancies. For example, the models may produce different results for future electric generation and fleet mix given the same electricity demand conditions. In other words, both models have the same demand but might determine different ways to meet that demand. The TX-EPS uses a built-in capacity expansion model with an annual timestep, while WIS:dom-P is a unit commitment model with 5-minute timestep that allows it to account for diurnal weather patterns. Start year conditions are more closely aligned between the models due to greater availability of data. Levers in the TX-EPS were used to match WIS:dom-P results as closely as possible. For example, there is no requirement in the net-zero scenarios (except in Electrification: Accelerated Clean Power) for the grid to decarbonize, but it does under the dual constraint of reaching economy-wide net-zero emissions by 2050 at the lowest costs. The Clean Electricity Standard lever was used to better match generation profiles in 2050 between the two models. Levers in the TX-EPS were also used to match the TX-EPS to WIS:dom-P results for DACS capacity, production of hydrogen from electrolysis, storage capacity, and transmission build out.

Discrepancies in the power sector lead to additional discrepancies in the final emission profiles between the two models. Power sector emissions are factored out of the TX-EPS load data that feed into WIS:dom-P, as WIS:dom-P calculates generation mix and emission intensity endogenously. These emission profiles are the ones presented in this report. However, because the generation mix was not completely matched between WIS:dom-P results and the TX-EPS, economy-wide emissions in the TX-EPS are calculated based off of a different grid emissions intensity. Because of this, emissions in the final TX-EPS pre-set scenario available on the TX-EPS do not completely reach zero in 2050.

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